UNIVERSITY OF SOUTHAMPTON

FACULTY OF HEALTH SCIENCES

Centre for Innovation and Leadership in Health Sciences

Relationship between Trunk Control and Recovery of Upper Extremity Function in Stroke Patients

by

Seng Kwee Wee

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ABSTRACT

FACULTY OF HEALTH SCIENCES

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RELATIONSHIP BETWEEN TRUNK CONTROL AND RECOVERY OF UPPER EXTREMITY FUNCTION IN STROKE PATIENTS

Seng Kwee Wee

Stroke affects the ability of the trunk muscles to maintain an upright posture and maintain the base of support during static and dynamic postural adjustments. The trunk is considered an important postural stabilizer which enables the dissociation of the upper extremity from the trunk for function. However, this common assumption in neurorehabilitation has not been validated in clinical trials. The association between trunk control and recovery of upper extremity function in stroke patients is not known currently.

The cross-sectional studies (Phase 1A and Phase 1B studies) investigated the relationship between trunk control and upper extremity function in 45 subacute stroke and 25 chronic stroke participants, and 34 age- and sex-matched healthy controls. Trunk control and upper extremity function were assessed using the Trunk Impairment Scale (TIS) and Streamlined Wolf Motor Function Test (SWMFT) respectively. The participants performed SWMFT tasks, with and without an external trunk support in random order. Kinematic data were captured with the Vicon motion capture system in the Phase 1A study with chronic stroke participants and healthy controls.

With trunk support, there was statistically significant improvement in trunk control (TIS) of subacute and chronic stroke participants; improvement in SWMFT performance time (SWMFT-Time) of the upper extremity of the stroke participants and the healthy controls; and improvement in SWMFT-Functional Ability Scale (SWMFT-FAS) in stroke participants. There was also statistically significant improvement in movement smoothness and elbow extension of the affected upper extremity of chronic stroke participants. The findings suggest that stabilization of the trunk enables an improved ability to use the upper extremity for functional activities. Significant strong associations were found between trunk control and upper extremity impairment (Fugl-Meyer score, FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS).

The longitudinal study (Phase 2 study) examined the recovery pattern of trunk control and upper extremity impairment and function in 45 subacute stroke participants in the first 6 months following stroke. The results further confirmed the findings of the cross-sectional studies (Phase 1A and Phase 1B studies) about the strong association between trunk control and upper extremity in the first 6 months post stroke. The rate of change of the recovery curves of trunk control and upper extremity impairment was found to be similar over time. As TIS scores improved over time, both the upper extremity impairment (FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS) improved almost in parallel with the TIS increase. The results imply that trunk control has an association with the recovery of the upper extremity.

This PhD work has deepened our understanding about trunk control and upper extremity in people with stroke and provided valuable insights for rehabilitation professionals and researchers. The findings will assist therapists to design comprehensive programmes for rehabilitation of trunk control and upper extremity at different stages of stroke recovery; and aid in the prognostication of trunk and upper extremity recovery post stroke and therefore, will have an impact on clinical practice.

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DECLARATION OF AUTHORSHIP

I, Seng Kwee Wee, declare that the thesis entitled 'Relationship between Trunk Control and Upper Extremity Function in Stroke Patients' and the work presented in the thesis are my own, and have been generated by me as the result of my own original research. I confirm that:

- this work was done wholly or mainly while in candidature for a research degree at this University;
- 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;
- where I have consulted the published work of others, this is always clearly attributed;
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- 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;
- parts of this work have been published or presented as:

Publications

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2015) Effect of trunk support on upper extremity function in people with chronic stroke and people who are healthy. *Physical Therapy*. Published online February 26, 2015. DOI: 10.2522/ptj.20140487. (Appendix 1)

Wee SK, Hughes AM, Warner MB and Burridge JH (2014) Trunk restraint to promote upper extremity recovery in stroke patients: a systematic review and meta-analysis. *Neurorehabilitation and Neural Repair*: 2014 Sep;28(7):660-77. DOI: 10.1177/1545968314521011. (Appendix 2)

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH, Yeo SCD, Kong KH and Chan KF (2015) Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. *Physiotherapy* 101(Supplement 1): eS1619. (Appendix 3)

Manuscripts in preparation for submission

Wee SK, Warner MB, Hughes AM, Brown S, Cranny A, Mazomenos EB, Burridge JH (2015) Kinematic analysis of the effect of trunk support on functional reaching in people with chronic stroke and healthy controls.

Wee SK, Warner MB, Hughes AM, Burridge JH, Yeo SCD, Kong KH, Chan KF (2015) Longitudinal analysis of the recovery of trunk control and upper extremity in people with subacute stroke: An individual growth curve approach.

Wee SK, Hughes AM, Warner MB, Burridge JH, Yeo SCD, Kong KH, Chan KF (2015) Is there a difference in the rate of recovery of the proximal and distal segments of the upper extremity post stroke? A longitudinal analysis.

Oral Presentations

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2014) Relationship between trunk control and upper extremity function in healthy individuals and chronic stroke patients. Invited Speaker at the 8th Annual Southern Stroke Forum Conference, United Kingdom, 14th February 2014.

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2015) Impact of trunk support on upper extremity function in chronic stroke patients and healthy controls: clinical and kinematic analysis. Oral presentation at the 4th Singapore Rehabilitation Conference 2015, Singapore, 26th – 27th March 2015.

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH, Yeo SCD, Kong KH, Chan KF (2015) Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. Oral presentation at the World Confederation for Physical Therapy (WCPT) Congress 2015, Singapore, 1st – 4th May 2015.

Wee SK (2014) Is this the missing link to better arm recovery in stroke patients? A peek into the core: trunk control. 3-Minute Thesis Competition, University of Southampton, United Kingdom, 26th February 2014.

Poster Presentations

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2014) Impact of trunk control on the performance of upper extremity functional tasks in healthy individuals and chronic stroke patients. Poster presentation at the Health Technologies Poster Exhibition, University of Southampton, United Kingdom, 19th February 2014. Awarded the ***Best Poster Presentation.***

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2014) Impact of trunk control on the performance of upper extremity functional tasks: a pilot study on healthy individuals. Poster presentation at the 8th World Congress for Neurorehabilitation 2014, Istanbul, Turkey, 9th April 2014.

Signed:

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Glossary of Abbreviations

ADL	Activities of daily living
AMC	Acromion marker cluster
APA	Anticipatory postural adjustment
ARAT	Action Research Arm Test
BBS	Berg Balance Scale
CIMT	Constraint-induced movement therapy
CMC	Coefficient of multiple correlation
cM1	Contralateral motor cortex
CNS	Central nervous system
CST	Corticospinal tract
DALYs	Disability-Adjusted Life Years
DTI	Diffusion tensor imaging
DTT	Diffusion tensor tractography
FIM	Functional Independence Measure
FMA	Fugl-Meyer Upper Extremity Assessment
fMRI	Functional magnetic resonance imaging
HMC	Humerus marker cluster
ICF	International Classification of Functioning, Disability and Health
IGC	Individual growth curve
iM1	Ipsilateral motor cortex
iMEP	ipsilateral motor evoked potentials
MCID	Minimal clinically important difference
MDC	Minimal detectable change
MEP	Motor evoked potentials
MVGF	Maximal voluntary grip force
NHS	National Health Service
NIHSS	National Institutes of Health Stroke Scale
PASS	Postural Assessment Scale for Stroke

PREP	Predicting Recovery Potential algorithm
PTMC	Posterior thorax marker cluster
RCT	Randomised controlled trial
ROM	Range of motion
RS	Radial styloid
SATCo	Segmental Assessment of Trunk Control
SD	Standard deviation
SPANOVA	Split plot analysis of variance
SWMFT	Streamlined Wolf Motor Function Test
SWMFT-FAS	Streamlined Wolf Motor Function Test-Functional Ability Scale
SWMFT-Time	Streamlined Wolf Motor Function Test-Time
TEMPA	Test Évaluant les Membres supérieurs des Personnes Âgées
TCT	Trunk Control Test
TD	Trunk displacement
TIS	Trunk Impairment Scale
TMS	Transcranial magnetic stimulation
TRE	Trunk repositioning error
UDP	Use-dependent plasticity
UE	Upper extremity
US	Ulnar styloid
UK	United Kingdom
UMN	Upper motor neuron
WMFT	Wolf Motor Function Test
WHO	World Health Organisation
YLD	Years of Life Lived with Disability

Glossary of Terms

Degrees of freedom	the number of possible ways in which a body can move in terms of translations and rotations
Euler angle	the angle that is represented by three sequential rotations about anatomical axes
Kinematic	motion analysis without regard to the force producing the motion
Minimal detectable change	the smallest amount of change that likely reflects true change rather than measurement error inherent in the score (Lin et al. 2009b)
Minimal clinically important difference	the minimal change in the score that is meaningful for patients
Neuroplasticity	the ability of the nervous system to respond to intrinsic and extrinsic stimuli by reorganizing its structure, function and connections (Cramer et al. 2011)
Trunk control	the ability to stabilize and activate selective movements of the trunk (Verheyden et al. 2007)

Word count: 74,967

Chapter 1: Introduction

1. Introduction

This Chapter presents a justification for this doctoral research, outlines the specific aims and objectives of the study and summarises the experimental components of the research and the main findings. The original contributions made to the body of knowledge in stroke rehabilitation arising from this study are outlined. The thesis structure is explained and the publications, oral and poster presentations resulting from the study are listed.

1.1 Justification for this research

1.1.1 Stroke and its impact

The World Health Organization (WHO) defines stroke as “rapidly developing clinical signs of focal (or global) disturbance of cerebral function, with symptoms lasting 24 hours or longer or leading to death, with no apparent cause other than of vascular origin” (World Health Organisation 1988).

Stroke is one of the top three causes of death and the largest cause of adult disability in England. Around 110,000 strokes occur in England each year. Approximately 300,000 people are living with moderate to severe disabilities as a result of stroke (National Audit Office 2010). This can place a tremendous burden on the carers to assist them in activities of daily living. In addition to physical burden, Greenwood and Mackenzie (2010) reported that carers experience biographical disruption which involves both loss and change in roles and relationships and in their sense of their identity. There is also a huge economic impact on the stroke patients, families and society (Feigin et al. 2008).

Between 2008 and 2009, at least £3 billion was spent on the direct care cost of stroke annually (National Audit Office 2010). Saka et al. (2009) reported that in the United Kingdom (UK), the treatment of stroke and productivity loss due to death and disability arising from stroke results in total societal costs of £8.9 billion a year. The annual direct cost of stroke care is approximately £4 billion,

of which £1 billion is accounted for by the inpatient and outpatient rehabilitation therapy cost. This is equivalent to 1.38% of total UK National Health Service (NHS) expenditure (Saka et al. 2009).

As stroke is an age-related disease (Di Carlo et al. 1999; Denti et al. 2008; Scarborough et al. 2009; Andersen et al. 2010; Berry et al. 2012; Zhang et al. 2012), without preventative measures, the cost is likely to increase with the changing demographics of an aging population. In England, the percentage of people above the age of 65 will increase from 16% in 2005 to 25% in 2050 (Knapp et al. 2007). Overall for the UK, it is estimated that the percentage of people above the age of 65 will increase by 66% from 2008 to 2040 (Kinsella & He 2009).

Stroke burden is projected to increase from around 38 million Disability-Adjusted Life Years (DALYs) lost globally in 1990 to 61 million DALYs in 2020 (Mackay & Mensah 2004; Murray et al. 2012). Extrapolating from this, there will be potential strain placed on the expenditure on healthcare in the future. Therefore, improving functional outcome of stroke survivors is critical to reduce the impact on the individual, their carers and the wider society.

1.1.2 Trunk control post stroke

Trunk control is commonly affected after stroke. The neurological insult affects control of the trunk muscles to allow the body to remain upright, adjust to weight shifts and perform selective movements of the trunk that maintain the base of support during static and dynamic postural adjustments (Fisher 1987; Verheyden et al. 2004).

The trunk has been considered to be the central key point or the core of the body (Davies 1990b; Edwards 1996; Davies 2000). It plays an integral role in postural stabilization and also enables mobility of the body and the extremities during task performance. Voluntary arm movements that are used in activities of daily living require the stabilization of more proximal segments, namely the trunk and legs, and the maintenance of seated or standing balance (Lee 1989).

It is stated by Carr and Shepherd (1987), Davies (1990a), Mohr (1990), Gillen (1998) and Shumway-Cook and Wollacott (2000) that the trunk is an important postural stabilizer which enables dissociation of the upper and lower

extremities for function. The development of trunk stability and central axis control is considered to be a prerequisite to upper extremity function and hand usage. It is hypothesized that proximal stability allows for the independent use of the arms and hands in manipulative and purposeful activity (Rosenblum & Josman 2003). However, this common assumption in neurorehabilitation has not been validated in clinical trials. The actual association of trunk control with upper extremity function in people with stroke is not known currently. This knowledge is critical to the design of targeted rehabilitation programmes for the trunk and upper extremity so that optimal functional outcomes for stroke patients can be achieved. Hence, this is a gap in knowledge that warrants research to illuminate this relationship.

1.1.3 Upper extremity post stroke

Extensive research into the patterns of recovery and functional outcomes of the upper extremity post stroke has been conducted over the past years. Studies have reported that 33% to 66% of stroke patients with a paretic upper extremity do not show any recovery of upper extremity function 6 months after stroke (Wade et al. 1983; Sunderland et al. 1994; Kwakkel et al. 2003). Depending on the outcome measures used, 5% to 34% of stroke patients achieve full functional recovery of upper extremity function at 6 months (Heller et al. 1987; Nakayama et al. 1994a; Hendricks et al. 2002; Nijland et al. 2010b; Kong et al. 2011). Based on a recent study, 41% of people with moderate to severe stroke and 78% with milder stroke are estimated to regain dexterity 6 months after onset (Houwink et al. 2013). Hence, improved upper extremity recovery will have a positive effect on activities of daily living (ADL).

With impairments of the upper extremity, stroke survivors face difficulty in performing everyday tasks that involve reaching and grasping. This impacts both daily living and well-being (Mayo et al. 2002; Nichols-Larsen et al. 2005; Feigin et al. 2008; Morris et al. 2013). Movements of the affected upper extremity in patients with stroke explain up to 40% of the variance in abilities to perform the normal activities of daily living (Mercier et al. 2001). Strong evidence exists to support that upper extremity paresis is one of the key predictors for outcome of ADL (Veerbeek et al. 2011).

1.1.4 Relationship between trunk performance and functional outcome

There is strong evidence that trunk performance is an important predictor of overall functional outcome after stroke (Franchignoni et al. 1997; Duarte et al. 2002; Hsieh et al. 2002; Sebastia et al. 2006; Verheyden et al. 2007; Di Monaco et al. 2010). The reported variance of functional recovery after stroke explained by trunk control ranges from 45% (Hsieh et al. 2002) to 71% (Franchignoni et al. 1997). These studies clearly illustrate that trunk control impacts on many facets of the recovery of stroke survivors, such as ADL, balance and gait. However, there is no research currently which builds upon these findings to investigate the impact of trunk control on recovery of upper extremity function in stroke patients specifically, even though the upper extremity plays a vital role in the performance of ADL (Clarke 2002; Desrosiers et al. 2003b).

This doctoral study will advance understanding of how the upper extremity recovers in relation to trunk control post stroke. The new knowledge is critical to the design of targeted rehabilitation programmes for the trunk and upper extremity so that optimal functional outcome for stroke patients can be achieved.

1.2 Study aim and objectives

The primary aim of this PhD research was to deepen and advance understanding of the relationship between trunk control and upper extremity function in subacute and chronic stroke patients. It would also shed light on the recovery of trunk control and upper extremity function over time, from subacute to chronic stages of stroke recovery.

This PhD research consists of Phase 1 and Phase 2 studies. The Phase 1 study is subdivided into Phase 1A and Phase 1B studies. The Phase 1A study serves to address the research question:

What is the relationship between trunk control and upper extremity impairment and function in chronic stroke participants?

The Phase 1B study serves to address the research question:

What is the relationship between trunk control and upper extremity impairment and function in subacute stroke participants?

The Phase 2 study addressed the following research question:

What is the relationship between trunk control and recovery of upper extremity impairment and function during the first 6 months post stroke?

The results of this doctoral study will provide valuable insights for rehabilitation professionals and researchers. The findings will deepen the understanding of the complex relationship between trunk control and upper extremity function in stroke patients. This will add to the body of knowledge in stroke rehabilitation. The findings will assist therapists to design comprehensive programmes for rehabilitation of trunk control and upper extremity at different stages of stroke recovery. In addition, the study will aid in the prognostication of trunk and upper extremity recovery after stroke, and therefore, has an impact on clinical practice.

1.3 Overview of this PhD research

Figure 1-1 illustrates the overview of this PhD research study and the key investigations conducted for the Phase 1 study and Phase 2 study.

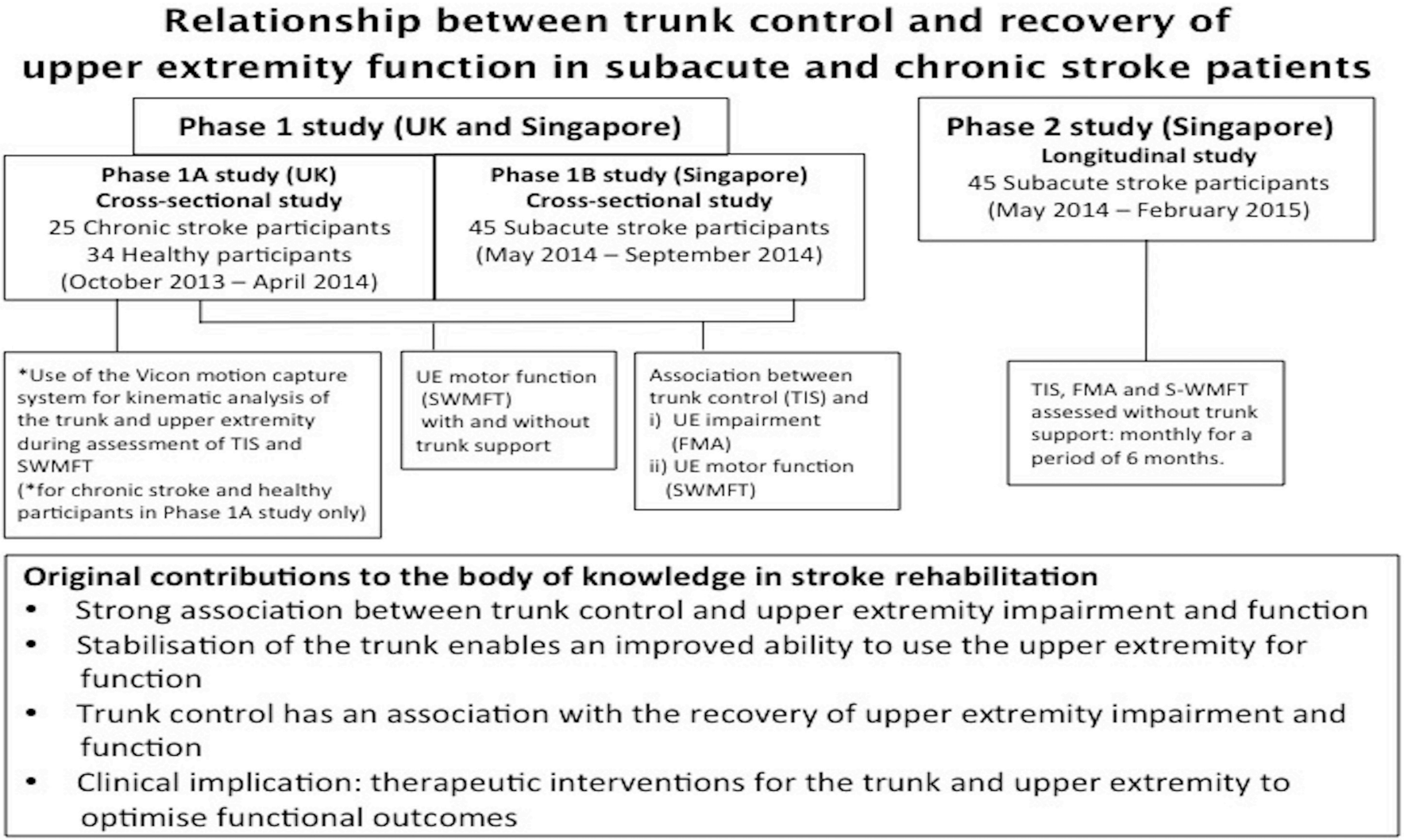


Figure 1-1 Overview of my PhD research study

1.4 Original contributions to the body of knowledge in stroke rehabilitation

The following findings are the original contributions made to the body of knowledge in stroke rehabilitation that arise from the Phase 1 study and Phase 2 study:

1) There is a statistically significant strong association between trunk control and upper extremity impairment and function in both subacute and chronic stroke participants.

2) Stabilization of the trunk enables an improved ability to use the upper extremity for function in subacute and chronic stroke participants and healthy participants. It also helps to improve the smoothness of movement and elbow range of motion during reaching.

3) Improving active control of the trunk has the potential to facilitate better control and coordination of the upper extremity in subacute and chronic stroke patients and hence promote recovery.

4) The recovery curves of the trunk and upper extremity were similar, with the most rapid recovery occurring in the first 3 months followed by a deceleration in the rate of recovery from the 4th to 6th month post stroke.

5) The rate of change of recovery in trunk control (Trunk Impairment Scale, TIS) was similar to the rate of change of upper extremity impairment (Fugl-Meyer Assessment, FMA) in the first 6 months post stroke.

   As trunk control (TIS) improved over time, both the upper extremity impairment (FMA) and upper extremity function (Streamlined Wolf Motor Function-Time and Streamlined Wolf Motor Function-Functional Ability Scale) improved in parallel with the TIS increase. Hence, trunk control has an association with the recovery of upper extremity impairment and function in the first 6 months post stroke.

1.5 Thesis structure and overview

This thesis is divided into 8 chapters. A summary at the end of each chapter highlights key points within the chapter.

Chapter 1 outlines the current gaps in knowledge related to trunk control and upper extremity function, and their recovery in the stroke population. It highlights the justification for this research and summarises the aim and objectives of this PhD research. It also details the main findings of this study and the original contributions made to the body of knowledge in stroke rehabilitation. The thesis structure is explained and the publications, oral and poster presentations resulting from the study are listed.

Chapter 2 presents a detailed literature review, providing the background of the research on trunk and upper extremity post stroke which underpins this PhD research. Trunk impairments post stroke will be outlined with reference to effects on balance, gait and functional outcome. Trunk involvement in reaching and pointing tasks will be discussed, and the impact of trunk support on performance of upper extremity tasks will be considered. In addition, literature on neuroplasticity and motor recovery of the upper extremity and trunk in stroke patients will be discussed. Clinical implications of this study are emphasized.

Chapter 3 provides a critical review of the outcome measures used for the assessment of the trunk and the upper extremity impairment and function in stroke patients. Justification for the selection of appropriate clinical and kinematic outcomes for this study will be discussed.

Chapter 4 describes the methodology for both Phase 1 and Phase 2 studies. The Chapter includes the aims and objectives of study, study design, sample size calculation, recruitment process, clinical and kinematic outcome measures, experimental procedures and ethical considerations. Methods of statistical analyses are discussed and justified.

Chapter 5 reports the detailed findings of the Phase 1A study and Phase 1B study.

Chapter 6 reports the detailed findings of the Phase 2 study.

Chapter 7 provides a detailed analysis of the results of the Phase 1 and Phase 2 studies. Discussion will be made in relation to previous research findings and the clinical implications of the findings are addressed. The limitations of the study will be discussed and directions of future research made.

Chapter 8 presents the conclusion of this PhD work.

References are listed at the end of the thesis, followed by the Appendices that include the relevant documents related to this study.

1.6 Publications and presentations

Some of the work in this thesis have been published or presented at scientific meetings listed below:

Journal publications:

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2015) Effect of trunk support on upper extremity function in people with chronic stroke and people who are healthy. *Physical Therapy*. Published online February 26, 2015; doi: 10.2522/ptj.20140487 (Appendix 1)

Wee SK, Hughes AM, Warner MB and Burridge JH (2014) Trunk restraint to promote upper extremity recovery in stroke patients: a systematic review and meta-analysis. *Neurorehabilitation and Neural Repair* 28(7): 660-677. (Appendix 2)

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH, Yeo SCD, Kong KH and Chan KF (2015) Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. *Physiotherapy* 101(Supplement 1): eS1619

Manuscripts in preparation for submission:

Wee SK, Warner MB, Hughes AM, Brown S, Cranny A, Mazomenos EB, Burridge JH (2015) Kinematic analysis of the effect of trunk support on functional reaching in people with chronic stroke and healthy controls.

Wee SK, Warner MB, Hughes AM, Burridge JH, Yeo SCD, Kong KH, Chan KF (2015) Longitudinal analysis of the recovery of trunk control and upper extremity in people with subacute stroke: An individual growth curve approach.

Wee SK, Hughes AM, Warner MB, Burridge JH, Yeo SCD, Kong KH, Chan KF (2015) Is there a difference in the rate of recovery of the proximal and distal segments of the upper extremity post stroke? A longitudinal analysis.

Conference presentations (Oral):

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2014) Relationship between trunk control and upper extremity function in healthy individuals and chronic stroke patients. Invited Speaker at the 8th Annual Southern Stroke Forum Conference, United Kingdom, 14th February 2014.

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2015) Impact of trunk support on upper extremity function in people with chronic stroke and healthy controls: clinical and kinematic analysis. 4th Annual Singapore Rehabilitation Conference 2015, Singapore, 26th – 27th March 2015.

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH, Yeo SCD, Kong KH, Chan KF (2015) Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. World Confederation for Physical Therapy (WCPT) Congress 2015, Singapore, 1st – 4th May 2015.

Conference presentations (Poster):

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2014) Impact of trunk control on the performance of upper extremity functional tasks: a pilot study on healthy individuals. Poster presentation at the 8th World Congress for Neurorehabilitation 2014, Istanbul, Turkey, 9th April 2014.

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2014) Impact of trunk control on the performance of upper extremity functional tasks in healthy individuals and chronic stroke patients. Poster presentation at the Health Technologies Poster Exhibition, University of Southampton, United Kingdom, 19th February 2014. Awarded the *Best Poster Presentation*.

Other oral presentation platform:

Wee SK (2014) Is this the missing link to better arm recovery in stroke patients? A peek into the core: trunk control. 3-Minute Thesis Competition, University of Southampton, United Kingdom, 26th February 2014.

1.7 Summary of Chapter 1

This Chapter has presented the current gaps in knowledge related to trunk control and upper extremity function, and their recovery in the stroke population. It highlights the justification for this PhD research and outlines the aim and objectives of this research. It also details the main findings of this study and the original contributions made to the body of knowledge in stroke rehabilitation. The thesis structure is explained and the publications and oral and poster presentations resulting from the study are listed.

The next Chapter presents a detailed literature review, providing the background of the research on trunk and upper extremity post stroke, which underpins this research.

Chapter 2: Background and literature review

2. Background and literature review

This Chapter begins with section 2.1 detailing the incidence of stroke and cost of stroke care in the UK and Singapore as the Phase 2 study was conducted in Singapore. This is followed by a section on the sequelae of stroke (section 2.2) and its impact on function of people with stroke.

Subsequent sections in this Chapter present a detailed literature review, providing the background of the research on trunk and upper extremity post stroke which underpins this research. Trunk impairments and performance post stroke will be outlined with reference to effects on balance, gait and functional outcome. Trunk involvement in reaching and pointing tasks and neuroplasticity and motor recovery of the upper extremity and trunk in stroke patients will be discussed.

2.1 Incidence of stroke and cost of stroke care

2.1.1 Incidence of stroke in the United Kingdom

In a study cohort of 32,151 UK patients with a first stroke between 1999 and 2008, Lee et al. (2011) found that the stroke incidence fell by 30%, from 1.48/1000 person-years in 1999 to 1.04/1000 person-years in 2008. This decline coincided with a marked increase in primary care prescription of primary and secondary cardiovascular prevention therapies. These therapies lead to a reduction of risk factors such as diabetes, hypertension, hypercholesterolemia, obesity and management of atrial fibrillation. The fall in stroke incidence is similar to the findings of previous studies (Rothwell et al. 2004; Heuschmann et al. 2008).

2.1.2 Incidence of stroke in Singapore

As the Phase 2 study of this PhD research was conducted in Singapore, it would be informative to compare the incidence of stroke in the UK and Singapore. The stroke incidence in Singapore was 1.86/1000 person-years in

2005 and fell to 1.54/1000 person-years in 2010 (National Registry of Diseases Office 2012). The reason for this decline in stroke incidence is similar to the findings of Lee et al. (2011). It is due to increased use of preventive treatments and a reduction in cardiovascular risk factors.

2.1.3 Cost of stroke care in the United Kingdom and Singapore

It is estimated that the percentage of people above the age of 65 in Singapore will increase by 316% from 2008 to 2040 (Kinsella & He 2009). In comparison, the UK will only see a 66% increase in the percentage of people above the age of 65 in the same period (Kinsella & He 2009). This is an exponential increase in the aging population in Singapore. As the risk of stroke increases with age (Venketasubramanian et al. 2005; Berry et al. 2012; Zhang et al. 2012), there is likely to be an increase in socio-economic cost and burden on carers due to long-term disability as a result of stroke.

Stroke is the largest cause of adult disability in England. Around 110,000 strokes occur in England each year. Approximately 300,000 people are living with moderate to severe disabilities as a result of stroke (National Audit Office 2010). This can place a tremendous burden on the carers to assist them in activities of daily living. In contrast, stroke is the eighth highest cause of disability burden in Singapore, with 3.5% of Years of Life lived with Disability (YLD) and 6.1% of Disability-Adjusted Life Years (DALYs) (National Registry of Diseases Office 2013).

There is huge economic impact on the stroke patients, families and society (Feigin et al. 2008). On average, each primary care trust in the UK spends £1.7 million per annum on stroke-related community care and rehabilitation (Healthcare for London 2009). The treatment of stroke and productivity loss due to death and disability arising from stroke has been reported to result in total societal costs of £8.9 billion a year (Saka et al. 2009). The annual direct cost of stroke care is approximately £4 billion (Saka et al. 2009). However, study examining the total societal cost of stroke in Singapore has not been conducted to date.

In Singapore, the mean annual direct medical cost for a stroke patient amounts to £6237 (Ng et al. 2015). With an estimated 10,000 admissions to hospital

due to stroke per year (Chow et al. 2010), the annual direct cost of stroke care is approximately £63 million. This huge contrast between the cost of stroke care in the UK and Singapore is attributed to differences in healthcare financing systems.

Healthcare services are provided free for all its residents in the UK, which is primarily funded through general taxation. In Singapore, citizens and permanent residents are entitled to subsidised healthcare services provided through government healthcare facilities. The amount of subsidy is based on a tier system which depends on the age and income of an individual. That means that it is a co-payment system to encourage an individual to be responsible for his/her own health. This system is aimed at reducing the overutilisation of healthcare services, which is a phenomenon commonly observed in fully subsidised universal health insurance systems.

As stroke is an age-related disease (Di Carlo et al. 1999; Denti et al. 2008; Andersen et al. 2010; Berry et al. 2012; Norrving & Kissela 2013), without preventative measures, the cost is likely to increase with the changing demographics of an aging population. In England, the percentage of people above the age of 65 will increase from 16% in 2005 to 25% in 2050 (Knapp et al. 2007).

Stroke burden is projected to increase from around 38 million DALYs lost globally in 1990 to 61 million DALYs in 2020 (Mackay & Mensah 2004; Murray et al. 2012). Johnston et al. (2009) reported that DALYs loss was highest in Eastern Europe, North Asia, Central Africa, and the South Pacific. Extrapolating from this, there will be potential strain placed on the expenditure on healthcare in the future. Therefore, improving functional outcome of stroke survivors is critical to reduce the impact on the individual, their carers and the wider society.

2.2 Sequelae of stroke

Stroke is a global health-care problem that is common, serious, and disabling. In most countries, stroke is the second or third most common cause of death and one of the main causes of acquired adult disability (Langhorne et al. 2011; Vaartjes et al. 2013). The disability which arises from stroke is due to the debilitating initial symptoms and long-term impact on functional activities (Zhang et al. 2012). Therefore, it is important to have an understanding of how stroke fits within the framework of World Health Organisation (WHO) International Classification of Functioning, Disability and Health.

2.2.1 International Classification of Functioning, Disability and Health (ICF)

The International Classification of Functioning, Disability and Health, known more commonly as ICF, is a classification of health and health-related domains (World Health Organisation 2013). These domains are classified from body, individual and societal perspectives.

Stroke can be classified within WHO ICF, which provides a framework for the effect of stroke on the individual in terms of pathology (disease or diagnosis), impairment (body function and structure), activity limitations (disability), and participation restriction (handicap) (Langhorne et al. 2011). The ICF defines the spectrum of problems in the functioning of people with stroke (Geyh et al. 2004). Figure 2-1 details the domains of body function and structure, activity and participation. This highlights the full impact of stroke on an individual and its long-term consequences.

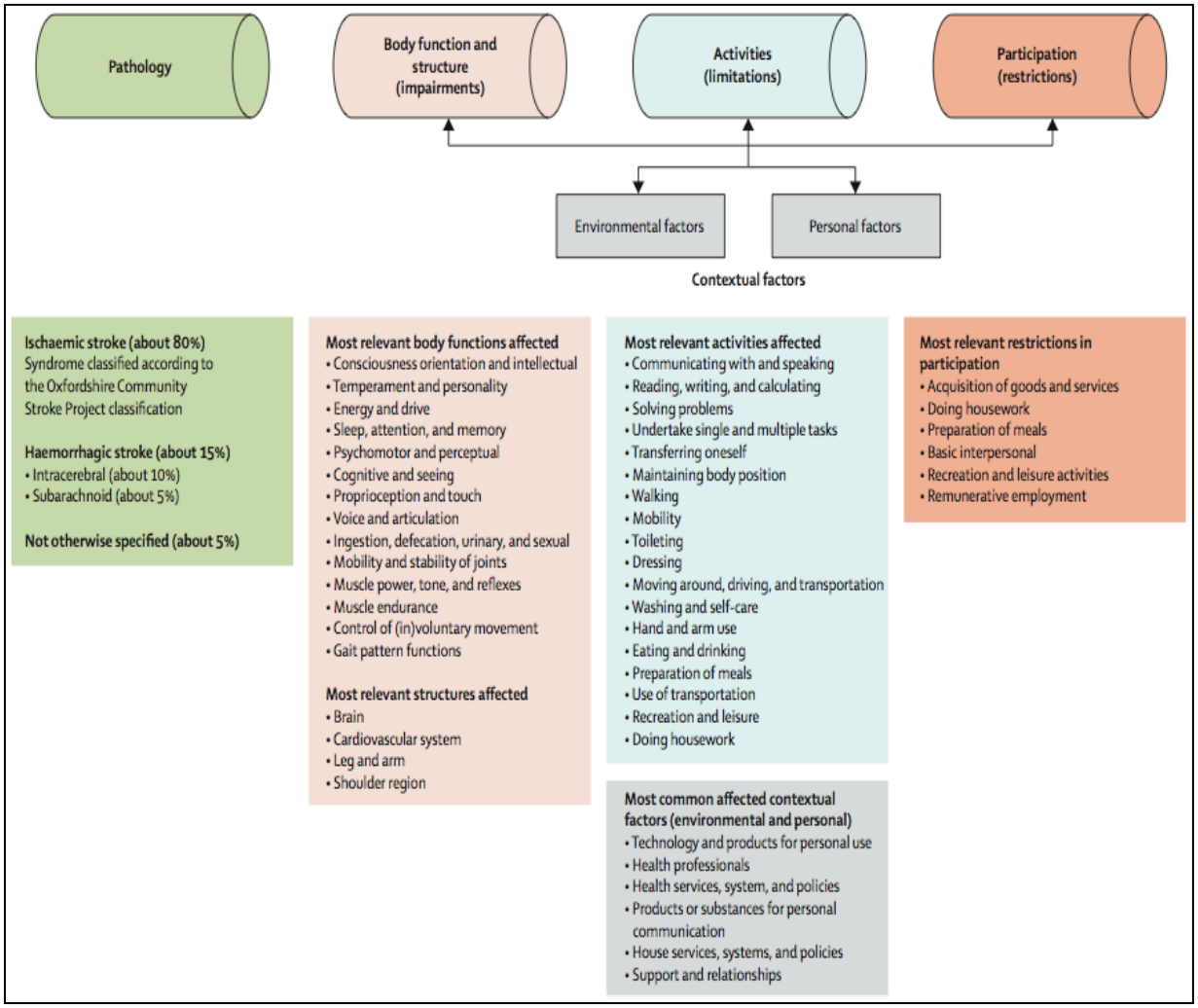


Figure 2-1 The International Classification of Functioning, Disability and Health framework for the effect of stroke on an individual. Reprinted from The Lancet, Vol. 377, Langhorne P, Bernhardt J and Kwakkel G, Stroke rehabilitation, page 1693-1702, Copyright (2011), with permission from Elsevier.

2.2.2 Consequences of stroke

Stroke can lead to a wide range of deficits in the physical, cognitive and psychosocial domains (Lai et al. 2002b). These deficits will result in activity and participation limitations. Typically, these deficits include neuropsychological impairments, such as amnesia, agnosia, aphasia, apraxia, executive dysfunction, and mood disorders, together with motor impairments

such as paresis, spasticity, and disorders of mobility (Chen et al. 2013a).

Due to the effect of stroke on various domains, it has an enormous physical, emotional and economic impact on the patients, families and society (Feigin et al. 2008). Researchers have found that inn stroke patients deemed highly recovered, their hand function, basic ADL, independent ADL, participation, and overall physical function were still affected as compared to the stroke-free community dwellers (Lai et al. 2002b).

2.2.3 Motor impairments post stroke

The most common and widely recognised impairment caused by stroke is motor impairment, which includes muscle weakness, spasticity, changes in muscle activation and control (sequencing, firing, initiation) and changes in sensation and proprioception (Ryerson 2007). This can lead to a limitation of function in muscle control or movement or a limitation in mobility (Langhorne et al. 2009). For these reasons, people with stroke will require an intensive rehabilitation programme to maxmise their recovery (Desrosiers et al. 2003a).

Following stroke, the associated upper motor neuron (UMN) syndrome often has a considerable impact on a person's activity and participation (Mayer & Esquenazi 2003; Burridge et al. 2009). The negative features of UMN syndrome include muscle weakness, slow and effortful movement, loss of dexterity, impaired motor control and fatigability (Barnes 2001; Mayer & Esquenazi 2003). The positive features of UMN syndrome include spasticity, clonus, hyper-reflexia, flexor and extensor spasms, mass reflex, dyssynergic patterns of coactivation during movement, associated reactions and other dyssynergic and stereotypical spastic dystonias (Barnes 2001; Mayer & Esquenazi 2003). Secondary consequences of the negative and positive features may lead to changes in the mechanical properties of muscles and connective tissue, loss of active range of movement and contracture (Thilmann et al. 1991). Taken together, the negative and positive features of UMN syndrome can have an effect on trunk control and the upper extremity in stroke patients.

The focus of this PhD research is on investigating the relationship between trunk control and the recovery of upper extremity function in stroke patients. Hence, the following sections of this Chapter will cover the topic on neuroplasticity and motor recovery following stroke, neuromuscular control of

the trunk, and review the literature relating to the trunk and upper extremity post stroke, which underpins this research.

2.3 Neuroplasticity and motor recovery following stroke

This doctoral research includes the investigation of the recovery pattern of the trunk and upper extremity function in stroke patients. Therefore, it is essential to understand about neuroplasticity and the mechanisms underlying motor recovery in stroke patients. This section will discuss the research related to brain plasticity and motor recovery.

The cerebral cortex adapts to the changing environmental demands throughout an individual's life (Bayona et al. 2005; Fuchs & Flugge 2014; Kolb & Muhammad 2014). The normal brain can reorganize itself in response to training and experience (Teasell et al. 2005). Enriched environment and motor learning in the adult human have been found to be associated with dendritic growth, increases in dendritic spines, and synaptogenesis (Waites et al. 2005; Yu & Zuo 2011; Starkey & Schwab 2014). The efficacy of synaptic contacts is modulated within a complex intracortical network (Nudo 2006).

After a neurological insult, such as a stroke or traumatic brain injury, there is potent disruption of integrated sensorimotor networks, resulting in loss of fine motor control and the employment of compensatory movement strategies (Nudo 2003). However, the brain exhibits an ability to adapt and reorganize through a process called neuroplasticity.

Neuroplasticity can be broadly defined as the ability of the nervous system to respond to intrinsic and extrinsic stimuli by reorganizing its structure, function and connections (Cramer et al. 2011). Post-injury plasticity has been documented not only at the molecular, cellular, synaptic, network and systems levels in experimental animals but also many of these plasticity events have been correlated with alterations in cortical function using neuroimaging and stimulation techniques in humans (Nudo 2006).

Whilst there are beneficial effects of brain plasticity, there are also possibilities of the occurrence of maladaptive plasticity following stroke. Adaptive plasticity in stroke describes plastic changes that facilitate recovery of an involved function, whereas maladaptive plasticity is said to occur when plasticity hinders the recovery of an injured function or causes the development of an unwanted symptom (Jang 2013). The phenomenon of learned nonuse of the affected upper extremity post stroke (Taub et al. 2006; Taub et al. 2014) is an example of maladaptive plasticity. Maladaptive plasticity has been reported in several studies that it can affect motor function and limit motor recovery after stroke (Murase et al. 2004; Duque et al. 2005; Takeuchi et al. 2007; Allred & Jones 2008b). Compensatory movement strategies used by people with stroke in performance of tasks may encourage maladaptive plasticity due to reinforcement of abnormal movement patterns, and therefore, it can affect motor recovery in the longer term (Jang 2013).

Hence, not all changes in the brain will have functional significance for skill reacquisition after stroke (Buma et al. 2013). It is also important to recognise that plastic reorganization are often not sufficient enough to return motor performance to pre-stroke levels (Starkey & Schwab 2014).

2.4 Mechanisms underlying motor recovery after stroke

Despite advances in neuroimaging technology, the mechanisms of motor recovery following stroke is still not fully understood. Many mechanisms have been proposed to play a role in the neurological recovery following stroke. Improving the understanding of the mechanisms underlying neuroplasticity can guide, direct, and focus the practice of current and future therapies to greater efficacy and better functional outcomes in clinical rehabilitation (Gillick & Zirpel 2012).

The following sections will discuss the recovery mechanisms that occur in the early and late phases of stroke, which include spontaneous recovery, diaschisis, cortical reorganisation, use-dependent plasticity, experience-dependent plasticity, ipsilateral motor pathways and integrity of corticospinal tracts.

2.4.1 Spontaneous recovery

In the acute phase of stroke, oedema may influence neuronal function in the area immediately surrounding the lesion or by compression in areas distant from the lesion. The presence of oedema may also render viable brain sensitive to further ischaemic damage (Goldstein & Davis 1990). Therefore, neurological improvement observed in patients after an acute stroke may partly be due to subsequent resolution of oedema (Todd et al. 1986). In addition, neurological recovery from stroke is also attributed to resolution of ionic fluxes, inflammatory processes and return of circulation within the ischaemic penumbra, which consists of potentially viable neurons (Kristián & Siesjö 1997; Kristian & Siesjo 1998; Brown 2002; Allan & Rothwell 2003; Lucas et al. 2006; Young & Forster 2007; Buma et al. 2013). Structural damage to the dendrites can even be reversed with reperfusion (Zhang et al. 2005).

There is also evidence of neurogenesis, whereby newly born, immature neurons are present in tissue adjacent to the stroke site within the first 2 to 4 weeks after stroke (Arvidsson et al. 2002; Ohab et al. 2006; Chopp et al. 2007; Font et al. 2010). Angiogenesis, the generation of new blood vessels, is found to be most prominent in the ischemic boundary zone (Chopp et al. 2007; Font et al. 2010). Magnetic resonance imaging indices of neurogenesis and angiogenesis have been found to be highly correlated with neurological recovery after stroke (Chopp et al. 2007).

Overall, this is a spontaneous recovery phase which can lead to initial clinical improvement, independent of behavior or stimuli (Teasell et al. 2005). Spontaneous recovery typically continues for 4 to 12 weeks post stroke (Biller et al. 1990; Rothrock et al. 1995; Furlan et al. 1996; Kwakkel et al. 2006; Cramer 2008; Zeiler & Krakauer 2013).

In a study on 29 patients with acute ischemic stroke, improvement (defined as a decrease of ≥2 points on the modified National Institutes of Health Stroke Scale [NIHSS]) was observed in 24% of patients at 1 hour and in 52% by 6 hours (Biller et al. 1990). In addition, the findings showed that younger patients, men, and those without a history of arterial hypertension or diabetes mellitus improved to a greater degree. There was no significant difference among the

stroke subtypes with regard to change in NIHSS scores and the incidence of spontaneous improvement.

In another study, Rothrock et al. (1995) found that 24% of the 68 stroke patients with moderate or severe neurological deficit (as assessed by the modified Rankin Scale) improved to the point of having no or mild functional neurological deficit at 1 week. Patients with lacunar stroke were more likely to experience early spontaneous improvement. Majority of the patients with acute remain significantly impaired 1 week post stroke.

Furlan et al. (1996) was the first research group that documented quantitatively and longitudinally one mechanism, namely, survival of the penumbra, underlying recovery from stroke. The results from 11 patients with acute ischaemic stroke demonstrated that the volume of the penumbra that escaped infarction was significantly correlated with neurological recovery. The researchers proposed that therapeutic measures, for example anti-ischaemic therapy, to prevent infarction of the penumbra may help to reduce residual neurological impairment. The surviving penumbra may offer opportunities for secondary perifocal neuronal reorganization to occur.

Taken together, the evidence from these studies supports that whilst spontaneous recovery can lead to initial neurological improvement, the process can only help stroke patients up to a certain level. Other mechanisms which occur will help to explain further neurological recovery in stroke patients.

2.4.2 Diaschisis

In 1914, Constatin von Monakow, a physician, established the concept of diaschisis as a principle for recovery from brain lesions (Finger et al. 2004). He termed his theory of neural depression caused by loss of inputs to structures tied to the damaged area as diaschisis. In other words, there are functional changes in brain structures remote from the site of a focal brain damage (Seitz et al. 1999; Witte et al. 2000).

Neuroimaging studies have provided first clues to the existence of diaschisis by revealing that focal brain lesions are accompanied by widespread metabolic changes involving the affected cerebral hemisphere, extending into brain areas

supplied by contralateral and cerebellar arteries (Feeney & Baron 1986). Remote neurotransmitters changes and degeneration of fiber tracts were also reported in experimental models of ischemia (Witte 1998).

Recovery following stroke is thought to result from the gradual reversal of diaschisis (Feeney & Baron 1986; Nudo et al. 2001). This is supported by the study by Seitz et al. (1999) that shed light on the role of diaschisis in stroke recovery. Performance of seven acute stroke patients was assessed by a motor score and by the finger movement rate during the regional cerebral blood flow measurements. Results showed that motor recovery after hemiparetic brain infarction was subserved by brain structures, such as the basal ganglia and thalamus, in locations remote from the stroke lesion. Restitution of function was mediated mainly by intact networks of the contralesional hemisphere (Seitz et al. 1999). Hence, the topographic overlap of the lesion-affected and recovery-related networks suggests that diaschisis may play a critical role in stroke recovery. These findings are in agreement with the works of Di Piero et al. (1992) and Pantano et al. (1996) which suggest that the degree of relative metabolic improvement in intact areas functionally connected to the site of ischaemic damage is correlated with the magnitude of clinical improvement.

As diaschisis undergoes gradual regression over time, resolution will parallel resumption of function in areas of diaschisis (Feeney & Baron 1986). However, diaschisis may persist for weeks (Biernaskie & Corbett 2001; Kwakkel et al. 2006) or for long periods of time (as long as 6 months) even after significant neurological recovery has occurred (Infeld et al. 1995; Seitz et al. 1999). There are still signs of hypometabolism and inhibition (Andrews 1991). Hence, other mechanisms also contribute to explain the motor recovery in stroke patients.

2.4.3 Cortical reorganisation

Studies in stroke patients and in experimental animal models suggest that the cerebral cortex undergoes functional and structural reorganization for weeks to months following injury (Green 2003). These cortical reorganisation of the human brain mediates the recovery from hemiparesis following stroke (Ward 2005).

An early work by Glees and Cole (1950) demonstrated that representational changes occurred in the motor cortex of monkeys following small cortical lesions. After a lesion of the thumb representation area, it was reported that the thumb representation reappeared in a zone surrounding the infarct. This is an early evidence for the role of representational plasticity in recovery from brain damage. A seminal study by Nudo and Milliken (1996) shed more light on the ability of the brain to undergo cortical reorganization with rehabilitative training which accounted for the recovery in motor function after neurological insults. In that study (Nudo & Milliken 1996), adult squirrel monkeys received 4 weeks of retraining of skilled hand use after ischemic damage to the hand motor area. Following training, the cortical representations of the digits, wrist, and forearm expanded into intact cortex that had been formerly occupied by the elbow and shoulder representation. In contrast, monkeys without training experienced a loss of the digit and wrist-forearm area in the surviving tissue (Nudo & Milliken 1996; Nudo et al. 1996a; Nudo et al. 1996b). These findings emphasized the importance of early task-specific rehabilitative training to facilitate cortical reorganisation and functional recovery after stroke. A recent study by Higo (2014) on macaque monkeys demonstrated that rehabilitative training was more effective in promoting recovery of manual dexterity when initiated immediately after the corticospinal tract lesion rather than 1 month later. This result further reinforces the importance of early rehabilitative training on motor recovery post neurological insults. Both functional brain imaging and gene expression analyses suggest that functional and structural changes may occur in undamaged motor areas during recovery of hand function after primary motor cortex or corticospinal tract lesions (Higo 2010; Higo 2014).

Different neuroimaging technologies, such as functional magnetic resonance imaging (fMRI), transcranial magnetic stimulation (TMS), positron emission tomography, magnetoencephalography, have enabled researchers to study cortical reorganisation in human subjects (Rossini & Pauri 2000). Numerous studies have provided a wealth of evidence of reorganization in several cortical areas in stroke patients (Chollet et al. 1991; Weiller et al. 1992; Weiller et al. 1993; Cicinelli et al. 1997; Liepert et al. 1998; Rossini et al. 1998; Liepert et al. 2000; Levy et al. 2001; Carey et al. 2002; Feydy 2002; Jang et al. 2002; Jang et al. 2003; Zemke et al. 2003; Fridman et al. 2004; Szaflarski et al. 2006;

Kwon et al. 2007a; Nudo 2007; Draganski & May 2008; Szameitat et al. 2012; Sun et al. 2013; Taub & Uswatte 2013; Zhang et al. 2014).

In one of the early neuroimaging studies on cortical reorganisation, Chollet et al. (1991) found that movement of the recovered paretic hand was associated with increased activation in ipsilateral and contralateral primary sensorimotor cortex, premotor cortex, cerebellum, insula and inferior parietal. In addition to those cortical areas, the basal ganglia and thalamus (Weiller et al. 1992), the supplementary motor areas and the rims of infarct area (Cramer et al. 1997; Cramer et al. 2006) were also activated in stroke patients. Therapy-related improvements in hand function was found to correlate with increases in fMRI activity in the premotor cortex and secondary somatosensory cortex contralateral to the affected hand, and in superior posterior regions of the cerebellar hemispheres bilaterally (Johansen-Berg et al. 2002). Thus, there is evidence to support that bilateral activation of motor pathways and the recruitment of other cortical areas are associated with recovery from stroke. However, greater motor impairment is associated with an increase of activation in motor areas of both hemispheres (Ward et al. 2003; Takeuchi et al. 2007; Calautti et al. 2010). In contrast, good functional recovery relies on the recruitment of the original functional network rather than on contralesional activity (Nelles et al. 2011; Rehme et al. 2011a; Rehme et al. 2012). Evidence suggests that best outcome is achieved by activating the brain in a pattern that most resembles the normal state (Cramer 2004). The studies also suggest that ipsilateral motor pathways also play a role in stroke recovery. This aspect of ipsilateral involvement will be discussed in greater depth under section 2.4.5.

Shortly following stroke, the excitability of the motor cortex of the affected hemisphere is reduced, and the cortical representation of the affected muscles is decreased (Cicinelli et al. 1997; Traversa et al. 1997; Clarkson & Carmichael 2009; Corti et al. 2012). This is partly due to the infarct itself and partly due to decreased use of the paretic extremity (Weiller et al. 1992) or the phenomenon of learned non-use of the paretic extremity (Taub 2012; Taub & Uswatte 2013). Inhibition from the unaffected hemisphere has been found to reduce the excitability of the affected hemisphere further (Ward & Cohen 2004; Nowak et al. 2009).

With the appropriate therapeutic interventions, the cortical representation of the affected muscles can be remodeled and changed. In a study on 18 subacute stroke patients, enlargement of the hand motor area on the affected hemisphere was observed, combined with significant improvement of clinical scores (Barthel Index and Canadian Neurological Scale) after 8 to 10 weeks of neurorehabilitation (Cicinelli et al. 1997). Therapy-related improvements in hand function was found to correlate with increases in fMRI activity in the premotor cortex and secondary somatosensory cortex contralateral to the affected hand, and in superior posterior regions of the cerebellar hemispheres bilaterally (Johansen-Berg 2002).

Another study on 13 chronic stroke (mean 4.9 years post stroke) patients using the constraint-induced movement therapy (CIMT) paradigm provided evidence for treatment-induced cortical reorganization (Liepert et al. 2000). In the CIMT paradigm, the unaffected upper extremity was constraint for 90% of waking hours and the patients received 6 hours per day of training in use of the affected arm in a variety of tasks involving “shaping”, over a period of 2 weeks (Taub 2012; Taub & Uswatte 2013). Shaping is a technique which a motor or behavioural objective is approached in small steps of “successive approximations” (Taub & Uswatte 2013). In the study by Liepert et al. (2000), the cortical representation area of the affected hand muscle was significantly smaller than the contralateral side before CIMT. After treatment, the muscle output area size in the affected hemisphere was significantly enlarged. The enlargement of cortical representation corresponds to a significant improvement in motor performance of the paretic limb (large effect size of 1.5). The shifts of the center of the output map in the affected hemisphere suggested recruitment of adjacent brain areas. At 6-months follow-up, the motor performance remained stable at a high level and the cortical area sizes in the two hemispheres became almost identical, representing a return of the balance of excitability between the two hemispheres toward a normal condition. The results from these human studies paralleled the results from animal studies by Nudo et al. (1996a) and Higo (2014), illustrating plasticity of the brain post injury and its capacity for recovery.

The next section will expand on the discussion of use-dependent plasticity and experience-dependent plasticity.

2.4.4 Use-dependent plasticity and experience-dependent plasticity

The functional organization of the motor cortex is modified by use, and it has been suggested that use-dependent plasticity may play a major role in the recovery of function after stroke (Nudo et al. 1996b; Butefisch et al. 2000; Kolb & Muhammad 2014; Yassi et al. 2015). Use-dependent plasticity (UDP) involves the strengthening of existing neural connections, and the formation of new connections within the primary motor cortex in response to voluntary motor activity (Nudo et al. 2001; Nudo 2013). UDP can develop as a consequence of motor reinforcement that occurs over days, weeks and even years (Karni et al. 1995; Classen et al. 1998; Liepert et al. 2000; Nielsen et al. 2015).

UDP, which involves cortical reorganization, has been demonstrated in human subjects performing simple, voluntary, repetitive thumb movements for 30 minutes continuously (Classen et al. 1998). The training rapidly, and transiently, established a change in the cortical network representing the thumb, which encoded kinematic details of the practiced movement. This phenomenon may be regarded as a short-term memory for movement and is the first step of skill acquisition (Classen et al. 1998). Similar results were found in another study whereby brief training of 120 synchronized thumb and foot movements induced a displacement of the centre of gravity of the abductor pollicis brevis muscle motor output map toward the leg representation medially. The observed effect developed within 45 minutes and was reversed after 1 hour (Liepert et al. 1999). Hence, UDP can occur rapidly and also reverse rapidly.

Studies have demonstrated that high repetition and high intensity of task training are required to induce lasting neural changes. For example, rats trained on a skilled reaching task do not show increases in synaptic strength (Monfils & Teskey 2004), increases in synapse number, or map reorganization (Kleim et al. 2004) until after several days of training, despite making significant behavioural gains (Nishibe et al. 2015). Those rats trained to perform 400 reaches per day demonstrated an increase in synapse number within the motor cortex (Kleim et al. 2002) while those that performed 60 reaches per day (Luke et al. 2004) did not exhibit such increase. Studies on

monkeys demonstrated that an average of 600 repetitions of training per day led to enlargement of hand representation on the motor cortex (Nudo et al. 1996a; Plautz et al. 2000).

In the individuals with chronic stroke, an intensive finger-tracking exercise of more than 100 repetitions per day led to significant cortical reorganization and functional improvement compared with healthy control individuals (Carey et al. 2002). This implies that longer periods of rehabilitative training with more repetitions are necessary to drive UDP optimally and reinforce any reorganization that has occurred. However, in an observational study of 312 physiotherapy and occupational therapy sessions across 7 North America sites, Lang et al. (2009b) found that the average number of repetitions of upper extremity functional movement training was 32. This is certainly way below the number of repetitions of reaching practice in animal studies that has shown to elicit cortical reorganisation. This implies that the current dose of task-specific upper extremity practice during rehabilitation may not be optimal to drive the neural reorganization that is needed to promote function in stroke patients (Lang et al. 2009b). Hence, the use of robotic technology in rehabilitation may be the solution to provide high intensity and high repetition trainings to drive cortical reorganisation and yield better patient outcomes. This is supported by a recent study that demonstrated that robot-assisted therapy for the upper extremity led to significant and clinically meaningful reduction in motor impairment in both subacute and chronic stroke patients (Mazzoleni et al. 2013).

From the studies discussed above, the intensive use of the extremity drives UDP. On the contrary, upper extremity immobilization in a cast for approximately 2 weeks led to a decrease in cortical thickness and functional aniosotropy of the corticospinal tract (CST) on the immobilised side, which was reversible once immobilization was removed (Langer et al. 2012). In another study, immobilization of the lower extremity by splinting for 4 to 6 weeks can reduce the motor output map of the involved muscles (Liepert et al. 1995). The area reduction was correlated to the duration of immobilization. However, the reduced motor map could be quickly reversed by voluntary muscle contraction. This illustrates that with appropriate training, positive changes in cortical reorganization is still possible. In one study on healthy volunteers, active training by voluntary flexion and extension movements of the wrist was

compared with passive training of the wrist provided by a torque motor (Lotze et al. 2003). The wrist movement control was significantly better after active training than after passive training. Active training resulted in significantly higher cortical activation and a larger size of activated area in the contralateral primary motor cortex than passive training. This result is consistent with the concept of a pivotal role of voluntary drive in motor learning (Lotze et al. 2003). This has implication for stroke rehabilitation. Patients should be encouraged to participate actively in therapy rather than being passively guided by the therapist.

In addition to voluntary motor activity, behavioural experiences can have diverse structural and functional effects on the central nervous system, such as induction of synaptic turnover (synaptogenesis), modulation of synaptic strength, remodeling of vasculature and glial processes, and alteration of the rate of neurogenesis (Stroemer et al. 1995; Kleim et al. 1996; Kleim et al. 2002; Kleim et al. 2004; Luke et al. 2004; Waites et al. 2005; Kleim & Jones 2008; Sun et al. 2008). A review paper by Kleim and Jones (2008) highlights 10 principles of experience-dependent neural plasticity which are derived from basic neuroscience research. The 10 principles are use it or lose it; use it and improve it; specificity matters; repetition matters; intensity matters; time matters; salience matters; age matters; transference; and interference. Some of these principles parallel motor learning principles, such as specificity, repetition, intensity and transference, that are commonly adopted by therapists in designing exercise programmes for stroke patients.

Experiences are continuously changing the nervous system throughout the lifespan (Kerr et al. 2011). There is evidence that experience-induced plasticity interacts with the post stroke neural environment to shape central nervous system reorganization (Kerr et al. 2011; Kolb & Muhammad 2014; Yassi et al. 2015). Hence, it appears that experience-dependent plasticity is closely intertwined with UDP. For example, when an individual with stroke uses his affected upper extremity, the environment plays a critical part to shape the whole experience for him. An unfamiliar environment with different task demands may yield a different set of challenges for the individual and he has to learn how to problem-solve to complete the tasks.

Following stroke, many patients may rely on their less-affected extremity for function. This self-taught compensatory strategy to cope with post stroke motor impairments may induce cortical reorganization that is maladaptive. Whilst it may enable the stroke patients to quickly resume performance of some daily tasks, it is not necessarily optimal for returning more normal function (Allred & Jones 2008a; Kerr et al. 2011). This behavioural change may contribute to the phenomenon of learned nonuse, where disuse of the impaired arm is believed to further limit its recovery (Sunderland & Tuke 2005; Taub et al. 2006; Hidaka et al. 2012; Han et al. 2013; Taub & Uswatte 2013; Taub et al. 2013). Hence, compensatory movements learnt shortly following stroke may be detrimental to optimal recovery. Another important issue to address is that the emphasis in current neurorehabilitation practice is on the rapid establishment of independence in activities of daily living through compensatory strategies, rather than on the reduction of impairment (Kitago & Krakauer 2013). In view of possible detrimental effects of compensatory strategies on recovery, rehabilitation professionals should adopt a remediation approach rather than compensatory approach in rehabilitation therapy.

Animal studies have confirmed that intact forelimb training following unilateral focal ischaemia caused a reduction in neuronal activation (Allred et al. 2005; Allred & Jones 2008b) and asymmetry in bilateral forelimb function (Luke et al. 2004), hence worsening the recovery of the impaired forelimb. The results suggest that the lack of recovery of the impaired forelimb may stem, not only from disuse, but also from disruptive influences of behavioural experience with the intact forelimb. Intensive training experience with the intact forelimb might have limited the neuronal activation in the remaining motor cortex, possibly suppressing or interfering with use-dependent plasticity that could have mediated better recovery in the impaired forelimb (Allred & Jones 2008b). In the experiments on rats, Allred et al. (2010) have demonstrated the disruptive interhemispheric influences of the contralesional cortex on the ipsilesional cortex when the intact forelimb was trained. Similar findings were shown in human stroke survivors (Murase et al. 2004). Thus, these findings suggest that inappropriate experience may lead to maladaptive plasticity. Rehabilitation professionals should educate patients about the detrimental effects of compensatory movements so that they are mindful about execution of movements without using compensatory strategies. This will aid to

minimise the possibility of maladaptive plasticity occurring early in the rehabilitation process which can impede recovery.

2.4.5 Role of ipsilateral motor pathways in recovery post stroke

Among the motor recovery mechanisms following stroke, the ipsilateral motor pathway from the unaffected motor cortex to the affected upper extremity has been the most actively researched area (Jang 2009a; Yeo & Jang 2012). Upper extremity movement is a fine balance between proximal stability and distal dexterity (Bradnam et al. 2013). Evidence suggest that skilled upper extremity function is under the control of both contralateral (cM1) and ipsilateral (iM1) motor cortices (Muellbacher et al. 2000; Hummel et al. 2003; Sohn et al. 2003; Strens et al. 2003; Duque et al. 2005; Verstynen et al. 2005; Davare et al. 2007; Perez & Cohen 2008; Lee et al. 2010). In healthy individuals, each M1 exerts reciprocal influences on homonymous body part representations in the opposite motor cortex via the corpus callosum (Meyer et al. 1995; Di Lazzaro et al. 1999). The transcallosal influence of iM1 on cM1 is initially inhibitory and then the inhibition decreases progressively, over a 100-millisecond period, and converts to facilitation just before the muscle becomes active (Murase et al. 2004). Following stroke, there is a decrease in the interhemispheric transcallosal inhibition from the affected hemisphere toward the unaffected hemisphere (Jang 2009b). Studies have demonstrated that there is an abnormally high level of interhemispheric inhibition targeting the affected hemisphere and its persistent influence therefore contribute to the paretic hand impairment (Murase et al. 2004; Duque et al. 2005). This abnormal inhibition is therefore maladaptive in nature.

It has been reported that ipsilateral corticospinal efferents are normally present at birth but become more and more inhibited during the first 10 years of development (Muller et al. 1997). After a stroke, the existing ipsilateral connections may then become unmasked due to lack of inhibition from the affected hemisphere (Jacobs & Donoghue 1991; Netz et al. 1997; Schwerin et al. 2008). This is supported by findings that the ipsilateral motor evoked potentials (iMEP) are difficult to obtain in healthy adults, particularly in the forearm and hand muscles (Benecke et al. 1991; Wassermann et al. 1991;

Talelli et al. 2006) but iMEP are most commonly elicited in stroke patients with moderate to severe motor deficits (Schwerin et al. 2008). The iMEP observed in stroke patients are usually small, with latencies of 5 to 14 ms longer than those of the contralateral MEP (Turton et al. 1996; Netz et al. 1997; Kim et al. 2004).

The ipsilateral motor pathway innervates mainly the trunk muscles and upper extremity muscles of the proximal joints more than the distal joints (Colebatch & Gandevia 1989; Colebatch et al. 1990; Nirkko et al. 2001; Jung et al. 2002; Schwerin et al. 2008; Montgomery et al. 2013). These characteristics may account partly for the better recovery of proximal motor function than distal motor function following stroke. It remains debatable as to whether the ipsilateral motor pathway originated from the anterior corticospinal tract (CST) or non-CST (cortico-reticulospinal and/or cortiovestibulospinal tracts) pathways (Jang 2009b).

Studies investigating distal arm muscles have found that the presence of ipsilateral activity is associated with poor motor recovery (Turton et al. 1996; Netz et al. 1997; Ward et al. 2003; Werhahn et al. 2003; Serrien et al. 2004; Kwon et al. 2007b; Schwerin et al. 2008; Buma et al. 2010). The recruitment of ipsilateral pathways by patients with more severe upper extremity impairment may be explained by the dependency on alternative motor pathways for organization of upper extremity movement as a result of decreased or loss of contralateral pathways. Ipsilateral reticulospinal projections have been proposed to be responsible for the flexor synergy pattern (shoulder abduction with elbow flexion) post stroke (Ellis et al. 2007). Increased excitability of ipsilateral pathways projecting to the proximal upper extremity may contribute to the expression of the extension synergy (shoulder adduction with elbow extension) following stroke, thus affecting movement control of the extremity (Beer et al. 2004; Beer et al. 2007; Sukal et al. 2007; Schwerin et al. 2008). Hence, the recruitment of ipsilateral pathways may be maladaptive for motor recovery in stroke patients. However, the increased ipsilateral activity may play a role in preserving some degree of motor function at the expense of independent joint control (Schwerin et al. 2008). Palmer et al. (1992) could not find any evidence of ipsilateral responses in a group of 10 recovered stroke patients. This is consistent with the findings of other studies whereby stroke patients who make a fuller upper extremity recovery organize movement-

related cortical activity from the contralateral (affected) hemisphere instead of ipsilateral hemisphere (Serrien et al. 2004; Nelles et al. 2011; Rehme et al. 2011a; Rehme et al. 2011b; Zhang et al. 2014).

In contrast to the above findings, studies of axial muscle activity (trunk muscles) have found positive correlation between ipsilateral activity and motor recovery level (Fujiwara et al. 2001; Misawa et al. 2008). The disparity in the relationship between ipsilateral activity and motor recovery between distal muscle and axial muscle groups may be accounted by the fact that distal muscles are primarily innervated by contralateral corticospinal projections (Palmer & Ashby 1992) whereas axial muscles receive extensive bilateral input from cortico-bulbospinal pathways (Ferbert et al. 1992). Hence, when contralateral projections are damaged following stroke, the axial muscles may be able to depend on a strong ipsilateral projection to a much greater extent than distal muscles (Schwerin et al. 2008).

Taken together, it appears that the utilization of ipsilateral pathways may not be beneficial for the motor recovery of the upper extremity but may be beneficial for recovery of the trunk muscles following stroke.

2.4.6 Integrity of corticospinal tract in motor recovery

The corticospinal tract (CST) is the most important neural tract that is fundamental to motor control and motor function in humans (Jang 2012; Vargas et al. 2013). Seventy to ninety percent of the CST fibers from the primary motor cortex crossed at the medulla to form the lateral CST (York 1987; Davidoff 1990; Canedo 1997). The lateral CST is responsible for the control of the distal musculature (wrist, finger, ankle, and toe) and enables complex and precise skilled movements of the entire extremity (Cho et al. 2012; Krebs et al. 2012). The anterior CST does not cross at the medullary decussation and continues descending ipsilaterally and the majority of fibers then cross over at the segmental level at which they will terminate (Krebs et al. 2012). The anterior CST is responsible for the control of the trunk and proximal musculature (shoulder, elbow, hip, and knee) (Cho et al. 2012; Krebs et al. 2012). In addition to the origin from the primary motor cortex, the CST has several areas of origin such as the premotor cortex and the parietal cortex

(York 1987; Davidoff 1990; Sanes et al. 1995).

The integrity of CST has been implicated in the motor recovery following stroke (Pineiro et al. 2000; Stinear et al. 2007; Jang 2009b; Burke & Cramer 2013). This is supported by numerous studies that demonstrated that extent of CST damage after stroke correlates with motor impairment (Binkofski et al. 1996; Lie et al. 2004; Konishi et al. 2005; Cho et al. 2007; Stinear et al. 2007; Lindenberg et al. 2010; Sterr et al. 2010; Zhu et al. 2010; Cho et al. 2012; Lotze et al. 2012; Schulz et al. 2012; Kou et al. 2013; Rosso et al. 2013).

Transcranial magnetic stimulation (TMS) of the motor cortex, eliciting motor evoked potentials (MEP), has been used to provide an objective evaluation of the integrity of CST in stroke patients (Nascimbeni et al. 2006; Stinear et al. 2007; van Kuijk et al. 2009; Bembenek et al. 2012) The clinical outcome of the upper extremity after stroke may depend on residual functional integrity of CST (Hendricks et al. 2003; Lotze et al. 2012). Studies using MEP as an outcome have demonstrated that greater upper extremity motor impairment is associated with increased motor thresholds and decreased motor recruitment (Binkofski et al. 1996; Pennisi et al. 1999; Brouwer & Schryburt-Brown 2006; Lotze et al. 2012). Pennisi et al. (1999) found that the absence of MEP in patients with complete hand palsy in the first 48 hours is predictive of absent or very poor, and not functionally useful hand motor recovery. In a study on chronic stroke patients, Stinear et al. (2007) found that those patients who exhibited MEP in their upper extremity muscles continued to make meaningful gains after 3 years post stroke while those without MEP had no meaningful gains. These findings imply that a great extent of damage to CST post stroke will lead to poorer outcome. A systematic review supports the value of MEP evaluation early after stroke onset in predicting motor recovery of the arm (Bembenek et al. 2012).

In recent years, another neuroimaging technique, diffusion tensor tractography (DTT), derived from diffusion tensor imaging (DTI), is used in research because it is able to visualize the architecture and integrity of the CST in three dimensions (Lindenberg et al. 2010; Sterr et al. 2010; Kou et al. 2013). Studies have demonstrated that the recovery of the hemiparetic upper extremity is associated with the integrity of CST (Cho et al. 2007; DeVetten et al. 2010; Lindenberg et al. 2010; Sterr et al. 2010; Globas et al. 2011; Cho et al. 2012;

Kou et al. 2013; Song et al. 2015). These findings are consistent with those studies that utilize fMRI (Pineiro et al. 2000; Zhu et al. 2010; Schulz et al. 2012; Rosso et al. 2013). A recent study using DTI demonstrated that the loss of CST axial diffusivity in the acute phase (3-7 days post stroke), and the loss of CST fractional anisotropy in the subacute phase (1-2 months post stroke), are strong prognostic indicators of future motor functions of the upper extremity for stroke patients with substantial initial motor impairment (moderately-severe and severe impairment levels) (Groisser et al. 2014).

In summary, the extent of CST damage following stroke can have a significant impact of the functional outcome of the upper extremity. The structural integrity of CST is crucial for good motor recovery in stroke patients.

2.5 True motor recovery versus compensation in stroke patients

The terminology “recovery” has been used to refer simultaneously to the restitution of damaged structures or functions and as a term to describe clinical improvements regardless of how these may have occurred, i.e. through restitution or adaptation (Levin et al. 2009). This can cause confusion and misinterpretation amongst clinicians and researchers from different disciplines. Therefore, Levin et al. (2009) proposed the definitions of recovery and compensation based on the first three levels of the ICF model, which are the *Health Condition* (neuronal) level, the *Body Functions/Structure* (impairment*)* level and the *Activity* (functional) level (Table 2-1).

Table 2-1 Definitions of motor recovery and compensation at three levels of ICF model (Levin et al. 2009)

ICF Level	Recovery	Compensation
Health Condition (neuronal)	Restoring function in neural tissue that was initially lost after injury	Neural tissue acquires a function that it did not have prior to injury
Body Functions/Structure (impairment)	Restoring the ability to perform a movement in the same manner as it was performed before injury	Performing an old movement in a new manner
Activity (functional)	Successful task accomplishment using limbs or end effectors* typically used by non-disabled individuals *end effectors refer to body part, such as a hand or foot, that interacts with an object or the environment	Successful task accomplishment using alternate limbs or end effectors

In brief, motor recovery refers to the capacity to perform a previously lost or impaired motor task in exactly the same manner as before the injury. Motor compensation refers to the use of new movements or movement sequences to perform a task in a manner different from that used prior to injury (Levin et al. 2009; Kleim 2011). Stroke patients may show true recovery as well as behavioural compensation (Kwakkel et al. 2004; Buma et al. 2013; Zeiler & Krakauer 2013); however, the interaction of both in any functional recovery process after stroke remains to be clarified (Timmermans et al. 2009).

The use of compensatory movement patterns may improve motor function but the improvement may be limited, as the study by Roby-Brami et al. (2003a) showed that the use of compensatory mechanisms was related to poorer functional outcome than when there was a genuine recovery of a more 'normal' motor pattern. Some patients develop strong and efficient motor compensations that prevent them from attempting to generate more 'normal' motor patterns in daily activities that may ultimately limit the final functional outcome (Roby-Brami et al. 2003a). Compensatory strategies may mask more

normal movement from emerging. This is supported by several research on trunk restraint incorporated into the upper extremity rehabilitation programme (Michaelsen & Levin 2004; Michaelsen et al. 2006; Woodbury et al. 2009; Thielman 2010; Wu et al. 2012a; Wu et al. 2012b). Restriction of compensatory trunk movements during upper extremity practice in chronic stroke patients led to reduced trunk displacement, improved shoulder and elbow movements, with straighter reach trajectories, resulting in improvements in reach-to-grasp movements. This will be discussed in greater detail in section 2.12.

Many clinical scales, for example, the Box and Block Test (Platz et al. 2005a), the Frenchay Arm Test (Heller et al. 1987), the Jebsen Taylor Hand Function Test (Bovend'Eerdt et al. 2004), that are used to measure upper extremity function cannot distinguish between true recovery and motor compensation when the scores on these tests show improvement. Tasks can be completed, either through improvement in motor patterns or through compensatory strategies. Hence, electromyographic analysis (Lum et al. 2009) and/or kinematic analysis (Subramanian et al. 2010; Kitago et al. 2013) is/are recommended to enable differentiation between functional gains achieved through compensation versus those achieved through true recovery of motor control. Kleim (2011) emphasized that distinguishing true recovery from compensation at both a neural and behavioural level is key towards understanding the relationship between neural plasticity and rehabilitation-dependent changes in function. To date, little is known about how different therapy modalities and therapy designs can influence brain reorganisation to support true motor recovery or compensation (Timmermans et al. 2009). Future studies that combine clinical outcome measures with kinematic and/or electromyographic analysis and neuroimaging techniques may be able to shed more light on brain plasticity, true motor recovery and compensation.

2.6 Neuromuscular control of the trunk

The trunk has been considered to be the central key point of the body (Edwards 1996). It plays an integral role in postural stabilization and also

enables mobility of the body and the extremities during task performance. Trunk control has been defined as part of postural control (Gjelsvik 2008). It involves the stabilization and selective movements of the trunk (Verheyden et al. 2007). Selective movements are controlled, specific and coordinated movements of a joint or body part in relation to other segments, which are the results of precisely graded neuromuscular activities (Gjelsvik 2008). Stability and selectivity are dependent on the range of motion, muscle length, alignment, the coordination between agonist and antagonist muscles, and the muscle synergy during concentric and eccentric contractions (Gjelsvik 2008).

The following subsections will discuss trunk movement and trunk stability in greater detail.

2.6.1 Trunk movement

The trunk consists of the thoracic and lumbar regions of the vertebral column. It is made up complex groups of muscles that provide stability and perform key movements of the body which enable function. The trunk is viewed as a core structure of the body.

Core stability is related to the body's ability to control the trunk in response to internal and external disturbances, including the forces generated from distal body segments as well as from expected or unexpected perturbations (Zazulak et al. 2007). Core stability, as generally defined in the sports medicine literature, is a foundation of trunk dynamic control that allows production, transfer, and control of force and motion to distal segments of the kinetic chain (Kibler et al. 2006). It is the body's ability to maintain or resume an equilibrium position of the trunk after perturbation. Deficits in neuromuscular control of the body's core may lead to uncontrolled trunk displacement during movement (Bazrgari et al. 2009).

The key muscle groups of the trunk consist of rectus abdominis, transverse abdominis, internal oblique, external oblique, erector spinae, multifidus and rotatores. These muscles enable the trunk to flex, extend, laterally flex and rotate. They are also the key muscles commonly studied in electromyographic research (Dickstein et al. 2004b; Cioni et al. 2010; Santos et al. 2010; Pereira et al. 2011). Table 2-2 summarises the key muscles involved in trunk movements.

Table 2-2 Key muscles involved in trunk movements

Trunk movement	Key muscles involved
Flexion	Rectus Abdominis External oblique Internal oblique
Extension	Erector spinae – longissimus iliocostalis spinalis Multifidus Rotatores
Right lateral flexion	Right rectus abdominus Right external oblique Right internal oblique Right iliocostalis Right longissimus
Left lateral flexion	Left rectus abdominus Left external oblique Left internal oblique Left iliocostalis Left longissimus
Right rotation	Right external oblique Left internal oblique Left multifidus Left rotatores
Left rotation	Left external oblique Right internal oblique Right multifidus Right rotatores

2.6.2 Trunk stability

Trunk stability describes the capacity of the body to maintain or resume a relative position (static) or trajectory (dynamic) of the trunk following perturbation (Zazulak et al. 2008). Trunk stability is dependent on the neuromuscular feedback control in response to internal and external disturbances, including the forces generated from distal body segments as well as from expected or unexpected perturbations (Zazulak et al. 2008).

The feedback controller for the spine or trunk (Figure 2-2) consists of intrinsic properties of intervertebral joints, intrinsic properties of trunk muscles and the central nervous system (CNS), which can respond to perturbations with both reflexive and voluntary muscle activation (Reeves et al. 2007).

Feedback control from intrinsic pathways (marked by red arrows in Figure 2-2) is instantaneous, whereas feedback control from reflexive (marked by blue arrow) and voluntary pathways (marked by orange arrow) has inherent delays (Reeves et al. 2007). These delays represent the time taken to sense a perturbation and respond with increased muscle activation to counteract the disturbance. Delays reflect signal transmission, CNS processing time, and time required to generate muscle force (Reeves et al. 2007). Information about the muscle length of the trunk musculature, joint position, velocity and force are fed back to CNS to be processed and the output is an "orchestrated neuromuscular activation pattern", described by Zazulak et al. (2008).

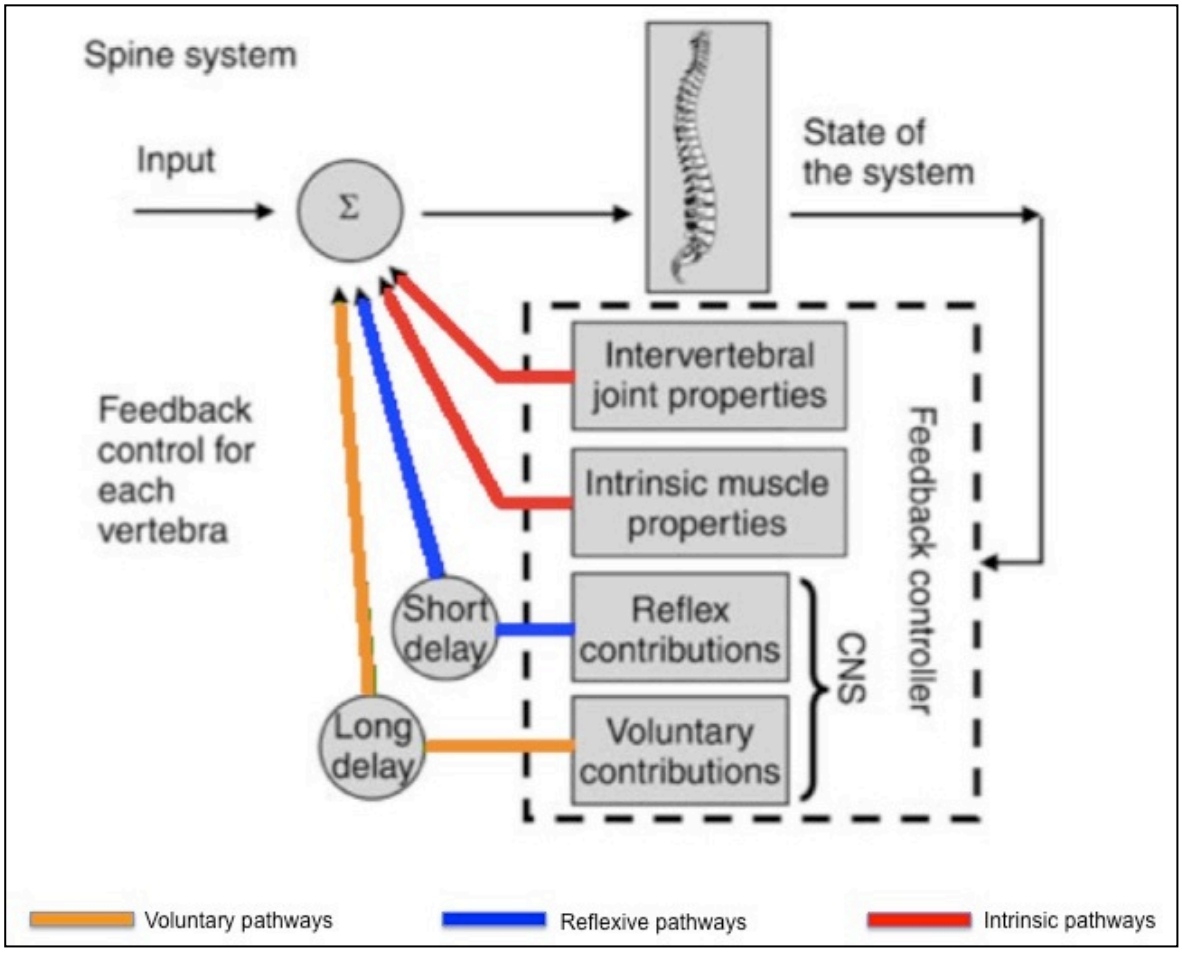


Figure 2-2 Components of the spine feedback controller. Reprinted from Clinical Biomechanics, Vol. 22, Reeves NP, Narendra KS and Cholewicki J, Spine stability: the six blind men and the elephant, page 266-274, Copyright (2007), with permission from Elsevier.

Feedforward input from the CNS can be used to increase trunk muscle coactivation prior to a perturbation, thus increasing muscle stiffness (Stokes et al. 2002). The stiffening of the trunk enables the intrinsic properties of the system to contribute more to the perturbation than the reflexive and voluntary pathways, which have inherent delays. Studies have demonstrated that voluntarily pre-tensioning of trunk muscles eliminates the need for a reflex response (Stokes et al. 2000; Granata et al. 2004).

Cholewicki and Van Vliet (2002) showed that the individual muscular contribution to spine stability depends greatly on the demands of the task, such as loading magnitude and direction. No single muscle can be identified as being the most or least important in stabilizing the spine. A study by Brown and Potvin (2005) concluded that spinal stability is a vital consideration for the CNS when dictating trunk muscle recruitment patterns. In other words, the CNS selects appropriate muscular activation patterns to optimize trunk stability.

Due to the various feedback pathways available, there is considerable flexibility in how the spinal system can maintain trunk stability. For each task, there is an optimal control strategy that minimises metabolic costs and/or maximises the system's performance (Reeves et al. 2007). Research indicates that three subsystems contribute to trunk stability (Panjabi 1992). The first subsystem is the passive contributions from the spinal ligaments, discs, and bone. The second subsystem is the steady-state active muscle recruitment contribution to spinal stability. The last subsystem is the neural feedback system that includes active and voluntary responses. Following a stroke, the feedback and feedforward pathways and/or the three subsystems may be disrupted to varying degree. This implies that trunk stability may be affected post stroke.

2.7 Trunk control post stroke

The sequelae of stroke can have an impact on the trunk control of patients. Trunk control post stroke may be affected by weakness of trunk musculature (Bohannon et al. 1995; Fujiwara et al. 2001), changes in muscle activation and control (sequencing, firing, initiation) (Ryerson 2007), decreased trunk position

sense (Ryerson et al. 2008), disuse atrophy (McComas 1994; Tanaka et al. 1997), unilateral neglect (Taylor et al. 1994; Cherney et al. 2001; Paolucci et al. 2001; Buxbaum et al. 2004), pusher syndrome (Davies 2000; Karnath & Broetz 2003; Babyar et al. 2007), head control (Di Fabio & Emasithi 1997; Cattaneo et al. 2005; Danna-Dos-Santos et al. 2007; Verheyden et al. 2011), spasticity (Barnes 2001; Zakaria et al. 2010) and spinal deformity (Zakaria et al. 2010).

The following subsections highlight the consequences of motor impairments such as muscle weakness and impaired trunk position sense on trunk control in stroke patients. Anticipatory postural adjustment in stroke will also be discussed.

2.7.1 Trunk muscle weakness post stroke

Anatomical studies have shown that trunk musculature is controlled bilaterally through crossed and uncrossed fibres of the anterior corticospinal tract (Kuypers 1981; York 1987; Davidoff 1990; Lemon 2008; Krebs et al. 2012), and ipsilaterally through the cortico-reticulospinal tracts (Peterson et al. 1979; Benecke et al. 1991). There is anatomic evidence that bilateral as well as ipsilateral inputs from higher brain centres reach mostly the axial trunk muscles (mainly erector spinae) (Ferbert et al. 1992; Carr et al. 1994). Electrophysiological studies using transcranial magnetic stimulation confirmed that cortical pathways to trunk muscles are represented bilaterally in the cortical hemispheres and the contralateral pathways are more dominant (Plassman & Gandevia 1989; Ferbert et al. 1992; Fujiwara et al. 2001).

Trunk muscle weakness post stroke has been considered to be primarily attributable to the loss of descending corticospinal pathway activation to spinal motorneurons (Tunstill et al. 2001; Park et al. 2009). The trunk muscle weakness has also been attributed to insufficient mobilisation of high-threshold motor units (Karatas et al. 2004). Poor or absent volitional control of motor units implies that muscles can neither be activated in a timely, coordinated manner nor activated with sufficient force (Hammond et al. 1988; Kamper & Rymer 2001; Lang & Schieber 2004; Silva-Couto Mde et al. 2014). This result in slower, less accurate and less efficient movements compared to healthy subjects (Lang et al. 2005; Lang et al. 2006) and hence, the

manifestation of muscle weakness. This can have an effect on the trunk control of stroke patients.

The other possible cause of muscle weakness is disuse atrophy (McComas 1994; Tanaka et al. 1997; Karatas et al. 2004). Due to loss of balance and mobility immediately post stroke, many patients are spending more time in bed than premorbid. There is reduction in muscle fibre size (Bourbonnais & Noven 1989; Evans & Campbell 1993; Weightman 1994; Gray et al. 2012), replacement of muscle fibre loss with fat and fibrous tissue (Porter et al. 1995; Triandafilou & Kamper 2012) and change of muscle properties toward slower and more fatigable muscle type (Hafer-Macko et al. 2008; Horstman et al. 2010). Similarly, disuse atrophy can affect trunk muscles and hence their optimal functioning as a postural stabilizer.

Studies have shown that following stroke, the trunk muscle weakness occur contralesionally and to a lesser extent ipsilesionally (Fujiwara et al. 2001; Tsuji et al. 2003). The findings tie in with the clinical observation that stroke patients exhibit lesser impairment of the trunk as compared to the paresis of the upper and lower extremities on the contralesional side.

Trunk muscle strength in stroke subjects is impaired multidirectionally (Bohannon et al. 1995). Weakness of the trunk flexor-extensor (Tanaka et al. 1998; Karatas et al. 2004), bilateral trunk rotator muscles (Tanaka et al. 1997) and lateral trunk flexors (Bohannon et al. 1995) have been determined by means of isokinetic dynamometer and hand-held dynamometer. The muscle strength of the trunk flexors and extensors in stroke patients were found to be 88% and 64% respectively as compared to those in healthy control subjects (Tanaka et al. 1998). The trunk rotators and lateral trunk flexors strength in stroke patients are approximately 50% of the healthy controls (Bohannon et al. 1995; Tanaka et al. 1997). In addition, the trunk muscle weakness of the paretic side was found to be significantly lower than the non-paretic side of the stroke patients. This is further confirmed by findings of Tsuji et al. (2003). The results have to be interpreted with caution because it is very challenging to isolate unilateral trunk strength. Nonetheless, the findings gave an indication of trunk impairment post stroke.

Other studies have found significant positive correlation between trunk muscle strength and sitting balance in stroke patients (Bohannon 1992; Bohannon 1995), as well as the Berg Balance score, which is a clinical measure of functional balance (Karatas et al. 2004). A recent systematic review also illustrates that trunk muscle strength is associated with variables of static and dynamic balance, functional performance, and falls in older adults (Granacher et al. 2013). This implies that trunk muscle strength can affect trunk control directly and has an impact on sitting and standing balance.

Drawing from the results of the above studies, it is evident that stroke patients have bilateral trunk muscle weakness. It may be challenging for rehabilitation professionals to detect trunk muscle weakness in clinical settings by physical examination alone without the necessary equipment such as dynamometer. Gathering information about the degree of trunk muscle weakness is critical because Karatas et al. (2004) demonstrated that even mild weakening of trunk muscles can interfere with balance, stability and functional ability. This suggests that it is important to incorporate trunk assessment as part of the routine neurorehabilitation assessment of a stroke patient.

2.7.2 Anticipatory postural adjustment

2.7.2.1 Anticipatory postural adjustment in healthy individuals

Maintenance of balance in sitting or standing is essential during task performance such as goal-directed upper extremity movement during reaching. In healthy individuals, anticipatory postural adjustment (APA) occur to counter the perturbation associated with the forthcoming voluntary movement in advance, such as elevation of the upper extremity (Bouisset & Zattara 1981; Bouisset & Zattara 1987; Baldissera et al. 2008; Lee et al. 2009). The activation of muscles in the trunk and legs occur at least 100 milliseconds prior to a forthcoming predictable perturbation (Girolami et al. 2011). The activities in the trunk muscles precede the arm movement which ensures that movement occurs against a background of dynamic stabilization of the body (Horak et al. 1984; Garland et al. 1997; Baldissera et al. 2008; Caronni & Cavallari 2009; Lee et al. 2009; Santos et al. 2010; Yiou et al. 2012). Hence, APA is essential for trunk stability (Pereira et al. 2014).

APA in the trunk muscles can also be executed along with an intended movement of the limb (Dickstein et al. 2004a). It helps to orientate the trunk in space so that the desired motor output can be achieved via the intended movement (Hodges et al. 2000; Dickstein et al. 2004a).

APA associated with the onset of arm movement are usually scaled according to load (Zattara & Bouisset 1986; Toussaint et al. 1998; Forssberga et al. 1999) and other movement parameters, such as velocity (Bertucco & Cesari 2010) and amplitude (Bouisset et al. 2000). The preparatory adjustments of the trunk are in a direction opposite to those produced by the reactive moments generated by limb movements (Aruin & Latash 1995; Hodges et al. 2000). Superficial trunk muscles, such as rectus abdominis, external oblique and erector spinae, have been found to become active and react based on the direction of the limb movement (Aruin & Latash 1995). On the contrary, the contraction of transversus abdominis (TrA) has been found to be active irrespective of the direction of limb movement (Hodges & Richardson 1997; Allison & Morris 2008; Allison et al. 2008). TrA contributes to stabilization and protection of the spine through either its role in the production of intra-abdominal pressure (Cresswell et al. 1994) or tensioning the thoracolumbar fascia (Akuthota & Nadler 2004).

The underlying mechanism of APA involves anticipating the effect of the movement on posture and coordinating the activation of postural adjustments and the intended (focal) movement to minimize the postural disturbance. This mechanism of control has been termed "feedforward control" by Cordo and Nashner (1982). In addition, control of APA has been demonstrated to be reproducible from one participant to another for a given experimental condition and are specific to the type of forthcoming movement. Thus, APA has been considered to be preprogrammed at the CNS level (Zattara & Bouisset 1986; Zattara & Bouisset 1988). The central preprogramming of motor command triggers the APA prior to voluntary movement of the limb. Forssberga et al. (1999) confirmed the existence of shared memory representations that were used to control arm movement in lifting tasks and control the APA.

2.7.2.2 Anticipatory postural adjustment in stroke patients

APA has been demonstrated to be reduced in stroke patients compared to healthy control subjects (Horak et al. 1984; Garland et al. 1997; Aruin 2002; Slijper et al. 2002; Dickstein et al. 2004a; Pereira et al. 2014). Major impairments in the activity of trunk muscles in hemiparetic subjects were manifested in the reduced activity level of the lateral trunk muscles (latissimus dorsi and external oblique), in delayed onset, and in reduced synchronization between activation of erector spinae and latissimus dorsi (Dickstein et al. 2004a; Dickstein et al. 2004b). A recent study demonstrated a delay of APA in the muscles on both sides of the body of stroke patients compared to healthy subjects. The delay was observed during performance of the reaching task with the fast and self-selected velocity (Pereira et al. 2014). The stroke patients were also less capable of adapting their APA to different speeds, and always recruiting the same motor synergies.

Lower activity of paretic latissimus dorsi was found to be associated ($r = -0.408$, $p < 0.055$) with a lower arm function score, as measured by the Motor Assessment Scale, in stroke patients (Dickstein et al. 2004a). This finding suggests a relationship between trunk muscle activity and upper extremity function. However, this association is considered a weak relationship ($r = -0.408$) statistically (Hinkle et al. 2003). In addition, muscle activation data alone does not give an indication of the degree of trunk control. In other words, muscle activity will only indicate the occurrence of muscle contraction and it will not provide information with regard to trunk control. Hence, there is a gap in knowledge regarding the impact of trunk control on upper extremity function in stroke patients.

APA has been thought to reflect the existence of an internal forward model within the central nervous system that takes into account the dynamic consequence of an expected perturbation and that generates responses to counteract these consequences (Yiou et al. 2012). This internal forward model is supported by findings that there is increased trunk muscle coactivation prior to a perturbation, thus increasing muscle stiffness. This is more than the contributions from the reflexive and voluntary pathways, which have inherent delays (Stokes et al. 2002; Granata et al. 2004). Based on this, if the internal forward model is disrupted post neurological insult, for example, following a

stroke, APA may be affected. Together with trunk muscle weakness following stroke, disrupted internal forward model may lead to serious impact on how trunk muscles are activated to counteract the destabilizing effect during upper extremity movement, as well as on the trunk stability. Hence, research investigating the impact of trunk control on upper extremity function is warranted.

2.7.3 Trunk position sense post stroke

Proprioception enables the body to maintain proper orientation during static and dynamic activities. Proprioception consists of the position sense and movement sense (Swinkels & Dolan 2000). Position sense provides information and awareness of the relative orientation of body parts in space while movement sense is the perception of velocity and acceleration. While trunk musculature provides some spinal stabilization, without adequate position sense, the trunk cannot be stable (Hodges & Richardson 1997; Ebenbichler & Oddsson 2001).

To date, Ryerson et al. (2008) is the only research group that had investigated trunk position sense in individuals following stroke. The researchers assessed trunk position sense by measuring trunk repositioning error (TRE), which has been proven to be a reliable and valid method (Pearcy & Hindle 1989). TRE during seated forward flexion movements was assessed in 20 chronic stroke subjects and 21 age-matched healthy controls by using an electromagnetic motion analysis system. Clinical outcome measures for balance, postural control and the upper and lower extremity motor impairment were Berg Balance Scale (BBS), Postural Assessment Scale for Stroke (PASS) and Fugl-Meyer Assessment (FMA) respectively.

Results showed significant between-group differences in the mean absolute TRE in both the sagittal ($p < 0.0001$) and transverse ($p < 0.0012$) planes. In the stroke group, the mean TRE in the sagittal plane was 6.9 degrees compared to 3.2 degrees in the control group. In the transverse plane, the mean TRE was 2.1 degrees compared to 1.0 degree in the control group. Hence, the mean TRE difference was two-fold that of the control group. In the frontal plane, mean absolute TRE value was not statistically different between the groups.

In the stroke group, the absolute TRE in the sagittal plane demonstrated a significant negative correlation with BBS scores (r = -0.49; p = 0.03) but was not correlated with either the PASS or FMA. Transverse plane TRE was negatively correlated with both BBS (r = -0.48; p = 0.03) and the PASS (r = -0.52; p = 0.02) scores, but was not related to the FMA score. There were no significant correlations between frontal plane TRE and any of the three clinical measures. A post-hoc analysis revealed no significant relationship between TRE and either upper or lower extremity FMA score.

It is proposed that the afferent inputs from the muscle spindles in the weakened trunk muscles are affected post stroke (Ryerson et al. 2008). In fact, Amonoo-Kuofi (1983) found that the greatest density of muscle spindles was located in the thoracic region, especially in the lateral column of trunk muscles. Therefore, trunk muscle weakness post stroke may possibly affect the afferent inputs from the muscle spindles in the thoracic region. The reduction in afferent inputs post stroke may lead to impaired trunk position sense. In addition, following a stroke, possible reduction in afferent inputs from the ligaments, thoracolumbar fascia, intervertebral discs and facet joints of the spine can play a role in affecting trunk position sense.

The findings from this study (Ryerson et al. 2008) suggest that individuals with deficits in trunk position sense post stroke are more likely to demonstrate impairments in balance and postural control. There appears to be no association between impaired trunk position sense and upper extremity motor impairment. However, the results need to be interpreted in the light that only chronic stroke individuals were recruited. The mean length of time post-stroke in this study was 5.3 years. It remains unknown about the extent of deficits in trunk position sense in the acute and subacute stroke individuals and how these deficits can impact balance, postural control and upper extremity. The greatest challenge in assessing trunk position sense in the acute and subacute stroke individuals is to differentiate motor control deficit from trunk position sense impairment. Motor control deficit in the trunk is evident in the acute and subacute phase of recovery due to trunk muscle paresis. This can potentially masks itself as impairment of trunk position sense during testing. In view of this challenge, there remains a need to find the best method to assess trunk position sense in the early phase of stroke recovery.

The main inclusion criteria for this study was the ability to reach forward and down to the floor, and return to an upright sitting position with arms folded across the chest and eyes closed. For an individual to complete the full range of motion of that nature, a good level of trunk control ability was essential. Despite having adequate voluntary control of the trunk, the findings clearly illustrate the presence of residual impairment of trunk position sense in the chronic phase of stroke. This suggests that full recovery of trunk position sense may not be attained even though the stroke individuals may be functional in performing their activities of daily living. The impact of such residual trunk impairment remains unknown until future research is conducted.

In this study, the testing protocol was only conducted in forward trunk flexion. Future studies should include trunk lateral flexion and rotation in order to provide a comprehensive understanding about the trunk position sense post stroke. Nonetheless, the current findings provide vital insights into the trunk impairment post stroke and have relevant clinical implications. Therapists should address the rehabilitation of trunk position sense to improve trunk stability as it can have an impact on balance and postural control.

In summary, this section highlights that trunk muscle weakness and impaired trunk position sense can seriously affect the stability of the trunk and its control. This links to the next section that will discuss the relationship between trunk performance and functional outcome in stroke patients.

2.8 Relationship between trunk performance and functional outcome following stroke

2.8.1 Measurement of trunk performance

Trunk performance is the terminology used in the literature that broadly encompasses trunk muscle strength, muscle activity, and trunk control ability during task performance. Various methods have been used to measure trunk performance post stroke. These methods include isokinetic muscle testing

(Tanaka et al. 1997; Tanaka et al. 1998; Karatas et al. 2004), manual dynamometry (Bohannon 1992; Bohannon 1995; Bohannon et al. 1995) electromyographic analysis (Dickstein et al. 1999; Dickstein et al. 2000; Winzeler-Mercay & Mudie 2002; Dickstein et al. 2004a; Dickstein et al. 2004b), transcranial magnetic stimulation (Fujiwara et al. 2001), computed tomography (Tsuji et al. 2003), and motion analysis (Messier et al. 2004; Messier et al. 2006; Robertson & Roby-Brami 2011; van Kordelaar et al. 2012).

Clinical scales are also used to evaluate trunk performance. These scales include Trunk Control Test (TCT) (Colin & Wade 1990), the trunk control items of the Postural Assessment Scale for Stroke Patients (PASS-TC) (Benaim et al. 1999), Verheyden's Trunk Impairment Scale (TIS-V) (Verheyden et al. 2004) and Fujwara's Trunk Impairment Scale (TIS-F) (Fujiwara et al. 2004). A worthy note when reading the literature is to be aware of the latter two scales with identical name (Trunk Impairment Scale). To date, only two published papers (Fujiwara et al. 2004; Likhi et al. 2013) used the Fujiwara's Trunk Impairment Scale while other numerous papers have utilized the Verheyden's Trunk Impairment Scale.

2.8.2 Trunk performance and functional outcome

There is strong evidence that trunk performance is an important predictor of overall functional ability, balance and gait after stroke (Franchignoni et al. 1997; Duarte et al. 2002; Hsieh et al. 2002; Sebastia et al. 2006; Verheyden et al. 2006; Verheyden et al. 2007; Di Monaco et al. 2010; Kim et al. 2012). In a recent study, weakness of the abdominal muscles was found to adversely impact the balance of people with mild stroke as well as their ability to dress, use a toilet, transfer, and walk (Fujita et al. 2015).

In a study on 49 subacute stroke patients, Franchignoni et al. (1997) reported high correlation between TCT at admission (TCT-adm) and motor subscore of Functional Independence Measure (FIM) ($r = 0.856$) and total FIM score ($r = 0.79$) at discharge. Similar findings of such high correlation between TCT and FIM score (motor FIM: $r = 0.723$; total FIM: $r = 0.738$) in 28 subacute stroke patients was also reported by Duarte et al. (2002). Both studies also confirmed that TCT can predict functional outcome (FIM score) at discharge. The value of TCT in predicting functional outcome was further confirmed in a large retrospective study on 245 subacute stroke patients by Sebastia et al.

(2006). Drawing from these results, it is clear that trunk control is closely associated with functional activities and is an important predictor of function post stroke.

The relationship between trunk performance and functional outcome are further supported by other studies (Verheyden et al. 2006; Verheyden et al. 2007; Di Monaco et al. 2010; Gialanella et al. 2012; Kim et al. 2012; Kim et al. 2015). A recent study on 30 chronic stroke patients demonstrated a highly significant correlation (r = 0.911) between trunk control (TIS-V) and Tinetti balance subscale (Jijimol et al. 2013). In a cross-sectional study on 51 subacute and chronic stroke patients, Verheyden et al. (2006) showed significant relationships between trunk performance (TCT and TIS-V) and measures of balance (Tinetti balance subscale), gait (Tinetti gait subscale; 10m walk test; Timed Up and Go Test), and functional ability (FIM) after stroke. It was also worthy to note from the study that trunk performance was still impaired to some extent in the chronic stroke patients as none of them attain maximum score on the Trunk Impairment Scale. This finding of residual trunk impairment post stroke is consistent with those in other studies (Bohannon et al. 1995; Tanaka et al. 1997; Tanaka et al. 1998; Dickstein et al. 1999; Dickstein et al. 2000; Fujiwara et al. 2001; Tsuji et al. 2003; Dickstein et al. 2004a; Dickstein et al. 2004b; Karatas et al. 2004; Messier et al. 2004). The trunk impairment in chronic stroke patients may affect their optimal functioning in ADL, balance and gait.

The reported variance of functional outcome after stroke explained by trunk performance ranges from 45% (Hsieh et al. 2002) to 54% (Duarte et al. 2002) to 71% (Franchignoni et al. 1997). The differences in reported variance could be due the different stroke population studied (14-15 days post stroke versus 46 days post stroke), different outcome measures used to measure trunk performance (Trunk Control Test versus PASS-TC) and the different time points used to measure outcome (3 weeks versus 3 months versus 6 months post stroke). In addition, the functional outcome measures used in both studies were different. Franchignoni et al. (1997) and (Duarte et al. 2002) used Functional Independence Measure (FIM), while Hsieh et al. (2002) used the comprehensive ADL as a measure of functional outcome. Comprehensive ADL

refers to the combined scores of Barthel Index (measuring basic ADL) and Frenchay Activities Index (measuring instrumental ADL) in this study.

In a large scale study on 169 subacute stroke patients, Hsieh et al. (2002) found that trunk control score (PASS-TC), age and Fugl-Meyer motor (upper and lower extremities) scores were the strongest predictors of comprehensive ADL. The trunk control score alone accounted for 45% of the variance in predicting comprehensive ADL function.

Currently, there is no research which builds upon these findings to investigate the impact of trunk control on recovery of upper extremity function in stroke patients specifically, even though the upper extremity plays a vital role in the performance of ADL (Clarke 2002; Desrosiers et al. 2003b; Houwink et al. 2013). It is reported that 80% of acute stroke patients and 40% of chronic stroke patients show a reduced ability to use the paretic upper extremity in ADL (Parker et al. 1986; Nakayama et al. 1994a; Langhorne et al. 2011).

The relationship between reaching and ADL independence is reflected in measures such as the Barthel Index and FIM, where the ability to reach is required for over 50% of the activity of daily living tasks (van der Putten et al. 1999; Ingram et al. 2008). Following stroke, difficulty with reaching may lead to further dependence and possible long-term disability (Lai et al. 2002a; Mayo et al. 2002; Lang et al. 2005; Wagner et al. 2007; Chen et al. 2013b). Arm motor function has been shown to correlate strongly ($r = 0.76$, $p < 0.05$) with the Barthel Index (Sveen et al. 1999). Furthermore, movements of the affected upper extremity in stroke patients explain up to 40% of the variance in abilities to perform the normal ADL (Mercier et al. 2001). Strong evidence exists to support upper extremity paresis as one of the key predictors for outcome of ADL (Veerbeek et al. 2011).

Given that evidence from the above-mentioned studies supports trunk performance as a predictor of ADL and the existence of a close relationship between upper extremity function and ADL, it is probable that there is an association between trunk control and upper extremity in ADL performance. Hence, research investigating the relationship between trunk control and recovery of upper extremity function in stroke patients is warranted.

The next section details the relationship between trunk control and reaching ability from the perspective of developmental science. It provides an insight into this close relationship that probably transits from childhood into adulthood. This will add another dimension to understanding about the association between trunk control and upper extremity in healthy adult individuals.

2.9 Developmental science perspective on trunk control and reaching ability

Trunk control, which is the foundation of posture, is a critical element for early reaching (Bertenthal & von Hofsten 1998; Rachwani et al. 2013). The ability to control the head, trunk and arm, both separately and with respect to each other is a skill that improves with age, even though the youngest infants were able to perform the reaching task in an elementary way (Sveistrup et al. 2008).

Developmental studies on newborn infants have provided deeper insights into the relationship between trunk control and reaching. When appropriate support of the entire trunk was provided to newborn infants, emergence of reaching movements was observed (Grenier & Amiel-Tison 1981; von Hofsten 1982; Rochat & Goubet 1995). Without such support, the reaching movements could not be performed. This observation suggests that stability of the trunk is key to enabling the dissociation of the upper extremities of the infant from the trunk for activity; in this case, reaching movements.

At around 3 months of age, reaching movements are characterised by variations with irregular and fragmented trajectories (van der Fits et al. 1999a; van der Fits et al. 1999b). At age 4 to 5 months, reaching movements become smoother and more fluid. In addition, reaching becomes more successful and functional (van der Fits et al. 1999a; van der Fits et al. 1999b). Emerging postural control of the head may play an important role in the onset of successful reaching (Thelen & Spencer 1998).

After 6 months, the kinematic parameters of a reach start to assume an adult-

like form in which straightness and smoothness are correlated; fewer movement units are associated with a straighter trajectory of reaching (von Hofsten 1991; Fallang et al. 2000; de Graaf-Peters et al. 2007). However, the stereotypic arm kinematics during reaching are not expressed before the second year of life (Konczak & Dichgans 1997).

Previous studies have investigated the relationship between postural control and reaching. Researchers had examined reaching in 4 and 6 month old infants in fully supported and unsupported states (Thelen & Spencer 1998; Hopkins & Rönnqvist 2002; de Graaf-Peters et al. 2007). They overcame the lack of trunk control in the infants by using supine or semi-reclined seating. Results showed that better postural control is associated with a larger success and a better quality of reaching. In addition, results showed that within the age period of 4 to 6 months, infants develop the capacity to select 'better' postural patterns. Such postural activity was associated with reaching movements with a better kinematic quality. At 6 months the infants often selected the complete pattern in which all dorsal neck and trunk muscles were activated in concert and a postural adjustment with top-down (cranio-caudal) recruitment. These findings highlight the critical role of head and trunk stability for the emergence of good trajectory control during reaching.

Although previous research has provided insights into the control of reaching development, they have not specifically addressed the contribution of upper and lower regions of trunk control to reaching. In a recent study, Rachwani et al. (2013) explored the influence of an external support at the thoracic and pelvic level of the trunk on the success of reaching, postural stability and reaching kinematics while infants reached for a toy. Seventeen healthy infants, aged between 4 to 6 months, were grouped based on their level of trunk control as assessed by the Segmental Assessment of Trunk Control (SATCo) (Butler et al. 2010). SATco is a clinical measure used to assess the trunk control of children with motor disabilities at various levels of support. The level of support included the shoulder girdle (head control), axilla (upper thoracic control), inferior scapula (mid-thoracic control), lower ribs (lower thoracic control), below ribs (upper lumbar control), pelvis (lower lumbar control) and eventually no support, in order to assess full trunk control (Butler et al. 2010).

Results showed that all infants were equally stable with the thoracic support and had similar kinematic parameters during the reaching sequence. However, with the pelvic support, only infants who had acquired control of their thoracic and lumbar regions performed significantly better in quality of reaching as compared to those with only thoracic control. There was significant ($p < 0.05$) decreased movement time, decreased movement units, improved straightness score and increased path length per movement unit. These findings are consistent with previous studies which demonstrated that the infants' ability to control the trunk influences the quality of reaching (Spencer et al. 2000; Hopkins & Rönnqvist 2002).

Drawing from the findings from developmental science, it is evident that trunk control has an impact on the quality of reaching. Inferring from this, trunk control is essential for appropriate dissociation of the upper extremity from the trunk for function. As the reaching task will cause postural perturbation as the upper extremity moves, appropriate postural adjustments are essential to counteract such perturbation. By having a stable base or platform, in the form of good trunk control, it will facilitate various musculatures of the distal and proximal segments of the upper extremity to work against a background of trunk stability, hence enabling the ability of the upper extremity for function.

In conclusion, the perspective offered by developmental science aid in understanding of the relationship between trunk control and upper extremity. This leads on to the next section on research related to pointing and reaching in adult stroke patients.

2.10 Compensatory trunk movements during pointing and reaching in stroke patients

The trunk plays an important role during reaching tasks. In the healthy subjects, when the target is within arm's length, the trunk is required to act only as a postural stabilizer and the target can be attained by motion at the shoulder and elbow joints (Kaminski et al. 1995; Archambault et al. 1999;

Yang & Feldman 2010). When the target was beyond arm's length, the trunk and scapula had to move in conjunction with the shoulder and elbow joints for goal attainment. Rossi et al. (2002) found that the trunk only begins to contribute to the hand displacement at peak hand velocity. They proposed that the central commands that determine the contributions of the arm and the trunk to the transport of the hand are generated sequentially. The threshold for the involvement of the trunk flexion in the kinematic chain for seated reaching is reported to be usually within 80% to 90% of arm's length (Mark et al. 1997; Ghafouri & Feldman 2001).

Numerous studies have demonstrated that stroke patients exhibit excessive trunk and shoulder girdle movements during pointing tasks, reach-to-grasp movement or when performing upper extremity elevation (Roby-Brami et al. 1997; Cirstea & Levin 2000; Steenbergen et al. 2000; Michaelsen et al. 2001; Levin et al. 2002a; Levin et al. 2002b; Roby-Brami et al. 2003a; Ustinova et al. 2004; Foroud & Whishaw 2006; Messier et al. 2006; Robertson & Roby-Brami 2011; Massie et al. 2012; Rundquist et al. 2012; van Kordelaar et al. 2012; Liu et al. 2013; Thielman 2013; Massie et al. 2014; Pereira et al. 2014; Shaikh et al. 2014). Excessive trunk displacement (TD) may occur in forward flexion and lateral flexion (Cirstea & Levin 2000; Esparza et al. 2003; Messier et al. 2006; Nakamura et al. 2008; Thielman 2013), and rotation (Cirstea & Levin 2000; Michaelsen et al. 2004; Robertson & Roby-Brami 2011; Massie et al. 2012; Merdler et al. 2013). In addition, studies have also confirmed the presence of deficits in interjoint coordination during pointing and reaching tasks following stroke (Trombly 1992; Levin 1996b; Beer et al. 2000; Cirstea & Levin 2000; Levin et al. 2000; Cirstea et al. 2003a; Cirstea & Levin 2007). Movements of the affected upper extremity in individuals with stroke are segmented, slower, and characterized by a greater variability and by deflection of the trajectory from a straight line (Archambault et al. 1999; Rohrer et al. 2002; Cirstea et al. 2003b; Foroud & Whishaw 2006; Dipietro et al. 2009). Abnormal muscle coactivation and abnormal joint torque production in the paretic shoulder and elbow also account for the difficulty faced by stroke patients during pointing and reaching to targets (Dewald et al. 1995; Dewald & Beer 2001; Liu et al. 2013).

TD was found to be more than 4.5 times the amount used by healthy subjects to compensate for a mean reduction of 25% active elbow extension or a mean

reduction of more than 50% in active shoulder flexion even when reaching to targets placed within the length of the arm (Michaelsen et al. 2001; Levin et al. 2002b; Levin et al. 2004). TD was found to be significantly ($p < 0.05$) inversely correlated with Fugl-Meyer Upper Extremity (FMA) score. The correlation coefficient ranged from r = -0.72 to r = -0.87 ($p < 0.05$), indicating a strong correlation (Cirstea & Levin 2000; Levin et al. 2002b; Cirstea et al. 2003b; Subramanian et al. 2010). In other words, TD varies with the severity of upper extremity hemiparesis. Similarly, Michaelsen et al. (2004) found that trunk rotation was significantly inversely correlated (r = -0.71, $p < 0.05$) with FMA score. In addition, TD was directly correlated with the degree of spasticity in the elbow flexors (r = 0.88, $p < 0.05$) (Cirstea & Levin 2000).

A retrospective study of kinematic data from research related to pointing and reaching in stroke patients revealed vital information about the contribution of the trunk (Subramanian et al. 2010). In the pointing task, TD alone explained 46% of the variance in FMA score. The combination of TD and shoulder flexion explained 51% of the variance in FMA score and it was confirmed as the best fit model in multiple regression analyses. Logistic regression revealed that TD was the only variable discriminating between mild (FMA score ≥50) and moderate-to-severe (FMA score <50) motor impairment levels. Stroke patients with mild impairment and those with moderate-to-severe impairment exhibited ≤4.8 cm and >4.8 cm of TD respectively during pointing task. On the other hand, in the reach-to-grasp task, TD alone explained 52% of the variance in FMA score and was deemed the best fit model. In addition, TD was also the only variable able to discriminate between mild impairment and moderate-to-severe impairment. For the reach-to-grasp task, stroke patients with mild impairment and those with moderate-to-severe impairment exhibited ≤10.2 cm and >10.2 cm of TD respectively.

In other studies on pointing tasks, mean TD of healthy and stroke individuals was 3.8 cm and 11cm respectively (Cirstea & Levin 2000; Cirstea et al. 2003b). Further analysis of the findings of the study by Cirstea et al. (2003b) showed that mean TD in those stroke patients with mild upper extremity impairment (FMA score ≥50) was 8.5 cm while those with moderate-to-severe impairment (FMA score <50) exhibited 18.1 cm of TD. In the reaching tasks, mean TD of

healthy individuals ranged from 1.7 cm to 2.7 cm, while the stroke individuals exhibited TD ranging from 10.2 cm to 12.5 cm (Michaelsen et al. 2001; Levin et al. 2002b; Alt Murphy et al. 2011). This is similar to the findings by Subramanian et al. (2010). Hence, the findings demonstrated that 3 to 5 times more TD occurred during pointing and approximately 4.8 to 6 times more TD occurred during reaching in stroke individuals compared to healthy individuals.

Many of these studies have small sample sizes ranging from 6 to 28 subacute and chronic stroke subjects. Nonetheless, the key findings highlight the presence of excessive compensatory trunk movements during pointing and reaching in stroke patients. The increased recruitment of trunk movement is a compensatory motor strategy by which the central nervous system may extend the reach of the arm when there is impaired joint movements and control of the upper extremity. The redundancy in the number of degrees of freedom of the motor system enables completion of tasks by substitution of other degrees of freedom for movements of impaired joints or control of the extremities (Kamper et al. 2002; Roby-Brami et al. 2003b; Michaelsen et al. 2004). However, the recruitment of the trunk during forward reach may not result in improved occupational performance because from an optimal control framework, the energy demands of trunk flexion would be greater than using the arm due to higher inertia (Dounskaia 2007). It remains unknown how the degree of trunk impairment post stroke will affect or contribute to the amount of trunk movement in reaching and grasping tasks for stroke patients with different levels of upper extremity control. Hence, there is still a gap in knowledge in this aspect.

In a recent study, Robertson and Roby-Brami (2011) observed significantly larger degree of trunk flexion ($p < 0.01$) and rotation ($p < 0.05$) in their sample of 16 stroke patients (11 subacute stroke and 5 chronic stroke patients) during reaching tasks in a large three-dimensional workspace adjusted to each individual patient's arm length. The researchers also questioned whether the significantly larger trunk flexion and rotation observed was a result of impaired trunk control or as a result of compensatory strategies of using the trunk to assist in reaching. Robertson and Roby-Brami (2011) recommended future research to investigate this aspect. Hence, this recommendation also supports the justification for this doctoral study to investigate the impact of

trunk control on upper extremity function in stroke patients.

A study by Massie and Malcolm (2012) on 11 chronic stroke patients demonstrated that emphasizing patients to increase their reaching speed between two targets led to improved kinematic of the trunk and upper extremity. Patients reached significantly faster and smoother during the task while maintaining target accuracy. A notable finding is that patients used significantly less anterior trunk displacement during the fast condition, and yet not exhibiting any significant change in shoulder flexion. Hence, this implies that increasing the speed of reaching may be a more optimal motor control strategy without compromising the accuracy of reaching. This serves as a valuable point for therapists to consider as they can vary the speed of task execution to challenge the patients and yet achieve a desirable minimal compensatory trunk movements during training.

Recently, van Kordelaar et al. (2012) provided further insights into the relationship between the trunk and upper extremity post stroke. The researchers investigated the interaction between pathological limb synergies and compensatory trunk movements during reach-to-grasp with the paretic upper extremity. Principal component analysis was used to identify components representing linear relations between the degrees of freedom of the upper extremity and trunk across stroke patients.

Data gathered from 46 subacute and chronic stroke patients identified four principal components which explained 84.6% of the total variance. The primary contributors to component 1 are horizontal shoulder rotation and elbow flexion. For component 2, the primary contributors are lateral trunk rotation and upward shoulder rotation. For component 3, the primary contributors are forward trunk rotation, axial trunk rotation and elbow flexion. For component 4, the primary contributors are external shoulder rotation and forearm pronation.

The presence of flexion synergy (shoulder abduction and elbow flexion) in component 1 and the use of trunk movements to compensate for lack of shoulder (component 2) and elbow (component 3) suggests that basic limb synergies and compensatory motor control play a crucial role during reach-to-

grasp after stroke. In addition, FMA was found to be significantly related to components 2 (p = 0.014) and 3 (p = 0.003) in stroke patients. This confirms that the use of compensatory trunk movements is related to the presence of basic limb synergies as quantified by the FMA. These results are consistent with previous studies which demonstrated increased compensatory trunk movements when there are impaired active movements of the shoulder and elbow in reaching tasks (Cirstea & Levin 2000; Levin et al. 2002b; Cirstea et al. 2003b; Michaelsen et al. 2004). Hence, this study provides deeper insights into the relationship between basic limb synergies and compensatory trunk movement. It will assist therapists to design rehabilitation programmes to reduce basic limb synergies early in the rehabilitation process, with the aim of improving motor control strategies.

2.11 Clinical implications of compensatory trunk movements

During rehabilitation, it is vital that therapists do not compromise the gain in functional improvement at the expense of tolerating the utilisation of compensatory movements for completion of a task. Research have shown that compensations may improve motor function in the short term but may impede recovery in the longer term (Roby-Brami et al. 2003a; Lum et al. 2009; Jang 2013).

Compensation rarely leads to efficient movement, and the use of compensatory movements can result in secondary complications such as muscle contractures, joint misalignment, pain and increased energy expenditure (Ada et al. 1994; Levin 1996b; Levin et al. 2005; Foroud & Whishaw 2006; Takeuchi & Izumi 2012). Once compensation has been learned, it is very challenging to modify and unlearn (Ada et al. 1994; Thielman 2013); possibly due to maladaptive plasticity (Takeuchi & Izumi 2012; Jang 2013). Some stroke patients develop strong and efficient motor compensations that prevent them from attempting to generate more 'normal' motor patterns in daily activities (Roby-Brami et al. 2003a). In other words, these complications can affect the execution of more efficient movement patterns of the upper extremity and impede its longer-term functional recovery. This can add to the frustration for patients who yearn for more improvement and recovery in their

upper extremity (Barker & Brauer 2005). This is in congruent with what was stated by Lum et al. (2009) that whilst compensatory movements may improve function, it may translate into less actual use in the real-world environment over time as the slow and awkward movements become frustrating for most stroke individuals.

Ongoing recovery at the neurological level has been demonstrated to occur, even in the chronic stage of stroke (Page et al. 2004; Teasell et al. 2012; Dobkin & Dorsch 2013; Simpson & Eng 2013). There may be further motor recovery in the upper extremity through daily therapeutic exercises. However, these improvements in the upper extremity may be masked if the stroke patient continues to use compensatory movements to fulfil the task requirement in activities of daily living. This is because the undesirable habit formed earlier in their recovery period is more difficult to unlearn as they become accustomed to the utilisation of compensatory movement which they may not be fully aware of.

It can become an uphill task for therapists to re-educate the patients to unlearn the compensatory movements. It may even cause frustration in therapists as they find it tougher to rehabilitate them to the next level of functional abilities (Chang & Hasselkus 1998; Demain et al. 2006). Some therapists reported feeling dissatisfied when the recovery did not take place or reach the level they had expected (Chang & Hasselkus 1998).

This section of the thesis highlights the presence of excessive trunk compensatory movements during pointing and reaching in stroke patients. The detrimental effects of compensation on long term functional recovery are also discussed. This links with the next section that details a therapeutic approach to minimise compensatory trunk movements during upper extremity training.

2.12 Research on trunk restraint

Observations of excessive compensatory trunk movements lead to other therapeutic approaches to improve the functional use of the upper extremity.

One of these approaches involves the incorporation of trunk restraints during task performance. The principle is based on the assumption that restriction of compensatory trunk movement may encourage the return of more normal movement pattern in the upper extremity. The approach is similar to the forced-use concept in constraint-induced movement therapy, whereby the unaffected upper extremity is constrained and the affected extremity is forced used for long periods throughout the day to facilitate neuroplasticity and recovery.

The first study which explored the potential of trunk restraint technique for rehabilitation was conducted by Michaelsen et al. (2001). Kinematics results of 11 healthy subjects and 11 chronic stroke patients were compared while they performed unrestrained and restrained reaching. In the stroke patients, there was abnormal trunk recruitment during unrestrained reaching. The amount of trunk displacement used for reaching was significantly correlated (r = -0.91, p < 0.05) with Fugl-Meyer Upper Extremity score. There was a significant negative correlation (r = -0.96, p < 0.05) between the amount of trunk displacement and the correlation coefficient of elbow-shoulder movement. This indicated that those patients who exhibited the most trunk displacement had the most disrupted coupling between arm joint movements. The limitations of this study were the small sample size and the lack of long-term follow-up of the stroke patients to determine if the gains obtained from the trunk restraint technique were maintained.

The findings of Michaelsen et al. (2001) were substantiated by subsequent studies by Michaelsen and Levin (2004), Michaelsen et al. (2006), de Oliveira et al. (2007), Thielman et al. (2008) and de Oliveira Cacho et al. (2015). The findings demonstrated that restriction of compensatory trunk movements during practice led to improved shoulder and elbow movements, with a straighter hand path. These led to greater improvement in reach-to-grasp movements in the chronic stroke patients in the studies.

To explore the benefits of trunk restraint technique further, four other studies examined the combination of trunk restraint with constraint-induced movement therapy (CIMT) and compared the outcome with CIMT without trunk restraint (Woodbury et al. 2009; Wu et al. 2012a; Wu et al. 2012b; Bang et al. 2015). CIMT is recognised as a therapy which is beneficial to improve upper

extremity function (Langhorne et al. 2009; Langhorne et al. 2011; Albert & Kesselring 2012). Better outcomes were found in the CIMT with trunk restraint group compared to CIMT without trunk restraint. Significant positive outcomes in this group, such as straighter reach trajectories, lesser trunk displacement, and improved functional arm ability, suggest that trunk restraint is a promising therapeutic technique to "unmask" the latent potential of the affected upper extremity. It may a useful adjunctive approach for stroke rehabilitation.

In a randomized pilot trial by Thielman (2010), the effect of auditory feedback was compared with tactile feedback from trunk restraint on reaching performance in 16 chronic stroke patients. Post training, the auditory feedback group (8 patients) improved significantly ($p < 0.05$) more on active shoulder range of motion, reaching ability (Reaching Performance Scale), upper extremity impairment scale (Fugl-Meyer Assessment), and upper extremity function test (Wolf Motor Function Test), compared to the tactile feedback group (8 patients). Although that study was limited by the small sample size in each group, it suggested that an auditory feedback device was a feasible alternative to impose trunk stabilization during training. This is more practical and clinically useful as the trunk need not be strapped to a chair and task training need not be restricted to a seated position. This allows more opportunities for task training in standing.

The limitations of these trunk restraint studies include sample size (ranging from 5 subjects to a maximum of 20 subjects in the experimental group), and population (all the studies on trunk restraint were conducted on chronic stroke patients except the study by Bang et al. 2015 that was conducted with subacute stroke patients). These limitations affect the generalizability of the results to the acute stroke population. Other than two studies (de Oliveira et al. 2007; de Oliveira Cacho et al. 2015) that followed the chronic stroke patients up to 3 months post training, there was no long-term follow-up of participants in the other studies to examine the longer term effects of trunk restraint technique.

Despite these limitations, the research findings on trunk restraint suggest that stabilization of the trunk is key to "unmasking" the latent potential recovery of

the upper extremity post stroke. Whether it is physical restraint of the trunk by a harness or by auditory feedback system to impose trunk stabilization, improvements in upper extremity movement and function are observed. Hence, the author postulates that improving active trunk control post stroke will aid trunk stabilization and therefore, it may lead to improvement in upper extremity function during task performance. One of the objectives of this doctoral study is to investigate the association between trunk control and upper extremity function post stroke.

Although a number of studies were conducted previously, there is no report of pooled analyses of the trunk restraint approach. Therefore, a systematic review (Appendix 1) was conducted by the author recently, and assisted by his PhD supervisors (Professor Jane Burridge, Professor Ann-Marie Hughes and Dr Martin Warner), to evaluate the evidence that trunk restraint limits compensatory trunk movement and/or promotes better upper extremity recovery in stroke patients (Wee et al. 2014). A search was conducted through electronic databases from January 1980 to June 2013. Only randomized controlled trials (RCTs) comparing upper extremity training with and without trunk restraint were selected for review. Three review authors (SKW, AMH and MW) independently assessed the methodological quality and extracted data from the studies. Meta-analysis was conducted when there was sufficient homogenous data. Six RCTs involving 187 chronic stroke patients were identified. Meta-analysis of key outcome measures showed that trunk restraint has a moderate statistically significant effect on improving Fugl-Meyer Upper Extremity (FMA) score, active shoulder flexion and reduction in trunk displacement during reaching (Figure 2-3 and Figure 2-4). There is insufficient evidence to demonstrate that trunk restraint improves upper extremity function and reaching kinematics trajectory smoothness and straightness in chronic stroke patients (Figure 2-4). Future research on stroke patients at different phases of recovery and with different levels of upper extremity impairment is recommended. The most recent systematic review also confirmed that trunk restraint decreased compensatory trunk displacement, increased elbow extension and increased shoulder flexion (Pain et al. 2015).

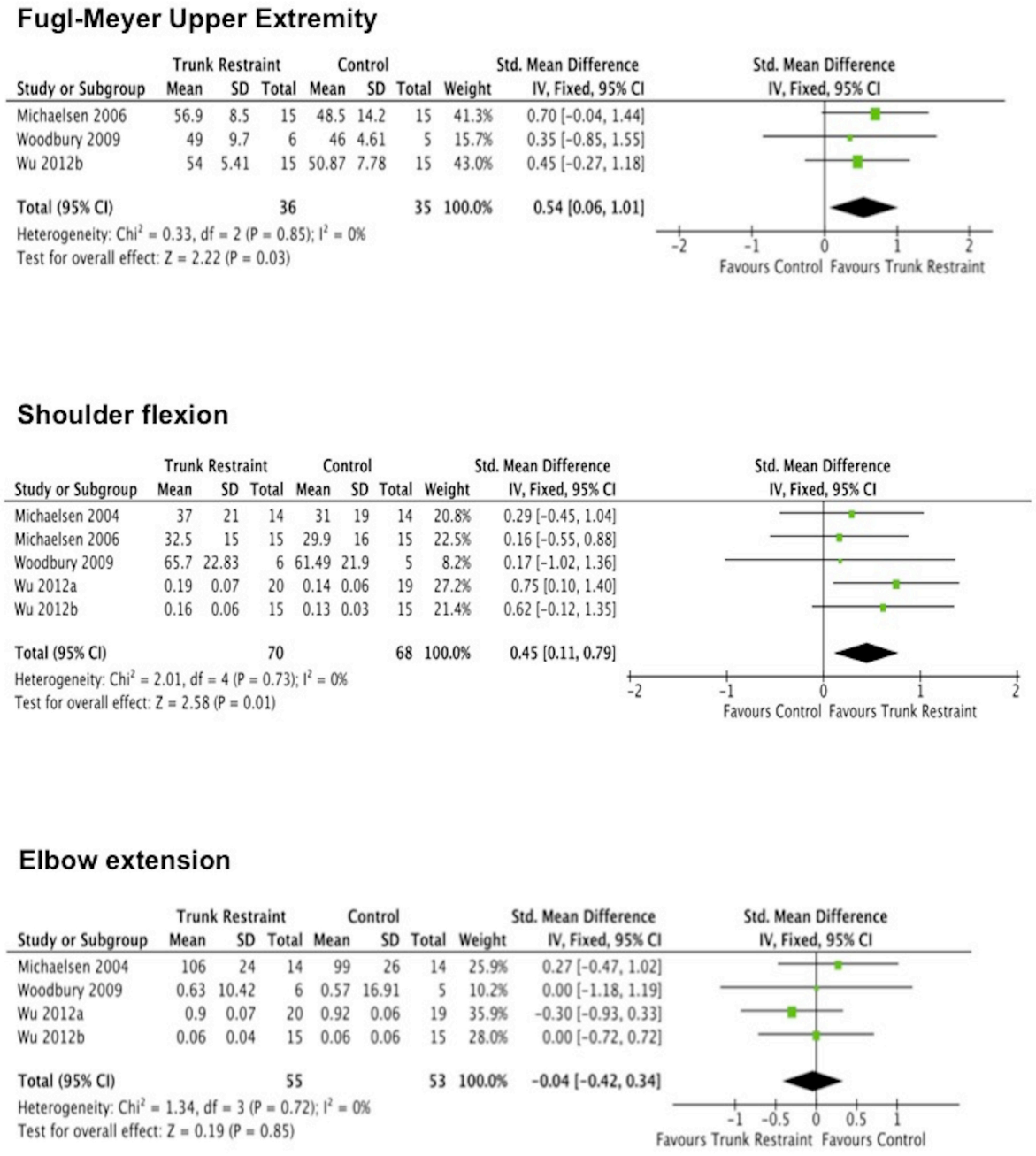


Figure 2-3 Forest plot for the effect of trunk restraint on Fugl-Meyer Upper Extremity score, shoulder flexion, and elbow extension (Wee et al. 2014)

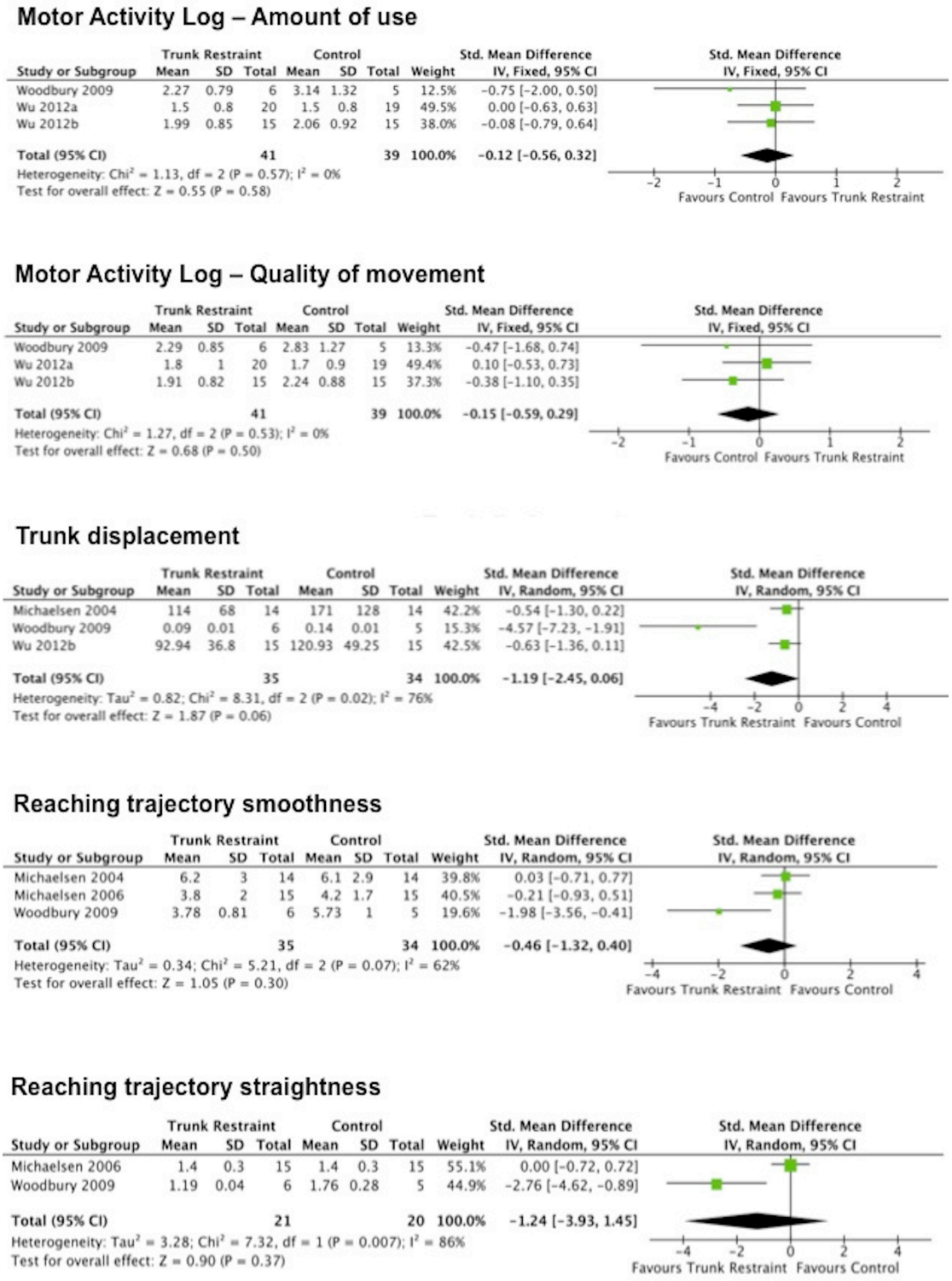


Figure 2-4 Forest plot for the effect of trunk restraint on Motor Activity Log-Amount of Use, Motor Activity Log-Quality of movement, trunk displacement, reaching trajectory smoothness, and reaching trajectory straightness (Wee et al. 2014)

As the focus of this PhD research is on trunk control and recovery of the upper extremity in stroke patients, the next section will examine the issues related to recovery of the upper extremity and trunk following stroke.

2.13 Recovery of upper extremity following stroke

The ability to live independently after stroke depends on the recovery of motor function, particularly of the upper extremity (Veerbeek et al. 2011). The upper extremity plays a vital role in the performance of ADL (Clarke 2002; Desrosiers et al. 2003b) as the ability to reach and grasp is required for over 50% of the ADL tasks (van der Putten et al. 1999; Ingram et al. 2008).

The prevalence of upper extremity motor impairment (weakness) post stroke has been reported to range between 75.5% to 77.4% (Lawrence et al. 2001; Rathore 2002). Eighty percent of acute and forty percent of chronic stroke patients experience a reduced ability to use the paretic upper extremity in ADL (Nakayama et al. 1994b; Langhorne et al. 2011), and therefore, has impact on both daily living and well-being (Mayo et al. 2002; Nichols-Larsen et al. 2005; Morris et al. 2013; Sprigg et al. 2013). Hence, improving upper extremity outcome will have a positive effect on the general well-being and quality of life of stroke patients.

Depending on the outcome measures used, 5% to 34% of stroke patients achieve full functional recovery of upper extremity function at 6 months (Heller et al. 1987; Nakayama et al. 1994a; Hendricks et al. 2002; Nijland et al. 2010b; Kong et al. 2011; Kong & Lee 2013). Full recovery of dexterous function of the upper extremity was reported to be 28.6% in a large scale prospective study on 140 chronic stroke patients (Kong et al. 2011) and 11.6% in 102 subacute stroke patients (Kwakkel et al. 2003). Based on the most recent study, 41% of people with moderate to severe stroke and 78% with milder stroke are estimated to regain dexterity 6 months after onset (Houwink et al. 2013).

2.13.1 Recovery pattern of upper extremity

The recovery pattern of the upper extremity has been well studied and a consistent finding is that the recovery follows an exponential pattern with most pronounced recovery occurring in the first 10 weeks post stroke and these changes subsequently gradually level off between 3 to 6 months (Skilbeck et al. 1983; Olsen 1989; Duncan et al. 1992; Duncan et al. 1994; Jorgensen et al. 1995; Feys et al. 1998; Desrosiers et al. 2003a; Goodwin & Sunderland 2003; Kwakkel et al. 2004; Higgins et al. 2005; Kwakkel et al. 2006; Verheyden et al. 2008; Paci et al. 2012; Kwakkel & Kollen 2013).

Numerous studies have shown that irrespective of the type and amount of therapy, the main pattern of recovery after stroke is determined by the process of spontaneous neurological recovery (Skilbeck et al. 1983; Kwakkel et al. 2004; Dobkin 2005; Kwakkel et al. 2006). In a study on 101 patients with first-ever ischaemic strokes, time explained a significant change of 42% on the Barthel Index for the first 10 weeks post stroke and 19% on the Action Research Arm Test (ARAT) for the first 6 and 8 weeks post stroke (Kwakkel et al. 2006). Approximately 25% (for Fugl-Meyer–arm) to 26% (for Motricity Index–arm) of the significant change in measurements units was explained by time alone for the upper extremity. These associations did not change after controlling for covariates such as age, gender, hemisphere of stroke, type of stroke, or intervention. Hence, approximately 19% to 26% of observed improvements in the upper extremity of stroke patients is a reflection of time-dependent changes due to intrinsic, spontaneous recovery which lasts for approximately 6 to 10 weeks.

Stroke patients show differential patterns of recovery of the upper extremity (Kwakkel et al. 2004; Meldrum et al. 2004; Prabhakaran et al. 2008; Verheyden et al. 2008; Zarahn et al. 2011; Kwakkel & Kollen 2013). Prabhakaran et al. (2008) studied 41 acute stroke patients and found that 95% of variance in recovery unexplained by clinical variables is almost exclusively attributable to true inter-individual, that is, biologically meaningful variability. Most patients exhibited a nearly proportional recovery and tended to recover approximately 70% of their initial motor impairment. The researchers (Prabhakaran et al. 2008) also found the existence of a subgroup of patients (outliers) with high initial impairment that did not show proportional recovery. Possible

mechanisms for poorer recovery of the outliers include integrity of the residual CST and poorer capacity of the remaining undamaged brain to reorganize and subsequently recruit the residual CST and other descending pathways.

2.13.2 Proximal and distal recovery of upper extremity

Based on the neurophysiologic and clinical data from studies (Nirkko et al. 2001; Cho et al. 2012), it is justifiable to discuss the proximal and distal arm as separate functional units in this section. Studies on humans demonstrated that the motor control of simple movements of the distal arm relies on the contralateral primary motor cortex, while sparing or even significantly deactivating the ipsilateral primary sensorimotor cortex (Nirkko et al. 2001). During proximal arm movement, bilateral primary motor cortices are activated, thus implying bilateral motor cortical representation (Turton et al. 1996; Nirkko et al. 2001; Lemon 2008). In addition, alternate descending pathways, such as the ipsilateral corticospinal tract and the reticulospinal tract, are better able to drive motor units of the more proximal muscles than the more distal muscles (Nathan et al. 1996; Turton et al. 1996). This possibly account for the statistically significant difference in the proximal and distal muscle weakness in stroke patients (Colebatch & Gandevia 1989; Colebatch et al. 1990; Hlustík & Mayer 2006; Cho et al. 2012).

Distal arm muscles (wrist, fingers and thumb) are more severely impaired than those of proximal muscles (shoulder and elbow) and recovery of distal movements is slower (Hlustík & Mayer 2006; Lang et al. 2006). Individual finger movements are a prerequisite for dexterous motor acts and these recover the least following stroke (Schieber et al. 2009). Lang and Schieber (2003) demonstrated that there is differential impairment of individuated finger movements after stroke. The independence of the middle, ring, and little fingers was substantially impaired while the index finger was slightly impaired and the thumb least impaired. The differential impairments may in part result from rehabilitative training that emphasizes tasks that require more independent control of the thumb and index finger than of the middle, ring, and little fingers (Lang & Schieber 2003). Examples of such tasks commonly used by therapists to train stroke patients include picking up small objects,

buttoning a shirt and writing. With more emphasis on independent thumb and index finger movements, the thumb and index finger representation in the primary motor cortex may have expanded at the expense of the representations of the middle, ring and little fingers.

Cortical representation area of the body parts increases or decreases depending on use (Hallet 2001; Hallet 2005). Reading Braille is associated with expansion of the sensorimotor cortical representation of the reading finger (Pascual-Leone & Torres 1993) and this enlargement is at the expense of the representation of other fingers (Pascual-Leone et al. 1993). Similarly, if a body part is not used, the representation area will shrink in size. For example, the representation area of the tibialis anterior was smaller after the ankle was immobilized in a cast for 4 weeks (Liepert et al. 1995); the representation area of the hand was smaller after the arm was immobilized in a cast for 2 to 3 weeks (Lissek et al. 2009; Langer et al. 2012). Hence, these studies illustrate the existence of a natural competition among body parts for territorial representation in the cortex based on the extent of usage.

Common observation in many upper extremity rehabilitation programmes reveals that much emphasis is placed on reaching training compared to hand rehabilitation. In accordance to previous studies discussed (Hlustík & Mayer 2006; Lang et al. 2006), distal arm muscles are more severely impaired than those of proximal muscles. During reaching training in the clinics, particularly in the very early phase post stroke, therapists may be inclined to facilitate scapula, shoulder and elbow movements toward the targets with lesser emphasis on hand opening and grasping components. This is in part due to the challenges of controlling numerous degrees of freedom of the shoulder, elbow, wrist and hand; and facilitating the movement components of the upper extremity simultaneously, especially in the presence of finger spasticity. With more training of the proximal muscles versus the distal muscles, it may further enhance the natural competition between the shoulder and hand representation in the cortex, possibly leading to larger shoulder representation area. Hence, this may be detrimental to recovery of the hand. A systematic review suggests that most therapeutic effects are mainly driven by improvements in proximal motor control, whereas improvements for hand recovery are poor (Langhorne et al. 2009). The seminal work by Nudo et al. (1996b) showed that intensive hand rehabilitation can alter such

representational changes. Retraining of skilled hand use in adult squirrel monkeys after cortical infarcts resulted in prevention of the loss of hand territory adjacent to the infarct. In some instances, the hand representations expanded into regions formerly occupied by representations of the shoulder and elbow (Nudo et al. 1996b).

In an investigation on 7 chronic stroke patients, Muellbacher et al. (2002) performed a regional anesthesia-induced deafferentation of the shoulder and upper arm, with sparing of the forearm and hand, during hand motor practice. The practice task involved metronome-paced pinch between index and thumb of the paretic hand. Post training, the patients demonstrated significant improvement in their grip force, grip acceleration and hand motor function. The practice-induced increase in peak grip force was strongly correlated ($r=0.86$, $p<0.03$) with the increased in motor-evoked potential amplitude, as assessed by transcranial magnetic stimulation, of the paretic hand muscles. Patients also reported significant functional benefits in some activities of daily living, such as holding small objects, cup and pen. The gains in grip force were retained at 2 weeks follow-up. Hence, the animal and human studies illustrate that intensive and focused training of the hand can lead to better hand function.

Drawing from the findings of Muellbacher et al. (2002), another group of researchers conducted a pilot trial on 40 acute stroke patients to investigate the effects of intensive hand therapy on the outcome of hand and shoulder function (Mikulecká et al. 2005). All the patients in the treatment group (n=20) and control group (n=20) received standard physiotherapy based on Bobath concept. Those in the treatment group received an additional differentiated manual treatment and sensory stimulation of the hand and of the forearm which included rubbing, release of soft tissues, mobilization of the joints of the wrist, metacarpals and fingers and of digital pressure of selected points. Following 12 days of training, the treatment group demonstrated significantly greater improvement in hand function and shoulder function compared with the control group.

Taken together, the findings suggest that more emphasis should be placed on hand motor training in the early phases of stroke rehabilitation while shoulder

and elbow training should be minimized. With the proximal muscles recovering earlier than the distal muscles, therapists may find it easier to engage patients in tasks that utilize mainly the proximal muscle groups, for example in reaching tasks. Reinforcement of the proximal muscles during acute stroke rehabilitation may be detrimental to the cortical representation of distal muscles and hence would tend to limit the recovery of hand movement (Nudo et al. 1996a). This is in line with the principle of natural competition among body parts for territory in the sensorimotor cortex (Hallet 2001; Hallet 2005; Hlustík & Mayer 2006).

2.13.3 Predictors of upper extremity recovery

Despite individual recovery patterns of the upper extremity, mathematical models have been found in the non-linear patterns of recovery, making the outcome highly predictable (Heller et al. 1987; Kwakkel et al. 2004; Koyama et al. 2005; Kwakkel et al. 2006; Kwakkel & Kollen 2007; Schweighofer et al. 2009; Nijland et al. 2010b; Zarahn et al. 2011)

Several studies have demonstrated that initial severity of hemiparesis, measured with either disability or impairment scales, is the best predictor of upper extremity recovery (Counsell 2002; Kwakkel et al. 2003; Counsell 2004; Hatakenaka et al. 2007; Smania et al. 2007; Beebe & Lang 2008; Beebe & Lang 2009; Nijland et al. 2010b; Zarahn et al. 2011; Kwakkel & Kollen 2013). This is confirmed by a systematic review on 58 studies that initial measures of upper extremity impairment (n=2715) and function (n=1512) were found to be the most significant predictors of upper extremity recovery (Coupar et al. 2012). A recent study on 129 acute stroke patients demonstrated that FMA is the best predictor for upper extremity recovery and general disability (modified Rankin Scale) at 3 months (Gebruers et al. 2014).

Motor evoked potentials (n=687) and somatosensory-evoked potentials (n=280) were consistently identified as being strongly associated with upper extremity recovery (Coupar et al. 2012). There was moderate evidence that less disability and lower limb impairment were associated with better upper limb recovery. No predictive value was found for lesion size (Coupar et al. 2012), which is in agreement with findings of other studies (Fries et al. 1993;

Pineiro et al. 2000; Werring et al. 2000; Wenzelburger et al. 2005; Ward et al. 2006; Sterr et al. 2010; Zhu et al. 2010; Riley et al. 2011).

Optimal prediction of upper extremity function outcome at 6 months can be made within 4 weeks after stroke onset based on the initial upper extremity impairment score (FMA). Lack of voluntary motor control of the leg in the first week with no emergence of arm synergies at 4 weeks is associated with poor outcome at 6 months (Kwakkel et al. 2003). Active range of motion of the shoulder (shoulder shrug and/or shoulder abduction) and active finger extension (Katrak et al. 1998; Smania et al. 2007; Beebe & Lang 2008; Beebe & Lang 2009; Nijland et al. 2010b; Stinear 2010; Stinear et al. 2012) have been found to predict the recovery of upper extremity function in stroke patients. These movements could predict 71% of the variance in upper extremity function at 3 months (Beebe & Lang 2009). Nijland et al. (2010b) found that patients who exhibited some voluntary extension of the fingers and some abduction of the hemiplegic shoulder as early as within 72 hours post stroke have a probability of 0.98 to regain some dexterity at 6 months. The preservation of voluntary finger extension may reflect the residual structural integrity of the CST that is essential for motor recovery.

Grip strength deficits appear to be good representation of the potential for paretic upper extremity function (Boissy et al. 1999). Boissy et al. (1999) found that maximal voluntary grip force (MVGF) explains 62% to 78% of the variance on all four upper extremity tests, namely Fugl-Meyer Assessment, Test Evaluant les Membres Superieurs des Personnes Agees (TEMPA), Box and Block test and finger-to-nose test. Hence, stroke subjects with MVGF deficits tend to demonstrate significant upper extremity motor impairments and poorer function. This is in agreement with other studies (Heller et al. 1987; Sunderland et al. 1989). Grip strength measurement has been demonstrated to have prognostic value. Failure to recover measureable grip strength within the first month post stroke was found to be associated with absence of useful upper extremity function at three months (Heller et al. 1987; Sunderland et al. 1989). Other studies have measured the whole upper extremity strength of stroke patients and confirmed its prognostic ability to predict functional outcome (Counsell 2002; Counsell 2004; Harris & Eng 2007; Reid et al. 2010;

Reid et al. 2012). The upper extremity function depends to a large extent on hand function. As grip strength is a prerequisite for a functional hand, it has an impact on the functional outcome of the upper extremity post stroke.

Boissy et al. (1999) proposed an explanation for the predictive value of grip strength with regard to upper extremity function in that it acts as a reliable index of the degree of loss of corticospinal control. This is supported by a study by Ward et al. (2007), which illustrated a relationship between brain activity and peak grip force. The researchers found that covariation between force output and brain activity in ipsilesional primary motor cortex diminishes with increasing corticospinal system damage.

Given that grip strength has been demonstrated to predict upper extremity function, it would be beneficial to incorporate strength training in upper extremity rehabilitation programme. A recent meta-analysis on 13 randomised controlled trials, totaling 517 stroke patients (subacute and chronic stages), demonstrated that upper extremity strength training has a significant effect on grip strength (SMD=0.95, p=0.04) and upper extremity function (SMD=0.21, p=0.03) (Harris & Eng 2010). The magnitude of the effect size for upper extremity function was higher for those patients with moderate upper extremity impairment (SMD=0.45, p=0.03) compared to those with mild (SMD=0.26, p=0.01) impairment. This suggests that strength training has a greater benefit for stroke patients with moderate level of upper extremity impairment.

A recent study assessed the feasibility of a newly created PREP (predicting recovery potential) algorithm to predict the potential for upper extremity recovery in acute and subacute stroke patients (Stinear et al. 2012). The PREP algorithm combines the shoulder abduction and finger extension scores (based on the Medical Research Council grading system), transcranial magnetic stimulation findings (to determine the presence or absence of motor evoked potentials) and diffusion-weighted magnetic resonance imaging (to assess the structural integrity of the posterior limbs of the internal capsules). Results from 40 acute stroke patients revealed excellent correspondence between the cluster analysis of Action Research Arm Test score at 12 weeks and predictions made with the PREP algorithm. The algorithm exhibited a positive, high predictive power of 88%. Thus, the PREP algorithm exhibits the ability to

predict the potential for upper extremity recovery. The algorithm may enable tailored planning of rehabilitation and more accurate stratification of stroke patients in clinical trials (Stinear et al. 2012).

Taken together, these findings are valuable to therapists as the assessments of the shoulder, finger movements and grip strength can be conducted easily by the patients' bedside without any complex equipment. It will assist therapists in goal-setting and planning of therapy programmes for patients. It will also enable therapists to make predictions of the upper extremity recovery and counsel patients accordingly.

2.14 Recovery of the trunk following stroke

2.14.1 Mechanisms underlying trunk recovery

Anatomical studies have shown that trunk musculature is controlled bilaterally through crossed and uncrossed fibres of the anterior CST (Kuypers 1981; York 1987; Davidoff 1990; Lemon 2008; Krebs et al. 2012), and ipsilaterally through the cortico-reticulospinal tracts (Peterson et al. 1979; Benecke et al. 1991). The contralateral pathways are found to be more dominant (Plassman & Gandevia 1989; Ferbert et al. 1992; Fujiwara et al. 2001). There is evidence that the majority of the inputs reach the erector spinae (Ferbert et al. 1992; Carr et al. 1994).

Due to the bilateral innervation of trunk muscles, trunk performance is less affected after stroke than the performance of the upper and lower extremities (Ferbert et al. 1992; Fujiwara et al. 2001; Misawa et al. 2008). A study using TMS shed more light on the mechanism of recovery of trunk function post stroke (Fujiwara et al. 2001). In that study, stimulation of the affected hemisphere did not elicit any MEP response in the trunk muscles (external oblique muscles and erector spinae) in 19 out of 20 subacute and chronic stroke patients. Stimulation of the unaffected hemisphere evoked bilateral MEP responses in 19 patients. The MEP recorded in the ipsilateral muscles of the stroke patients was significantly larger than those of the 11 healthy

individuals. In addition, the clinical assessment scores of trunk function (Trunk Control Test and trunk items of Stroke Impairment Assessment) were correlated with the amplitudes of the MEP of the ipsilateral external oblique muscle that were evoked by stimulation of the unaffected hemisphere. In another study, similar results of the presence of bilateral MEP responses in the rectus abdominis, external oblique muscles, and erector spinae muscles were also observed in 9 stroke patients (1-10 months post stroke onset) when the unaffected hemisphere was stimulated (Park et al. 2009). Hence, the findings suggest that the unaffected hemisphere is responsible for the restoration of trunk function, most likely by potentiating the effects of preexisting uncrossed motor pathways. The preexisting uncrossed pathways may be unmasked due to lack of inhibition from the affected hemisphere (Jacobs & Donoghue 1991; Netz et al. 1997; Schwerin et al. 2008).

Another study conducted with 40 acute stroke patients demonstrated that the presence of ipsilateral trapezius MEP was associated with less severe paresis in the trapezius and deltoid but not in the more distal muscles (abductor digiti minimi) (Misawa et al. 2008). Therefore, the ipsilateral CST in the trunk and proximal muscles is facilitated early following stroke. Activation of such a pathway appears to partly compensate motor dysfunction of the trunk and proximal muscles (Misawa et al. 2008; Schwerin et al. 2008).

Considered together, these two studies illustrates that ipsilateral pathways are crucial for the recovery of trunk function in stroke patients. In recent years, many studies have been conducted to investigate the use of non-invasive brain stimulation to enhance the recovery of upper extremity post stroke (Hoyer & Celnik 2011; Najib et al. 2011; Kandel et al. 2012; Edwardson et al. 2013). However, no study has been conducted to date to explore the feasibility of TMS to the unaffected hemisphere to improve the recovery of trunk in stroke patients. This is worth investigating because there is strong evidence that trunk performance is an important predictor of overall functional ability, balance and gait after stroke (Franchignoni et al. 1997; Duarte et al. 2002; Hsieh et al. 2002; Sebastia et al. 2006; Verheyden et al. 2006; Verheyden et al. 2007; Di Monaco et al. 2010; Kim et al. 2012).

2.14.2 Recovery pattern of the trunk

The prevalence of trunk impairment post stroke has not been reported to date. The recovery of the trunk has not received as much attention as compared to the recovery of the upper extremity. This is partly due to the lack of routine clinical practice to measure or chart trunk impairment post stroke, compared to the more frequent comprehensive assessment of upper and lower extremities, balance and gait. This is a gap in current clinical practice that should be addressed as evidence supports trunk performance as an important predictor of ADL, balance and gait.

Verheyden et al (2008) explored the time course of trunk recovery with the patterns of recovery of arm, leg, and functional ability in 32 stroke patients recruited from acute neurology wards. Patients were evaluated at 1 week, 1 month, 3 months and 6 months after stroke. They were assessed with the Trunk Impairment Scale, Fugl-Meyer arm and leg test, and Barthel Index. Analysis of stroke recovery patterns of motor and functional performance revealed that the most rapid improvement for all measures occurred from 1 week to 1 month followed by a significant improvement from 1 month to 3 months. No significant improvement was found between 3 and 6 months for any of the measures. There was no significant difference between time course of trunk, arm, leg, and functional recovery.

The conclusion of the study (Verheyden et al. 2008) was that the time course of recovery of the trunk is similar to the recovery of arm, leg, and functional ability. However, the results of the study must be interpreted with considerations of the limitations in that study. Firstly, it may be difficult to generalise the result to the whole stroke population because the sample size was small and the mean age of stroke patients in this study was 69 years old. Thus, only older adult stroke patients were studied and it remains unknown whether the recovery pattern of the trunk, arm and leg for younger stroke patients is different from older patients. Secondly, there was a large variability in the recovery pattern in the upper extremity in the study sample at 1 week, 1 month, 3 months and 6 months. Hence, the recovery pattern of the upper extremity of some participants may not be similar to the recovery pattern of the trunk.

In addition, there was no documentation of the types of therapy and intensity of therapy received by the stroke patients at various time points during the 6 months period. It is vital to know the intensity of therapy as these parameters have been shown to impact functional outcome; evidence suggests that higher intensity of therapy results in better functional outcome (Kwakkel et al. 1999; Kwakkel et al. 2002; Cifu et al. 2003; Jette et al. 2005; Peiris et al. 2011; Foley et al. 2012; Wang et al. 2013).

The findings of the study by Verheyden et al. (2008) are in accordance with results of other studies (Olsen 1989; Duncan et al. 1994; Desrosiers et al. 2003b; Higgins et al. 2005; Paci et al. 2012). However, these five studies (sample size range from 55 to 132 participants) did not examine trunk recovery pattern. The studies also confirmed that the severity of motor impairments and the patterns of motor recovery from impairments were similar for the upper and lower extremities. This is contrary to popular belief that recovery of the upper extremity is slower and less complete than that of the lower extremity.

One of the key findings from these studies was the period of most rapid recovery occurring in the first 30 days. Understanding the recovery pattern will assist therapists to plan and provide appropriate intensive therapy to capitalise on this rapid recovery period and facilitate motor recovery. It will also enhance therapists' ability to make a more accurate prediction of recovery.

2.15 Summary of research findings

It has been commonly stated that the trunk is an important postural stabilizer that enables dissociation of the upper and lower extremities for function. However, this common assumption in neurorehabilitation has not been validated in clinical trials. After reviewing the literature, gaps in knowledge about trunk control and upper extremity function post stroke have been identified. Research investigating the relationship between trunk control and upper extremity function is warranted.

Studies have demonstrated that excessive compensatory trunk movements, which occurred during reaching in stroke patients, were associated with

impaired upper extremity control and coordination. However, it remains unknown how the degree of impaired trunk control affects or contributes to the amount of trunk movement during reaching in stroke patients with different levels of upper extremity control. Hence, there is still a gap in knowledge in this aspect.

Positive outcomes from trunk restraint research suggest that restraining the trunk may help to "unmask" the latent potential for recovery of the affected upper extremity. The author postulates that improving active trunk control post stroke will aid trunk stabilization and that may lead to improvement in upper extremity function. One of the objectives of this doctoral study is to investigate the association between trunk control and upper extremity function post stroke.

Whilst Verheyden et al. (2008) have studied the time course of recovery for the trunk, arm and leg in stroke patients, they did not examine the relationship between trunk control and recovery of upper extremity function. To the best of the author's knowledge, there are currently no studies which examine this relationship. Understanding the recovery pattern of trunk control and upper extremity function will assist therapists to plan and provide appropriate intensive therapy to capitalise on the most rapid recovery period within the first month post stroke and facilitate motor recovery. It will also enhance therapists' ability to make a more accurate prediction of recovery. Hence, a research examining the complex relationship between trunk control and recovery of upper extremity function is warranted.

2.16 Research questions

Based on the key gaps identified from the literature, the overarching research question for this doctoral study is:

What is the relationship between trunk control and recovery of upper extremity function in subacute and chronic stroke patients?

Before establishing any cause and effect relationship, it is important to first establish whether there is an association between trunk control and upper extremity function. The proposed study, carried out in two phases, will address the following specific questions:
1) Is there any change in the trunk control ability and the upper extremity function when the trunk is stabilised with an external trunk support?

2) Is there a relationship between trunk control and upper extremity impairment in a) subacute, and b) chronic stroke patients?

3) Is there a relationship between trunk control and upper extremity function in a) subacute, and b) chronic stroke patients?

4) Is there an association between trunk control and the amount of trunk, scapula and upper extremity movement during reaching?

5) Is there a relationship between trunk control and recovery of upper extremity function during the first 6 months following stroke?

2.17 Summary of Chapter 2

This Chapter has presented a detailed literature review, providing the background of the research on trunk and upper extremity post stroke which underpins this research. Trunk impairments post stroke were outlined with reference to effects on balance, gait and functional outcome. Trunk involvement in reaching and pointing tasks was discussed, and the impact of trunk support on performance of upper extremity tasks considered. In

addition, literature on neuroplasticity and motor recovery of the upper extremity and trunk in stroke patients were discussed. Clinical implications of this study were emphasized. With the gaps in knowledge identified after the literature review, the research questions for this PhD study were drawn.

The next Chapter will provide a critical review of the potential outcome measures to be used in this study.

Chapter 3: Critical review of outcome measures for trunk control, upper extremity impairment and function in stroke patients

3. Critical review of outcome measures for trunk control and upper extremity

This Chapter will discuss the various outcome measures used for assessment of trunk control, and upper extremity impairment and function post stroke. The critical review is important to identify appropriate outcome measures for this doctoral research.

3.1 Measurement of trunk performance

Trunk performance is the terminology used in the literature that broadly encompasses trunk muscle strength, muscle activity, and trunk control ability during task performance. Various methods have been used to measure trunk performance post stroke. These methods include isokinetic muscle testing (Tanaka et al. 1997; Tanaka et al. 1998; Karatas et al. 2004), manual dynamometry (Bohannon 1992; Bohannon 1995; Bohannon et al. 1995) electromyographic analysis (Dickstein et al. 1999; Dickstein et al. 2000; Winzeler-Mercay & Mudie 2002; Dickstein et al. 2004a; Dickstein et al. 2004b), transcranial magnetic stimulation (Fujiwara et al. 2001), computed tomography (Tsuji et al. 2003), and motion analysis (Messier et al. 2004; Messier et al. 2006; Robertson & Roby-Brami 2011; van Kordelaar et al. 2012). Other than the motion capture method (with the Vicon system) used in this doctoral research for kinematic analysis, the other methods will not be discussed further as they are not within the scope of this research.

3.2 Clinical outcome measures for trunk control

In an attempt to select the best clinical outcome measure for assessing trunk control for this research, an extensive search was conducted using electronic databases (CINAHL, EMBASE, MEDLINE, AMED, Web of Knowledge and Cochrane Library) from January 1980 to July 2013. The following keywords were used: stroke, trunk, trunk performance, trunk control, assessment, outcome measure. Only journal articles published in English were reviewed. Additional

relevant studies were identified by examining the references from retrieved articles.

The following criteria was set by the author in order to identify the most appropriate outcome measure for assessment of the trunk control in the stroke participants for this research:

1) the measure is appropriately tested in stroke population

2) the measure demonstrates adequate psychometric properties

3) the measure exhibits discriminative ability to differentiate participants with different degree of trunk control

4) the measure enables the assessment of trunk control in a seated position; reason being that the participant will be performing different upper extremity tasks in a seated position under two conditions, with and without an external trunk support

5) the measure can be administered in less than 30 minutes to minimise fatigue in the participants

A summary of the review of outcome measures for trunk control is presented in Table 3-1.

Following an extensive search, 8 clinical outcome measures for trunk control were selected for review. Some of these outcome measures assess trunk control as part of the total motor assessment in stroke patients. In other words, they consist of items related to trunk control and they are not specifically developed for assessment of trunk control in stroke patients. Examples of these measures include the Rivermead Motor Assessment (RMA) (Lincoln & Leadbitter 1979; Endres et al. 1990; Kurtais et al. 2009), Motor Assessment Scale (MAS) (Carr et al. 1985; English et al. 2006), Chedoke-McMaster Stroke Assessment (CMSA) (Gowland et al. 1993; Agarwal et al. 2003), Stroke Impairment Assessment Set (SIAS) (Tsuji et al. 2000; Liu et al. 2002) and Postural Assessment Scale for Stroke Patients (PASS) (Benaim et al. 1999; Mao 2002; Wang et al. 2005; Chien et al. 2007; Liaw et al. 2008; Yu et al. 2012).

Other outcome measures are specifically developed to assess trunk control in stroke patients. These include the Trunk Control Test (TCT) (Colin & Wade 1990), Verheyden's Trunk Impairment Scale (TIS) (Verheyden et al. 2004) and Fujwara's Trunk Impairment Scale (TIS-F) (Fujiwara et al. 2004). A worthy note when reading the literature is to be aware of the latter two scales with identical name (Trunk Impairment Scale). To date, only two published papers (Fujiwara et al. 2004; Likhi et al. 2013) used the Fujiwara's Trunk Impairment Scale while other numerous papers have utilized the Verheyden's Trunk Impairment Scale.

Of the 8 outcome measures, 4 measures demonstrated the closest fit to the criteria and were shortlisted for the final review. These outcome measures included PASS-TC, TCT, TIS and TIS-F.

PASS-TC and TCT are very similar in content. PASS-TC has an additional item, which is moving from sitting at the edge of bed to supine position. PASS-TC uses 4-point scale (0 to 3) (Benaim et al. 1999; Hsieh et al. 2002), while TCT uses 3-point scale (arbitrary weights 0, 12, 25) (Colin & Wade 1990). Both PASS-TC and TCT demonstrate good internal consistency (Franchignoni et al. 1997; Mao 2002), inter-rater reliability (Colin & Wade 1990; Mao 2002) and predictive validity (Duarte et al. 2002; Hsieh et al. 2002). However, both measures exhibit notable ceiling effects that limit their discriminative abilities (Franchignoni & Duarte 2003; Wang et al. 2005; Verheyden et al. 2006). Only one item each in PASS-TC and TCT is administered in a seated position. This is inadequate for the purpose of this research whereby the trunk will be assessed during the performance of the upper extremity tasks in a seated position. Taken together, PASS-TC and TCT are not appropriate outcome measures for this research.

Both TIS and TIS-F are specifically developed for assessment of trunk control in stroke population. TIS was developed by Verheyden et al. (2004). It consists of 17 test items of trunk control, which are divided into 3 subscales, namely static sitting balance, dynamic sitting balance, and coordination of the upper and lower trunk. Each item is scored on an ordinal scale, ranging from 2-points to 4-points. The minimum score of TIS is 0 and maximum score is 23. A higher score indicates better trunk control. It is reported that an increase of 4 points

on the TIS could be interpreted as an improvement without reproducibility bias (Verheyden et al. 2004).

Adequate psychometric properties for the TIS in stroke patients have been reported. TIS exhibits good test-retest reliability, inter-rater reliability, internal consistency, construct validity and concurrent validity (Verheyden et al. 2004). In addition, TIS shows predictive validity. Total TIS score and the subscale static sitting balance score predicted 52% and 50% of the variance in the Barthel Index score respectively at 6 months after stroke (Verheyden et al. 2007). Di Monaco et al. (2010) found that total TIS score predicted 48.3% of the variance in the Functional Independence Measure (FIM) score. This illustrates that TIS score can predict functional outcome (Barthel Index and FIM) in stroke patients.

Verheyden et al. (2005) found that the TIS has the ability to discriminate between stroke patients and healthy individuals. A TIS score of 20 was in the 90th percentile for the stroke patients and in the 10th percentile for the healthy individuals. Another vital finding was that TIS has no ceiling effect for the subacute and chronic stroke population (Verheyden et al. 2006).

The other outcome measure, TIS-F was developed by Fujiwara et al. (2004). It consists of 7 items: i) perception of trunk verticality; ii) trunk rotation muscle strength on the affected side (rolling from supine); iii) trunk rotation muscle strength on the unaffected side (rolling from supine); iv) righting reflex on affected side in sitting; v) righting reflex on unaffected side in sitting; vi) verticality test in unsupported sitting; and vii) abdominal muscle strength. The last two items, verticality test and abdominal strength, are actually extracted from the trunk control items of the Stroke Impairment Assessment Set (SIAS) (Tsuji et al. 2000). TIS-F score ranges from a minimum of 0 to maximum of 21. A higher score indicates better trunk control.

Similar to TIS, TIS-F also exhibits good inter-rater reliability, internal consistency, construct validity, concurrent validity and responsiveness (Fujiwara et al. 2004). However, there are no reports of test-retest reliability and discriminative ability of TIS-F to date. There is also no establishment of any floor or ceiling effect of TIS-F. One of the criteria for selecting the appropriate outcome measure is that the assessment of trunk control occurs in a seated position due to the position for data requisition for this research. All

the items of TIS are tested in a seated position while 5 out of 7 items of TIS-F fit this criteria. After consideration of the criteria for this study and weighing out the different psychometric properties of TIS and TIS-F, it was decided that TIS is the most appropriate outcome measure for a comprehensive assessment of trunk control for this doctoral research. In addition, a recent publication also reported that TIS is an outcome measure with good psychometric properties and good clinical utility (rating of 3 on the StrokEDGE Scoring Matrix) that is appropriate for the subacute and chronic stroke population (Sullivan et al. 2013).

Table 3-1 Review of outcome measures for trunk control in stroke patients

Outcome measure / Criteria	Rivermead Motor Assessment (RMA)	Motor Assessment Scale (MAS)	Chedoke-McMaster Stroke Assessment (CMSA)	Stroke Impairment Assessment Set (SIAS)	Postural Assessment Scale for Stroke Patients (PASS)	Trunk Control Test (TCT)	Trunk Impairment Scale (Verheyden) (TIS)	Trunk Impairment Scale (Fujiwara) (TIS-F)
Patient population tested	Stroke Traumatic brain injury Elderly	Stroke	Stroke Brain injury Other neurological disorders	Stroke	Stroke	Stroke Elderly (recovering from acute illness)	Stroke Traumatic brain injury Multiple sclerosis Parkinson's Disease Children and adolescents with cerebral palsy	Stroke
Number of items and item description	Leg and trunk section of RMA (RMA-lt): 10 items But only 2 items are related to trunk control: 1) rolling to affected side 2) rolling to unaffected side	MAS total 8 items Only 3 items related to trunk control: 1) supine to side lying on unaffected side 2) supine to sitting over edge of bed 3) balanced sitting	Postural control section of CMSA is part of impairment inventory Note: scoring is for documenting stages of motor recovery. In the disability inventory, only 5 out of 15 items are related to trunk control: 1) Supine to side lying on unaffected side side 2) Supine to side lying on affected side 3) Side lying to long sitting through unaffected side 4) Side lying to sitting on side of the bed through unaffected side 5) Side lying to sitting on side of bed through the affected side	SIAS total 22 items Trunk control section of SIAS: 2 items 1) verticality test -unsupported sitting 2) abdominal muscle strength	PASS total 12 items Trunk control items of PASS (PASS-TC): 5 items 1) supine to side lying on unaffected side 2) supine to side lying on affected side 3) supine to sitting over edge of bed 4) sitting to supine 5) balanced sitting	TCT total 4 items All are related to trunk control: 1) supine to side lying on unaffected side 2) supine to side lying on affected side 3) sit up from lying 4) balanced sitting	TIS total 17 items All are related to trunk control 3 categories: 1) Static sitting balance: 3 items 2) Dynamic sitting balance: 10 items 3) Coordination: 4 items	TIS-F total 7 items All are related to trunk control: 1) perception of trunk verticality 2) trunk rotation muscle strength on the affected side (rolling from supine) 3) trunk rotation muscle strength on the unaffected side (rolling from supine) 4) righting reflex on affected side in sitting 5) righting reflex on unaffected side in sitting 6) verticality test - unsupported sitting 7) abdominal muscle strength

Table 3-1 (Continued)

Outcome measure / Criteria	Rivermead Motor Assessment (RMA)	Motor Assessment Scale (MAS)	Chedoke-McMaster Stroke Assessment (CMSA)	Stroke Impairment Assessment Set (SIAS)	Postural Assessment Scale for Stroke Patients (PASS)	Trunk Control Test (TCT)	Trunk Impairment Scale (Verheyden) (TIS)	Trunk Impairment Scale (Fujiwara) (TIS-F)
Trunk assessment in seated position	No	Yes - for only 1 item	No	Yes	Yes - for only 1 item	Yes -for only 1 item	Yes - for all 17 items	Yes - for 5 items
Test-retest reliability	r = 0.93 (Lincoln & Leadbitter,1979)	r = 0.98 (Carr et al, 1985)	Not available for postural control section of CMSA ICC for total CMSA 0.98 (Gowland et al, 1993)	Not reported	k-coefficient 0.72 (Benaim et al, 1999)	Not reported to date	ICC 0.96 (Verheyden et al, 2004)	Not reported
Inter-rater reliability	Not reported	r = 0.95 (Carr et al, 1985)	Postural control section of CMSA ICC 0.92 (Gowland et al, 1993)	Trunk control section of SIAS: 1) verticality test - weighted kappa 0.63 2) abdominal muscle strength - weighted kappa 0.93 (Liu et al, 2002)	ICC 0.97 (Mao et al, 2002)	r = 0.76 (Collin and Wade, 1990)	ICC 0.99 (Verheyden et al, 2004)	Weighted kappa values between 0.66 and 1 (Fujiwara et al, 2004)
Responsiveness	Not reported	Moderate to large effect size (range from 0.61 to 1.03) for the 3 items related to trunk control (English et al, 2006)	The CMSA Disability Inventory is more sensitive to the FIM at detecting clinically important change. (Gowland et al, 1993)	more responsive to clinically important changes than the Brunnstrom staging, the Motricity Index, and the NIH Stroke Scale	PASS: high internal responsiveness (effect size $d \geq 0.87$) (Yu et al, 2012)	TCT test showed a good sensitivity to change 72% of the 36 stroke patients showed	Not reported	Standardized response mean (SRM) 0.94 (Fujiwara et al, 2004)

Table 3-1 (Continued)

Outcome measure / Criteria	Rivermead Motor Assessment (RMA)	Motor Assessment Scale (MAS)	Chedoke-McMaster Stroke Assessment (CMSA)	Stroke Impairment Assessment Set (SIAS)	Postural Assessment Scale for Stroke Patients (PASS)	Trunk Control Test (TCT)	Trunk Impairment Scale (Verheyden) (TIS)	Trunk Impairment Scale (Fujiwara) (TIS-F)
				(Liu et al, 2002)		changed in overall TCT score at discharge (Franchignoni et al, 1997)		
Internal consistency	Cronbach α-coefficient 0.88 (Kurtais et al, 2009)	Not reported	ICC for total CMSA 0.98 (Gowland et al, 1993)	Rasch analysis confirmed internal consistency - the mean square fit statistic was within 1.3 for the two trunk control items of SIAS (Tsuiji et al, 2000)	Cronbach α-coefficient 0.94 (Mao et al, 2002)	Cronbach α-coefficient 0.83 (Franchignoni et al, 1997)	Cronbach α-coefficient 0.89 (Verheyden et al, 2004)	Rasch analysis confirmed internal consistency –the mean square fit statistic was within 1.3 for all items except i) perception of trunk verticality ii) trunk rotation muscle strength on the unaffected side, and iii) abdominal muscle strength (Fujiwara et al, 2004)
Construct validity	Not reported for RMA-lt	Not reported for the 3 items related to trunk control	Not reported	Not reported	Not reported	Correlation with gross motor function subscale of RMA at 6, 12 and 18	Correlation with Barthel Index (r=0.86) (Verheyden et al, 2004)	Rasch analysis (logits)

Table 3-1 (Continued)

Outcome measure / Criteria	Rivermead Motor Assessment (RMA)	Motor Assessment Scale (MAS)	Chedoke-McMaster Stroke Assessment (CMSA)	Stroke Impairment Assessment Set (SIAS)	Postural Assessment Scale for Stroke Patients (PASS)	Trunk Control Test (TCT)	Trunk Impairment Scale (Verheyden) (TIS)	Trunk Impairment Scale (Fujiwara) (TIS-F)
						weeks post stroke. (between 0.70 and 0.79) (Collin and Wade, 1990)		
Concurrent validity	Correlation with Barthel Index: 1 month (r=0.78) 1 year (r=0.63) (Endres et al, 1990)	Not reported for the 3 items related to trunk control	Score of Impairment Inventory correlated with FMA (r=0.95) Score of disability Inventory correlated with FIM (r=0.79) (Gowland et al, 1993)	Correlation with Motricity Index (Spearman ρ=0.87) and Brunnstrom stage (Spearman ρ=0.69) (Liu et al, 2002)	concurrent validity between the PASS and the TIS (α=0.849) (Di Monaco et al, 2010)	Correlation with admission FIM (r =0.71) and discharge FIM (r=0.79) (Franchignoni et al, 1997)	Correlation with TCT (r = 0.83) (Verheyden et al, 2004)	Correlation with TCT (r = 0.91) (Fujiwara et al, 2004)
Predictive validity	Not reported for RMA-lt	Not reported	Postural control section of CMSA significantly ($p<0.05$) predicted discharge location classified as either no change or change in premorbid accommodation in a sample of 104 stroke patients (Agarwal et al, 2003)	age, admission FIM scores and SIAS total scores, accounted for 64% of variance in discharge FIM score (Tsuiji et al, 2000)	PASS-TC score alone accounted for 45% of the variance in predicting comprehensive ADL function. (Hsieh et al, 2002)	Initial TCT predicts the 52% of the variation in length of stay and 54% in the discharge FIM (Duarte et al, 2002)	Total TIS and static sitting balance predicted 52% and 50% of the variance in the Barthel Index score respectively at 6 months after stroke (Verheyden et al, 2007)	Addition of TIS-F as one of the predictors to age, time from onset, and admission FIM motor score increased the adjusted R^2 from 0.66 to 0.75 in predicting discharge FIM motor score

Table 3-1 (Continued)

Outcome measure / Criteria	Rivermead Motor Assessment (RMA)	Motor Assessment Scale (MAS)	Chedoke-McMaster Stroke Assessment (CMSA)	Stroke Impairment Assessment Set (SIAS)	Postural Assessment Scale for Stroke Patients (PASS)	Trunk Control Test (TCT)	Trunk Impairment Scale (Verheyden) (TIS)	Trunk Impairment Scale (Fujiwara) (TIS-F)
							TIS predicted 48.3% of the variance in the FIM score (Di Monaco et al, 2010)	(Fujiwara et al, 2004)
Discriminative ability	Not reported for RMA-Jt	Not reported	Not reported	Not reported	discriminative ability is limited over the first 6 months post stroke due to large ceiling effect (Wang et al, 2005)	Poor – due to pronounced ceiling effect (Franchignoni et al, 2003)	TIS discriminates between stroke patients and healthy individuals. Cut-off score is 20. TIS score of 20 is the 90th and 10th percentile for the stroke patients and healthy individuals, respectively (Verheyden et al, 2005)	Not reported
Minimal Detectable Change (MCD)	Not reported	Not reported	Not reported	Not reported	***For subacute stroke patients***: MDC_{95} = 2.22 (Chien et al, 2007) ***For chronic stroke patients***: MDC_{95} = 3.2 (Liaw et al, 2008)	Not reported	An increase of 4 points on the TIS can be seen as an improvement without reproducibility bias (Verheyden et al, 2004)	Not reported

Table 3-1 (Continued)

Outcome measure / Criteria	Rivermead Motor Assessment (RMA)	Motor Assessment Scale (MAS)	Chedoke-McMaster Stroke Assessment (CMSA)	Stroke Impairment Assessment Set (SIAS)	Postural Assessment Scale for Stroke Patients (PASS)	Trunk Control Test (TCT)	Trunk Impairment Scale (Verheyden) (TIS)	Trunk Impairment Scale (Fujiwara) (TIS-F)
Minimal Clinically Important Difference (MCID)	Not reported	Not reported	MCID = 7 points (total CMSA) (Gowland et al, 1993)	Not reported	Not reported	Not reported	Not reported	Not reported
Floor / Ceiling effect	Floor effect in earlier phases of stroke noted (Kurtais et al, 2009)	No floor effect Percentage of 61 stroke patients who attained maximum score on MAS item: 1)rolling 73.8% 2)lie to sit 86.9% 3)balanced sitting 91.8% (English et al, 2006)	Not established	Not established	PASS-TC: notable ceiling effect at the 4 time points (>30% of the stroke subjects), indicating a limited discriminative ability between individuals (Wang et al, 2005)	Large ceiling effect (Franchignoni et al, 2003; Verheyden et al, 2006)	No ceiling effect (Verheyden et al, 2005)	Not established

3.3 Clinical outcome measures for upper extremity impairment and function post stroke

An extensive search was conducted using electronic databases to identify the most appropriate outcome measures for the upper extremity of stroke participants at the impairment and function level. The electronic databases utilised include CINAHL, EMBASE, MEDLINE, AMED, Web of Knowledge and Cochrane Library and the period of search from January 1980 to July 2013. The following keywords were used: stroke, upper limb, upper extremity, arm, impairment, function, assessment, outcome measure. Only journal articles published in English were reviewed. Additional relevant studies were identified by examining the references from retrieved articles.

3.3.1 Outcome measures for upper extremity impairment

Common upper extremity impairments after stroke include paresis, loss of fractionated movement, abnormal muscle tone, and/or changes in somatosensation (Lang et al. 2013). Within the context of this research, only the motor impairment will be considered.

Four outcome measures for UE motor impairment post stroke include the upper extremity subsection of the Fugl-Meyer Assessment (FMA) (Fugl-Meyer et al. 1975), Motricity Index (MI) (Colin & Wade 1990), grip strength and pinch strength using the dynamometer (Mathiowetz et al. 1985). The latter three measures only assess one aspect of impairment (strength) and do not assess voluntary movement of upper extremity.

MI consists of two subsections, namely arm (MI-arm) and leg (MI-leg). MI-arm is a global measure of range and power in the hemiparetic UE. It only rates the pinch grip, elbow flexion and shoulder abduction (Colin & Wade 1990). The three items are rated using the Medical Council Research (MRC) grading of 0 to 5 and then converted into weighted scores. MI-arm has been reported to be a valid instrument for characterising the strength of the paretic UE post stroke (Bohannon 1999). This is in accordance with the findings of Sunderland et al. (1989). MI exhibits good criterion validity due to significant and high correlation coefficients with dynamometer measures (r value ranged from 0.74 to 0.93) (Bohannon 1999). In addition, MI demonstrates good construct validity

(Cronbach α-coefficient 0.968) (Bohannon 1999).

FMA is widely used in stroke rehabilitation research and has been regarded as the gold standard for measurement of UE impairment against which the validity of other measures has been assessed (Fugl-Meyer et al. 1975; Gladstone et al. 2002; Baker et al. 2011; Page et al. 2012b). FMA assesses the ability of the individual to perform movements in accordance with specified joint motion pattern of the shoulder, elbow, wrist and hand. Each of the 33 items of FMA is rated on a 3-point scale. The maximum score is 66 points.

Numerous studies have confirmed that FMA has adequate psychometric properties for rehabilitation research and clinical applications. FMA demonstrates excellent test-retest reliability (ICC = 0.97) (Platz et al. 2005a); inter-rater reliability (ICC = 0.96) (Sanford et al. 1993); internal consistency (Cronbach α-coefficient 0.94 to 0.98 at 14, 30, 90, and 180 days after stroke) (Lin et al. 2009a); construct validity (correlation between FMA and Wolf Motor Function Test-Time = 0.76) (Hsieh et al. 2009); concurrent validity (correlation between FMA and Arm Motor Ability Test functional ability scores, r = 0.94) (Chae et al. 2003); predictive validity (correlation between FMA and Barthel Index at discharge, r = 0.66) (Hsueh et al. 2008). In addition, FMA exhibits moderate responsiveness to change, as measured by the standard response mean (SRM) (SRM = 0.74) (Rabadi & Rabadi 2006). The minimal detectable change (MDC) for FMA was 5.2 points (95% confidence interval) (Wagner et al. 2008). The minimal clinically important difference (MCID) of FMA was reported to range from 4.25 to 7.25 points for chronic stroke patients (Page et al. 2012a), and 9 to 10 points for subacute stroke patients (Arya et al. 2011). The FMA does not exhibit any significant floor or ceiling effect (Lin et al. 2009a).

The reliability of a measurement is the ratio of true inter-individual variance to total variance and so varies from 0 to 1 (Prabhakaran et al. 2008). The closer the reliability is to 1, the greater the extent to which variability in the measurement reflects true inter-individual variability. FMA has been shown to have a reliability close to value of 1, implying that inter-individual

differences almost entirely reflect biologically meaningful variability (Gladstone et al. 2002; Prabhakaran et al. 2008).

After comparing the psychometric properties of MI and FMA, a final decision was made to use FMA for the assessment of the upper extremity motor impairment of the participants in this doctoral research as it is regarded as the gold standard for stroke research (Gladstone et al. 2002; Baker et al. 2011; Page et al. 2012b). In addition, FMA provides a more comprehensive assessment of the upper extremity because it assesses the shoulder, elbow, wrist movements as well as coordination of the upper extremity while MI only include global assessment of the pinch strength, elbow flexion and shoulder abduction. A recent publication also supports that FMA is an outcome measure with good psychometric properties and good clinical utility (rating of 3 on the StrokEDGE Scoring Matrix) that is appropriate for the subacute and chronic stroke population (Sullivan et al. 2013).

3.3.2 Outcome measures for upper extremity function

The extensive electronic database search yielded numerous outcome measures for upper extremity function. The following criteria was set by the author to identify the most appropriate outcome measure for assessment of the upper extremity function in the stroke participants for this research:

1) the measure is appropriately tested in stroke population

2) the measure demonstrates adequate psychometric properties

3) the measure exhibits discriminative ability to differentiate participants with different levels of upper extremity function

4) the measure should consist of items with difficulty levels that range from easy to difficult to suit varying degrees of upper extremity function in the stroke participants

5) the items should include using common real-life objects and tasks related to activities of daily living

6) the measure can be administered in less than 30 minutes to minimise fatigue in the participants

Outcome measures that focused on the assessment of gross dexterity (eg. Box and Block Test), finger dexterity (eg. Nine Hole Peg Test) or only hand function (eg. Jebsen-Taylor Hand Function Test) were excluded. All self-reported outcome measures or questionnaire for upper extremity function (eg. Motor Activity Log and ABILHAND) were also excluded. This is because they do not fit within the context of this research whereby the assessment of the whole upper extremity and the functional ability is essential for gathering data related to overall performance and quality of movement.

Following the extensive search, 6 clinical outcome measures for upper extremity function in stroke population were selected for review. These measures include the Frenchay Arm Test (FAT), Motor Assessment Scale-Upper Limb subscale (MAS-UL), Chedoke Arm and Hand Activity Inventory (CAHAI), Arm Motor Ability Test (AMAT), Action Research Arm Test (ARAT) and the Wolf Motor Function Test (WMFT). A summary of the review of outcome measures for upper extremity function is presented in Table 3-2.

Of the 6 outcome measures, 4 measures demonstrated the closest fit to the criteria and were shortlisted for the final review. These outcome measures included CAHAI, AMAT, ARAT and WMFT.

All the CAHAI items require bilateral upper extremity involvement and do not focus on the more affected upper extremity (Barreca et al. 2004; Barreca et al. 2005; Barreca et al. 2006a; Barreca et al. 2006b). Thus, it does not fit within the scope of investigation for this study, which aims to examine the recovery of the affected upper extremity post stroke. AMAT exhibits adequate psychometric properties, such as internal consistency, inter-rater reliability, test-retest reliability, construct validity, concurrent validity and responsiveness (Kopp et al. 1997; Chae et al. 2003; O'Dell et al. 2011; O'Dell et al. 2013). However, AMAT is not able to discriminate between varying levels of upper extremity motor impairments in stroke patients (Chae et al. 2003). In addition, AMAT also exhibits significant ceiling and floor effects with respect to Fugl-

Meyer Assessment (FMA) (Chae et al. 2003). The predictive validity, minimal detectable change (MCD) and minimal clinically important difference (MCID) of AMAT have not been established yet. Some assessment tasks in the AMAT include mobility components (for example, opening a door and turning off a light switch), which do not fit within the scope of investigation for this study of examining the affected upper extremity function in a seated position.

ARAT and WMFT are two of the most common standardized measures used in upper extremity treatment studies (van der Lee et al. 2001; Lang et al. 2008; Fritz et al. 2009; Lin et al. 2009b; Edwards et al. 2012). From Table 3-2, it is evident that ARAT and WMFT have good psychometric properties for measurement of upper extremity function post stroke. The high concurrent validity between both tests suggests that ARAT and WMFT have significant overlap with regard to the underlying construct that is being measured (Nijland et al. 2010a). Both measures also exhibit comparable responsiveness. However, WMFT appears to be slightly more responsive than ARAT for the acute and subacute stroke patients (Edwards et al. 2012) while ARAT appears to be slightly more responsive than WMFT for the chronic stroke patients (O'Dell et al. 2013). Two different acceptable methods for evaluating responsiveness (effect size method and standardized response mean) were used in these two studies. Taken together, ARAT and WMFT are equally good outcome measures for assessment of the upper extremity function in stroke rehabilitation and research.

Table 3-2 Review of outcome measures for upper extremity function in stroke patients

Outcome measure / Criteria	Frenchay Arm Test (FAT)	Motor Assessment Scale-Upper Limb subscale (MAS-UL)	Chedoke Arm and Hand Activity Inventory (CAHAI)	Arm Motor Ability Test (AMAT)	Action Research Arm Test (ARAT)	Wolf Motor Function Test (WMFT)
Patient population tested	Stroke	Stroke	Stroke	Stroke	Stroke Multiple sclerosis Traumatic brain injury	Stroke Traumatic brain injury
Number of items and Item description	5 items: 1) Stabilize a ruler, while drawing a line with a pencil held in the other hand. 2) Grasp a cylinder and lift it 3) Pick up a glass, half full of water drink some water and replace 4) Remove and replace a sprung clothes peg from a dowel 5) Comb hair	3 items: 1) Upper arm function 2) Hand movements 3) Advanced hand activities	13 items: 1) Open a jar of coffee 2) Dial 911 3) Draw a line with a ruler 4) Pour a glass of water 5) Wring out a washcloth 6) Do up five buttons 7) Dry back with a towel 8) Put toothpaste on a toothbrush 9) Cut medium consistency putty 10) Clean eye glasses 11) Zip up a zipper 12) Place a container on a table 13) Carry a bag up the stairs	13 items: 1) Cut meat 2) Pick up sandwich and bring to mouth 3) Eat with spoon 4) Drink from mug 5) Comb hair 6) Open jar 7) Tie shoelace 8) Use telephone 9) Wipe up spilled water 10) Put on cardigan 11) Put on T-shirt 12) Prop on extended affected arm, reach across body with unaffected arm and pick up small object 13) Flip light switch, grasp door handle and close door	19 items: divided into 4 sub-tests 1) Grasp – 6 items 2) Grip – 4 items 3) Pinch – 6 items 4) Gross arm movement – 3 items	Original WMFT: 21 items (Wolf et al, 1989) Modified WMFT: 17 items (Morris et al, 2001) (a) 2 strength items: weight to box and grip strength (b)15 functional task items: 1) Forearm to table (side) 2) Forearm from table to 25.4-cm box (side) 3) Extend elbow table top (side) 4) Extend elbow table top (1-lb weight) 5) Hand to table (front) 6) Hand to box (front) 7) Reach and retrieve 1-lb weight 8) Lift can to mouth 9) Lift pencil from table 10) Lift paper clip from table 11) Stack 3 checkers 12) Flip 3 cards 13) Turn key in lock 14) Fold towel 15) Lift basket with 1.35-kg weight in standing position

Table 3-2 (Continued)

Outcome measure / Criteria	Frenchay Arm Test (FAT)	Motor Assessment Scale-Upper Limb subscale (MAS-UL)	Chedoke Arm and Hand Activity Inventory (CAHAI)	Arm Motor Ability Test (AMAT)	Action Research Arm Test (ARAT)	Wolf Motor Function Test (WMFT)
Test-retest reliability	Not reported	For MAS: Test-retest correlations were excellent ranging from r=0.87 to r=1 (Carr et al, 1985)	ICC excellent for all shortened versions: CAHAI-7 (ICC = 0.96) CAHAI-8 (ICC = 0.97) CAHAI 9 (ICC = 0.97) (Barreca et al, 2006a)	r = 0.99 (Kopp et al, 1997)	ICC 0.963 (Platz et al, 2005)	Performance time (WMFT-Time): ICC 0.99 Functional Ability Scale (WMFT-FAS): r = 0.97 (Whitehall et al, 2006)
Inter-rater reliability	Correlation coefficient of FAT was within range r = 0.75 to 0.99 (Heller et al, 1987)	For MAS: r = 0.95 (Carr et al, 1985)	ICC = 0.98 (Barreca et al, 2005)	r = 0.99 (Kopp et al, 1997)	ICC 0.99 (Yozbatrin et al, 2008)	ICC 0.97 (Wolf et al, 2001)
Responsiveness	Limited sensitivity (Heller et al, 1987)	Effect size were small for all items: - Upper arm function: 0.36 - Hand movements: 0.43 - Advanced hand activities: 0.50 (English et al, 2006) over 80% of the 61 stroke subjects were rated at the extremes of the scales on all MAL-UL items (English et al, 2006)	CAHAI and CAHAI-9 demonstrated more sensitivity to change than the ARAT (Barreca et al, 2006b)	Standardized response mean (SRM) SRM = 0.98 (O'Dell et al, 2013)	***For acute to subacute stroke patients:*** Effect size method: ARAT 1.02 (day 0–day 14) 1.39 (day 0–day 90) (Edwards et al, 2012) ***For chronic stroke patients:*** Standardized response mean (SRM) SRM = 0.89 (O'Dell et al, 2013)	***For acute to subacute stroke patients:*** Effect size method: WMFT-FAS 1.09 (day 0–day 14) 1.63 (day 0–day 90) (Edwards et al, 2012) ***For chronic stroke patients:*** Standardized response mean (SRM) SRM = 0.81 (O'Dell et al, 2013)
Internal consistency	Not reported	Not reported	Cronbach α-coefficient = 0.98 (Barreca et al, 2004)	Cronbach α- coefficient = 0.94 (Kopp et al, 1997)	Cronbach α- coefficient = 0.985 (Nijland et al, 2010)	Cronbach α- coefficient = 0.92 (Morris et al, 2001)

Table 3-2 (Continued)

Outcome measure / Criteria	Frenchay Arm Test (FAT)	Motor Assessment Scale-Upper Limb subscale (MAS-UL)	Chedoke Arm and Hand Activity Inventory (CAHAI)	Arm Motor Ability Test (AMAT)	Action Research Arm Test (ARAT)	Wolf Motor Function Test (WMFT)
Construct validity	Not reported	Convergent Validity: - - Sitting arm raise (r = 0.33) - Sitting forward reach (r = 0.54) (Tyson & DeSouza, 2004)	Correlation with ARAT (r = 0.93) (Barreca et al, 2005)	Rasch analysis confirmed the construct validity of AMAT (O'Dell et al, 2013)	Correlation with FMA-UE (r = 0.925) (Platz et al, 2005)	Known group's validity (using Wilcoxon 2-sample test): WMFT scores for the dominant and the non-dominant hand of individuals without impairment were significantly higher when compared to the most and to the least affected upper extremities of stroke patients (p<0.0001) (Wolf et al, 2001)
Concurrent validity	Not reported	MAS correlation with Fugl-Meyer (FMA) total scores (r = 0.96) (Malouin et al, 1994)	Correlation with ARAT (r = 0.93) (Barreca et al, 2005)	Correlation with ARAT (r = 0.79) Correlation with WMFT (r = 0.78) (O'Dell et al, 2013)	Correlation with FMA-UE (r = 0.94) (Yozbatrin et al, 2008)	Correlation with FMA-UE WMFT-Time (r = -0.88) WMFT-FAS (r = 0.88) (Whitehall et al, 2006) Correlation with ARAT: WMFT-Time (r = -0.89) WMFT-FAS (r = 0.86) (Nijland et al, 2010)
Predictive validity	Not reported	Not reported	Not reported	Not reported	Moderate to good correlation with WMFT: WMFT-Time (Spearman ρ = -0.66) WMFT-FAS (Spearman ρ = 0.76) (Chen et al, 2012)	Moderate to good correlation with ARAT: WMFT-Time (Spearman ρ = -0.66) WMFT-FAS (Spearman ρ = 0.76) (Chen et al, 2012)

Table 3-2 (Continued)

Outcome measure / Criteria	Frenchay Arm Test (FAT)	Motor Assessment Scale-Upper Limb subscale (MAS-UL)	Chedoke Arm and Hand Activity Inventory (CAHAI)	Arm Motor Ability Test (AMAT)	Action Research Arm Test (ARAT)	Wolf Motor Function Test (WMFT)
Discriminative ability	Not reported	Not reported	Not reported	AMAT time of performance is not able to discriminate between varying levels of motor impairments (Chae et al, 2003)	Not reported	WMFT can classify 86.7% of individuals with stroke into different levels according to Brunnstrom's stages of recovery (Ang & Man, 2006)
Minimal Detectable Change (MCD)	Not reported	Not reported	MDC_{90} = 6.3 points (Barreca et al, 2005)	Not reported	MDC_{90} = 9.6 points (Beebe, 2008)	***For subacute stroke patients*:** **WMFT-Time:** MDC_{95} = 0.7 seconds **WMFT-FAS:** MDC_{95} = 0.1 points (Fritz et al, 2009) ***For chronic stroke patients:*** **WMFT-Time:** MDC_{90} = 4.36 seconds **WMFT-FAS:** MDC_{90} = 0.37 points (Lin et al, 2009)
Minimal Clinically Important Difference (MCID)	Not reported	Not reported	Not reported	Not reported	***For acute stroke patients:*** MCID : 12 points if dominant upper extremity affected MCID : 17 points if non-dominant upper	***For acute stroke patients:*** **WMFT-Time:** MCID 19 seconds if dominant upper extremity affected Unable to estimate for affected non-dominant upper extremity

Table 3-2 (Continued)

Outcome measure / Criteria	Frenchay Arm Test (FAT)	Motor Assessment Scale-Upper Limb subscale (MAS-UL)	Chedoke Arm and Hand Activity Inventory (CAHAI)	Arm Motor Ability Test (AMAT)	Action Research Arm Test (ARAT)	Wolf Motor Function Test (WMFT)
Minimal Clinically Important Difference (MCID)					extremity affected (Lang et al, 2008) ***For chronic stroke patients:*** MCID : 5.7 points (van der Lee et al, 2001)	**WMFT-FAS:** MCID 1.0 point if dominant upper extremity affected MCID 1.2 points if non-dominant upper extremity affected (Lang et al, 2008) ***For chronic stroke patients:*** **WMFT-Time:** MCID 1.5-2sec **WMFT-FAS:** MCID 0.2-0.4 points (Lin et al, 2009)
Floor / Ceiling effect	Not reported	Acceptable floor (14%) and ceiling (9%) effects (Miller et al, 2010)	Not reported	AMAT time of performance exhibited significant ceiling and floor effects with respect to FMA. (Chae et al, 2003)	- Floor effects for scores < 3 - Ceiling effects for scores > 54 (Nijland et al, 2010)	Adequate floor and ceiling effects: only 5 to17% of patients scoring the lowest or highest scores (Nijland et al, 2010)

Closer analysis of ARAT and WMFT items by the author (SKW) reveals that majority of the ARAT items require the stroke patient to have some degree of active finger flexion and extension in order to attain higher scores. The ARAT consists of 6 items for assessing grasp domain, 4 items for grip domain, 6 items for pinch domain and 3 items for gross arm movements (Yozbatiran et al. 2008). Thus, 16 items out of 19 test items require the control of finger flexion and extension in order to complete the tasks successfully. These test items can be very challenging for stroke patients who do not have any active finger flexion and extension. Those patients who exhibit moderate to severe degree of spasticity in their hand muscles are likely to face difficulty in active control and coordination of finger movements for the successful completion of the majority of ARAT test items.

The WMFT consists of 6 joint-segment movements (gross arm movements), 9 integrative functional tasks and 2 strength items (Wolf et al. 2001; Ang & Man 2006). Therefore, there are more items that assess gross arm movements in WMFT compared to only 3 items assessing gross arm movements in ARAT. This implies that stroke patients with lower functional ability of upper extremity may still be able to perform or complete those items of WMFT to some extent and scoring can be achieved.

Overall, WMFT is assessed by the author to be the most appropriate outcome measure for upper extremity function for this research because it consists of a mixture of easy and difficult test items which will suit stroke patients with various level of upper extremity function. In addition, the ordinal scale used for scoring the quality of movement in WMFT is a 6-point scale versus the 4-point scale used in ARAT. This implies that WMFT has a more sensitive scale to rate the quality of movement during task performance, which may help to improve the sensitivity of WMFT to detect smaller degrees of change in patients. A recent publication also supports that WMFT is an outcome measure with good psychometric properties and good clinical utility (rating of 3 on the StrokEDGE Scoring Matrix) that is appropriate for the subacute and chronic stroke population (Sullivan et al. 2013).

3.3.3 Wolf Motor Function Test and Streamlined Wolf Motor Function Test

On average, WMFT may take approximately 30 to 45 minutes for the clinician to complete (Bogard et al. 2009). This may cause fatigue in some stroke patients who have poorer exercise tolerance. A study conducted by Bogard et al. (2009) showed that WMFT can be streamlined from 17 tasks to 6 tasks. This shortened version is termed as streamlined Wolf Motor Function Test (SWMFT), which requires a shorter period of time (approximately 15 minutes) to administer. The SWMFT has well-established psychometric properties (Wu et al. 2011; Chen et al. 2012). It exhibits comparable responsiveness to WMFT and improved clinical utility (Wu et al. 2011). Hence, a decision was made by the author to use SWMFT instead of WMFT for this doctoral research.

Two versions of SWMFT are recommended based on Rasch analysis (Bogard et al. 2009; Chen et al. 2012). One version of SWMFT is appropriate for subacute stroke patients (<9 months) and another version of SWMFT is appropriate for the chronic stroke patients (>9 months) (Appendix 4 and Appendix 5). There are 4 common tasks for the two groups, which are hand to box (front), lift can, lift pencil and fold towel. In addition, the subacute version of SWMFT (SWMFT-s) includes hand to table (front), and reach and retrieve tasks while the chronic version of SWMFT (SWMFT-c) includes extend elbow (1lb weight) and turn key in lock. Bogard et al. (2009) reported that the 4 common tasks of SWMFT-s and SWMFT-c are the best tasks for the WMFT core evaluation because they were significantly related to the overall WMFT changes in subacute and chronic stroke patients. Hence, comparison can be made between subacute and chronic stroke patients by using these 4 core tasks. Refer to Appendix 6 and Appendix 7 for the movement components assessed by each item of SWMFT.

There is a vital point to highlight about the administration of SWMFT for the Phase 1 study and Phase 2 study of this doctoral research. The final data analysis of results from both phases of the study will include comparison of the task performance between healthy participants, subacute and chronic stroke patients. Hence, the research protocol requires all participants to perform all 8 tasks (4 core tasks plus 2 each from the subacute and chronic

versions of SWMFT) so that comparison can be made across all three groups, as this has been demonstrated to be a valid test (Chen et al. 2014). The 8 tasks of SWMFT for this research are: hand to table (front), hand to box (front), reach and retrieve, lift can, lift pencil, fold towel, extend elbow (1 lb weight), and turn key in lock (Appendix 8).

3.4 Kinematic measures

Kinematic measures of movement can be captured by a motion capture system and wearable inertial sensors. Such data are useful objective measurements for research and for guiding clinical practice. The kinematic measures help to quantify normal and pathological movements, quantify the degree of impairment, plan rehabilitation strategies and assess the effects of therapeutic interventions (Cuesta-Vargas et al. 2010).

This section details the features of the systems and comparison of their applications in research and clinical practice.

3.4.1 Motion capture systems

High-end motion capture systems have been in the market for many years (Thewlis et al. 2013). These system have been recognized by the researchers and clinicians as the laboratory gold standard for capturing objective and quantifiable data of human movement (Richards 1999; Cuesta-Vargas et al. 2010).

Two common types of motion capture systems currently are the video-based optical tracking system and the electromagnetic system. Some optical tracking systems, such as the Vicon system, utilise markers that reflect light back to the sensor. Other systems, such as the CODA system, utilise markers that emit the source of light for the sensors. These markers are designed to be easily identifiable by image processing software with algorithms for data processing. With these markers, they enable the visualization of multiple body regions and tracking of motions in three-dimensions. These motion capture systems are considered as the gold standard for motion analysis due to their reliability and accuracy (Cuesta-Vargas et al. 2010). However, they are expensive, complex

and time-consuming for the set up, calibration process and operation (Wong et al. 2007). The cameras and accessories required also confine the motion analysis to a laboratory environment (Hadjidj et al. 2013). Another limitation of the motion capture systems, as well as in some wearable inertial sensors, is a possibility of line-of-sight difficulties, which can result in missed data (Goodvin et al. 2006). Skin artifact, i.e. skin movement relative to the underlying bone, is a factor that may compromise accuracy and validity of data (Reinschmidt et al. 1997; Benoit et al. 2006). For example, if a reflective marker is placed on the inferior angle of the scapula, the marker will not be exactly on the bony landmark during upper extremity movement as the scapula will glide underneath the skin. These artifacts may contribute to incorrect interpretations of movement data.

In an electromagnetic system, the magnetic sensors are attached to the subject. A transmitter will emit electromagnetic field during assessment and the sensors will then return both their position and orientation. There is no need for clear line-of-sight between sensor and transmitter. Thus, this feature improves the range of motion that is possible to capture and is advantageous over the optical tracking systems which require the markers to be in the line-of-sight of the cameras. The electromagnetic systems are very reliable and accurate, and the data is clean and the processing time is low (Roetenberg et al. 2007; Picerno et al. 2008; Martin-Schepers et al. 2010). The downside of these systems is that they are prone to electromagnetic interference and presence of metallic material (Milne et al. 1996).

A comprehensive comparison of the accuracy of seven commercially available motion capture systems was reported by Richards (1999). The systems that were compared include the Ariel system, Qualisys' ProReflex system, BTS's ElitePlus system, Motion Analysis' HiRes system, Peak Performance's Motus system, Charnwood Dynamic's CODA system and Vicon's 370 system. In this study (Richards 1999), the measured distance between the two markers on the top of the rigid bar was calculated for each frame of the trials. The root mean square (RMS) for the different systems were calculated. The RMS refers to the difference between the average measured distance and the measured distance in each frame of the data. It was demonstrated that in the static tests, the

optical motion capture systems generally produced (RMS) errors of less than 1 mm. During dynamic tests, the RMS error increased to up to 4.2 mm in some systems. As for the measurement of angles, the average RMS error was within 1.5 degrees. From the summary table (Table 3-3), it is clear that the Vicon system exhibits the smallest RMS errors during the static and dynamic tests as well as for the measurement of angles. In other words, the Vicon system produces the best results in terms of accuracy. Hence, the Vicon system will be used in this research to capture kinematic of the trunk, scapula, shoulder and elbow movements during the TIS assessment and SWMFT task performance.

Table 3-3 Root mean square (RMS) errors of different motion capture systems

Motion capture System / Measurement	Ariel	Qualisys	Elite	Motion	Peak	CODA	Vicon
Static test (two markers 5cm apart) - in cm	Not reported	0.054	0.123	0.085	0.125	0.074	0.047
Dynamic test (two markers 9cm apart on a rotating plate) - in cm	0.151	0.221	0.446	0.149	0.177	0.225	0.129
Angles (between plate markers) - in degrees	2.109	4.498	4.287	1.761	3.772	3.392	1.421

3.4.2 Kinematic analysis of the trunk, scapula and upper extremity

Kinematic motion analysis can provide more specific information about movement components and strategies (Alt Murphy et al. 2011). It is a feasible method to measure motor change, distance (linear and angular displacements), velocity, acceleration and angles in which a person moves (Hewett et al. 2007).

Kinematic analysis is recognized as a valid, sensitive and objective method for capturing and quantifying improvements in upper extremity impairment and function (Hingtgen et al. 2006; Subramanian et al. 2010; Patterson et al. 2011; Alt Murphy et al. 2013; van Dokkum et al. 2014; Alt Murphy & Häger 2015), trunk control (Messier et al. 2006; Simoneau et al. 2013; Thielman 2013), and scapular movements post stroke (Meskers et al. 2005; Niessen et al. 2008; Niessen et al. 2009; Hardwick & Lang 2011b; De Baets et al. 2013a).

Analysis at the kinematic level will enable differentiation between functional gains achieved through compensation versus those achieved through true recovery of motor control (Subramanian et al. 2010; Alt Murphy et al. 2013; Kitago et al. 2013). Kinematic analysis is sensitive enough to capture small changes and is influenced neither by the ceiling effect nor by subjective observation of clinicians and researchers (van Dokkum et al. 2014). For example, if the upper extremity function (measured with SWMFT) improves without any significant improvement at the motor impairment level (FMA) and in the kinematics variables, then compensation will have occurred and that accounts for the improvement in the upper extremity function observed.

In this doctoral research, the kinematic analysis of trunk, scapula and upper extremity movements during the TIS assessment and SWMFT task performance will be evaluated by the 12-camera motion analysis system (VICON MX T-series; Vicon Motion Systems, Oxford, UK).

The rationale for selecting the appropriate kinematic variables for this doctoral research are detailed in the next section.

3.4.3 Rationale for selection of the kinematic variables to be captured for this doctoral study

The overarching aim of this doctoral research was to investigate the relationship between trunk control and the recovery of upper extremity function in subacute and chronic stroke patients. To meet this aim, the kinematic variables that would be captured for analysis include movement duration, movement smoothness, movement straightness (index of curvature: path-line ratio), ulnar styloid peak velocity, trunk flexion, trunk rotation, trunk lateral flexion, scapular internal and external rotation, scapular upward and downward rotation, scapular anterior and posterior tilt, shoulder flexion and elbow extension.

Numerous studies have demonstrated that stroke patients exhibit compensatory trunk movements during pointing and reaching (Roby-Brami et al. 1997; Cirstea & Levin 2000; Steenbergen et al. 2000; Michaelsen et al. 2001; Levin et al. 2002b; Roby-Brami et al. 2003a; Ustinova et al. 2004; Foroud

& Whishaw 2006; Messier et al. 2006; Robertson & Roby-Brami 2011; Massie et al. 2012; Rundquist et al. 2012; van Kordelaar et al. 2012; Thielman 2013). The compensatory trunk movements may occur in forward flexion and lateral flexion (Cirstea & Levin 2000; Esparza et al. 2003; Messier et al. 2006; Nakamura et al. 2008; Thielman 2013), and rotation (Cirstea & Levin 2000; Michaelsen et al. 2004).

Movements of the affected upper extremity in stroke patients are found to be segmented, slower, and characterized by a greater variability and by deflection of the trajectory from a straight line (Archambault et al. 1999; Rohrer et al. 2002; Cirstea et al. 2003b; Beer et al. 2004; Foroud & Whishaw 2006; Dipietro et al. 2009; Woodbury et al. 2009). These movement dysfunction may arise from pathological synergy (Cauraugh et al. 2000), spasticity (Marciniak 2011), abnormal muscle co-activation pattern (Dewald et al. 1995; Dewald et al. 2001) and abnormal interjoint coordination (Levin 1996a; Cirstea et al. 2003a).

It is widely recognized that following a stroke, the ipsilesional non-paretic upper extremity is not the same as premorbid status (Ketcham et al. 2007; Nakamura et al. 2008; Noskin et al. 2008; Finley et al. 2012; Morris & Van Wijck 2012; Metrot et al. 2013; Son et al. 2013). The effects of stroke on the ipsilesional upper extremity have been documented from the acute through chronic phases of stroke recovery (Jung et al. 2002; Meskers et al. 2005; McCombe Waller et al. 2008; Nakamura et al. 2008; Niessen et al. 2008). Studies have demonstrated that the ipsilesional hand trajectory is slower and more segmented (Sugarman et al. 2002; Ketcham et al. 2007); gross and fine manual dexterity are reduced (Smutok et al. 1989; Desrosiers et al. 1996; Hermsdorfer et al. 1999; Noskin et al. 2008); reaction time is reduced (Jones et al. 1989; Baskett et al. 1996) and the interjoint coordination is altered (Schaefer et al. 2009). Inferring from these findings, it is vital to capture the clinical scores and kinematic data of the affected and “less-affected” ipsilesional upper extremities in this doctoral research.

In a recent study, Alt Murphy et al. (2013) demonstrated that movement duration, movement smoothness and trunk displacement are three kinematic variables that are responsive outcome measures for the upper extremity during the first 3 months post stroke. Further analysis revealed that the movement duration and movement smoothness could detect smaller changes

and demonstrated a higher sensitivity to identify subjects with clinically meaningful improvements (6-point change in ARAT score) compared to trunk displacement. A 6-point change in ARAT score was found to be clinically meaningful improvement in chronic stroke patients (van der Lee et al. 2001). A most recent study demonstrated that movement duration is the dominant variable associated with motor impairment and functional capacity in individuals with stroke (Li et al. 2015).

In another study, van Dokkum et al. (2014) found that movement duration, trajectory length, directness, smoothness, mean and maximum velocity of the hand in acute stroke patients were sensitive to change over time and distinguished between movements of paretic, non-paretic, and healthy control limbs. The FMA score increased with movement smoothness over time, explaining 62.5% of FMA variability. This finding regarding FMA is in consistent with another study which confirmed a significant strong correlation between movement smoothness of the upper extremity and FMA (r = 0.70 for self-selected speed; r = 0.76 for fast speed) (Finley et al. 2012), thus reinforcing the importance of capturing movement smoothness as an outcome for the upper extremity.

In a study on 86 subacute and chronic stroke patients, Subramanian et al. (2010) found that trunk displacement alone explained 52% of the variance in FMA scores. There was a significant strong correlation between trunk displacement and FMA (r = -0.72; $p < 0.005$). In comparison with other variables (elbow extension, shoulder flexion and shoulder horizontal adduction), trunk displacement was the only variable able to discriminate between mild (FMA ≥50) and moderate-to-severe (FMA ≤49) motor impairment levels.

Drawing from these findings, it would be vital to capture the movement duration, movement smoothness, movement straightness, trunk flexion, trunk rotation, trunk lateral flexion, shoulder flexion, and elbow extension for monitoring the recovery of trunk and upper extremity in stroke patients in this doctoral research. Movement smoothness is measured by the number of velocity peaks (Woodbury et al. 2009; van Dokkum et al. 2014). To calculate

movement smoothness for this doctoral research, the ulnar styloid velocity peaks will be captured. This also informs about the velocity of movement during task performance, which is another useful outcome measure for the upper extremity.

The scapula is anatomically and biomechanically intimately involved with shoulder and upper extremity function (Kibler & McMullen 2003; Kibler & Sciascia 2010). The scapula serves as a stable base for the glenohumeral joint and contributes to upper extremity elevation (McClure et al. 2001). During the execution of shoulder and upper extremity movements to perform activities of daily living (ADL), the scapular movements are closely linked to those movements. Full range motion of the upper extremity has been shown to necessitate motion of both the scapula and spine (Crosbie et al. 2008). The scapula, shoulder, and upper extremity are either stabilized in or move to certain positions to generate, absorb, and transfer forces that accomplish ADL tasks (Kibler & McMullen 2003).

Altered scapular position and/or orientation may interfere with optimal shoulder coordination (Borsa et al. 2003; Amasay & Karduna 2009). There is evidence of scapular kinematic alterations associated with shoulder impingement, rotator cuff tendinopathy, rotator cuff tears, glenohumeral instability, adhesive capsulitis, and frozen shoulders (Fayad et al. 2008; Ludewig & Reynolds 2009; Scibek et al. 2009; Hardwick & Lang 2011a; Roren et al. 2012).

Following stroke, the scapular muscles are affected and the weakened muscles can cause alterations in scapular position and control. Muscle imbalance associated with weaknesses of the rotator cuff muscles may negatively affect the upper extremity performance of individuals with stroke during ADL tasks (Phadke et al. 2009; Nascimento et al. 2012).

Relatively small changes in the scapular muscles can affect the alignment and forces around the shoulder complex (Song 2013). The alterations can then have an impact on the scapulothoracic motion, which is the movement of the scapula in relation to the trunk. The combination of paresis of the upper extremity and the altered position and control of the scapula can have an impact on the scapulohumeral rhythm (SHR). SHR is the ratio of glenohumeral

motion to scapulothoracic motion during upper extremity elevation (Rundquist et al. 2012). Inman et al. (1944) were the first to measure SHR using radiography and suggested what became the widely accepted 2:1 ratio between glenohumeral elevation and scapulothoracic upward rotation (Scibek & Carcia 2012). However, Rundquist et al. (2012) found that SHR in stroke patients was not a consistent 2:1 ratio. It varied according to the degree of the upper extremity elevation. SHR ratio was 4.1:1 in stroke patients whose maximum upper extremity elevation ranged from 45 to 50 degrees; 1.5:1 from 80 to 95 degrees; and 2.1:1 from 105 to 130 degrees. In addition to altered SHR, stroke patients demonstrated less glenohumeral elevation and more scapular upward rotation during elevation in their affected upper extremity (Price et al. 2001; Meskers et al. 2005; Niessen et al. 2008; Rundquist et al. 2012).

A recent study used the Vicon motion capture system to investigate the dynamic scapular kinematic of stroke and healthy individuals (De Baets et al. 2013b). Results demonstrated that scapular kinematic can be measured reliably and with precision within one measurement session. The range of motion of scapular upward rotation showed the smallest measurement error within and between sessions, thus emphasizing the value of this angle in shoulder assessment, clinical decision-making and evaluation of treatment efficacy (De Baets et al. 2013b).

Taken together, it is crucial for clinicians and researchers to assess the trunk, scapula and upper extremity when evaluating any upper extremity movement during task performance as the three components are closely linked. Hence, the scapular kinematic variables (scapular internal and external rotation, scapular upward and downward rotation, and scapular anterior and posterior tilt) will be captured for this doctoral research to aid the understanding of the relationship between trunk control, scapular movement and upper extremity movement during performance of SWMFT tasks.

3.5 Summary of Chapter 3

This Chapter detailed a critical review of the outcome measures for clinical assessment of the trunk and upper extremity impairment and function. The TIS, FMA and SWMFT were selected as the most appropriate outcomes for this doctoral research. These outcome measures demonstrate good psychometric properties and good clinical utility that are appropriate for the subacute and chronic stroke population. In addition, the motion capture system to be utilised for kinematic assessment of the trunk, scapula and upper extremity was also discussed and justified.

The next Chapter will detail the methodology for this study.

Chapter 4: Methodology

4. Methodology

This Chapter describes the methodology for both Phase 1 and Phase 2 studies. The Chapter includes the aims and objectives of study, study design, sample size calculation, recruitment process, outcome measures, experimental procedures and ethical considerations. Methods of statistical analyses are discussed and justified.

4.1 Aims and objectives of study

4.1.1 Phase 1 study

The aims of the Phase 1 study were to investigate the effect of external trunk support on trunk control and upper extremity function, and to examine the relationship between trunk control and upper extremity function in chronic stroke participants, subacute stroke participants and healthy participants.

The Phase 1 study objectives:

1) To evaluate the change in the trunk control and upper extremity function when the trunk is stabilised with an external trunk support.

2) To evaluate the following relationships in subacute and chronic stroke participants:
i) between trunk control and upper extremity impairment; and
ii) between trunk control and upper extremity function.

3) To evaluate the relationship between trunk control and kinematics of the trunk, scapula, shoulder and elbow during reaching.

4) To evaluate the interaction effect between the healthy group, subacute and chronic stroke groups (between-subjects), and the support conditions (within-subject).

4.1.2 Phase 2 study

The aim of the Phase 2 study was to investigate the relationship between trunk control and recovery of upper extremity function during the first 6 months post stroke.

The Phase 2 study objectives:
1) To chart the recovery pattern of trunk control and upper extremity (impairment and function levels) over a period of 6 months.

2) To investigate the relationship between recovery of trunk control and recovery of upper extremity at impairment and function levels.

4.2 Study design

4.2.1 Phase 1 study

The Phase 1 study was subdivided into Phase 1A and Phase 1B studies, both of cross-sectional study design (Figure 4-1). The Phase 1A study was conducted with chronic stroke participants and healthy participants at the University of Southampton, United Kingdom. The Phase 1B study was conducted with subacute stroke participants at the Rehabilitation Centre, Tan Tock Seng Hospital, Singapore.

All the chronic stroke and subacute stroke participants and healthy participants were matched for age and sex for the assessments. The Phase 1A study was conducted over 7 months, from October 2013 to April 2014. The Phase 1B study was conducted over 5 months, from May 2014 to September 2014.

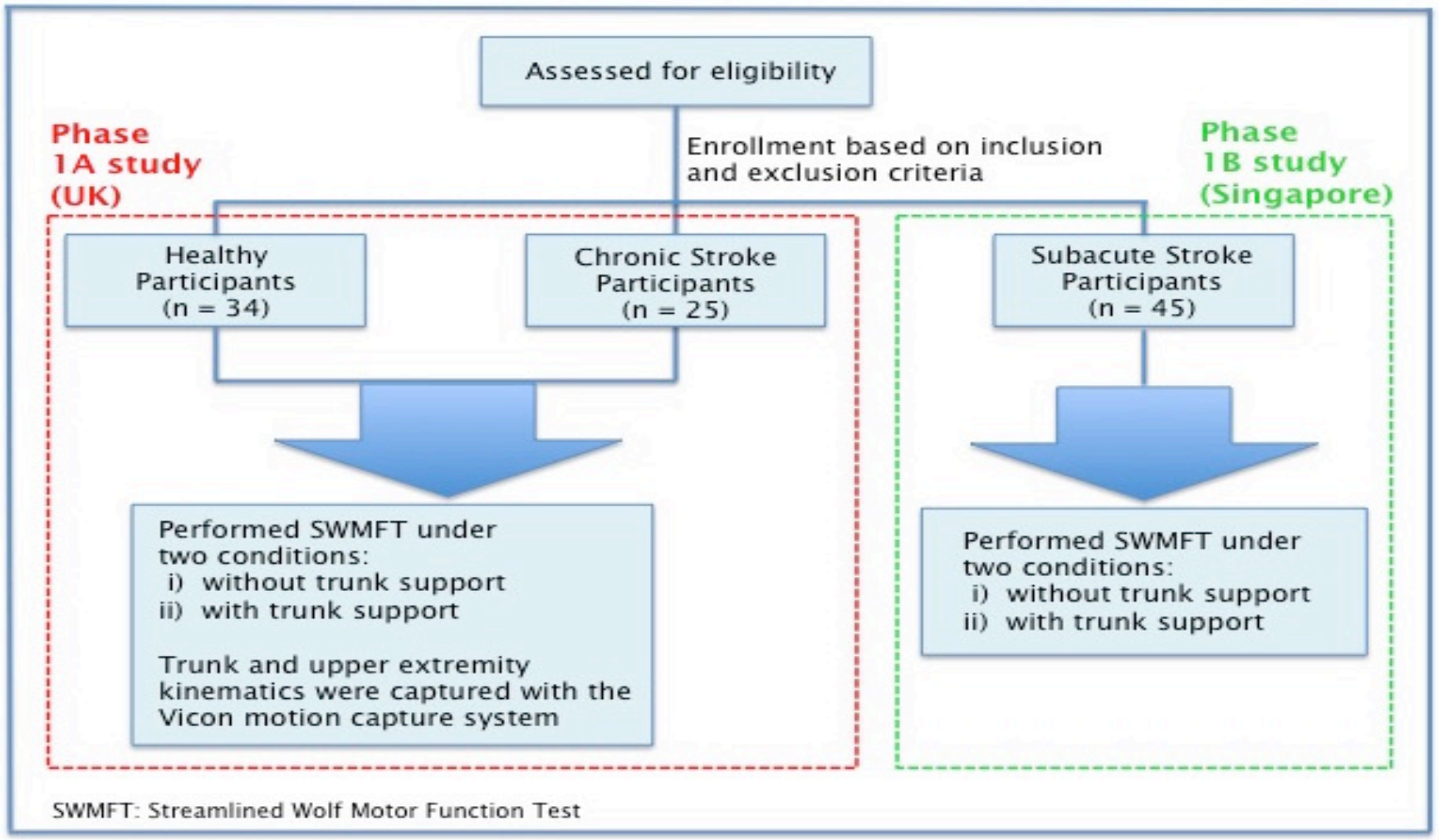


Figure 4-1 Flow diagram of the Phase 1 study

4.2.2 Phase 2 study

The Phase 2 study was a longitudinal study of the recovery of trunk control and upper extremity impairment and function of subacute stroke participants, whereby they were assessed monthly till 6 months post stroke (Figure 4-2). In other words, participants were assessed at similar time points at 1-month, 2-month, 3-month, 4-month, 5-month and 6-month post stroke. However, if a participant was recruited, for example, at 2-month post stroke, he/she would only have five time points of assessment, i.e. five data sets for analysis.

The Phase 2 study was conducted with a pool of subacute stroke participants who were undergoing inpatient rehabilitation at the Rehabilitation Centre of Tan Tock Seng Hospital, Singapore. The Phase 2 study was conducted over 10 months, from May 2014 to February 2015.

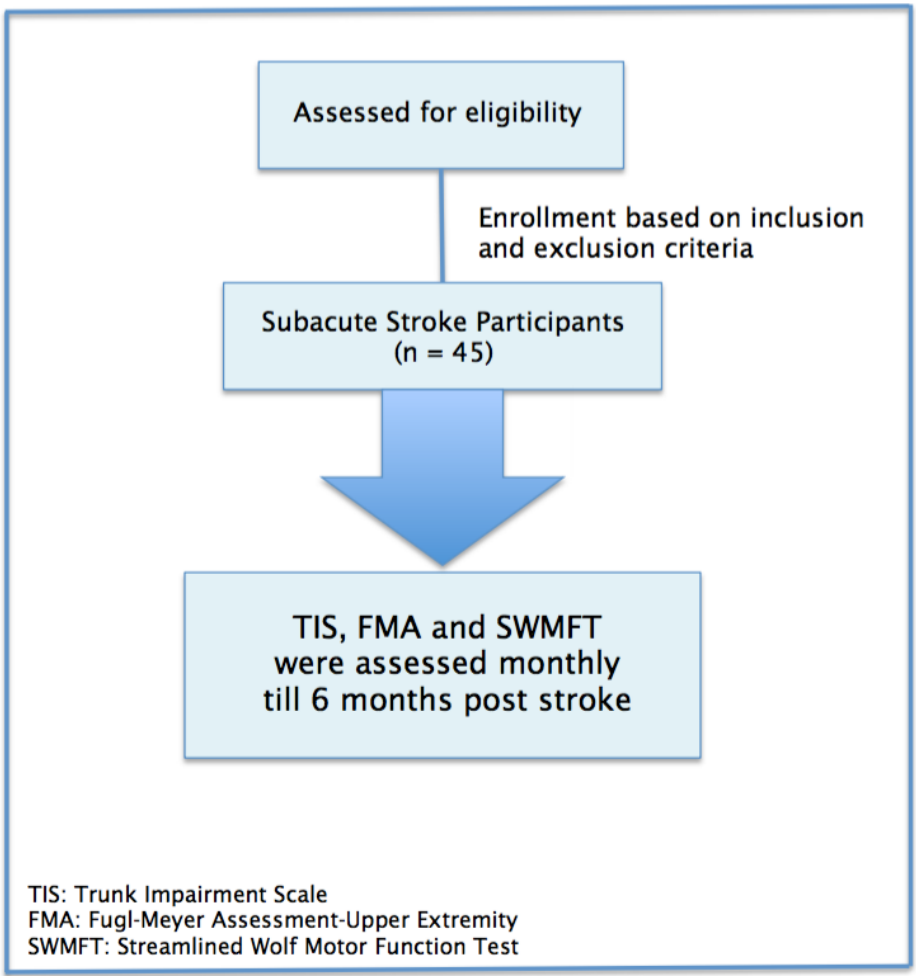


Figure 4-2 Flow diagram of the Phase 2 study

4.3 Sample size calculation

4.3.1 Phase 1 study sample size

Based on the critical review of different outcome measures for upper extremity function in Chapter 3, section 3.3.2, WMFT is assessed by the author (SKW) to be the most appropriate outcome measure for upper extremity function for this doctoral research because it consists of a mixture of easy and difficult test items which will suit stroke patients with various level of upper extremity function. WMFT is an outcome measure with good psychometric properties and good clinical utility (rating of 3 on the StrokEDGE Scoring Matrix) that is appropriate for the subacute and chronic stroke population (Sullivan et al. 2013). Hence, the sample size per group for this study was determined using a power calculation based on the between-group difference for the WMFT performance time.

The mean WMFT for healthy participants has been recorded as 1.20 seconds with a standard deviation of 0.20 seconds (Wolf et al. 2006). The mean WMFT for chronic stroke patients was reported to be 7.05 seconds with a standard deviation of 6.85 seconds (Lin et al. 2009b). It was calculated (using a web-based sample size calculator available on http://www.stat.ubc.ca/~rollin/stats/ssize/n2.html) to detect a difference of 5.85 seconds in the WMFT performance time between groups, 25 participants per group are required to achieve a 85% power in a 2-sided test at 5% significance level. To allow for dropout, it was planned that 35 healthy participants and 35 chronic stroke patients would be recruited for the Phase 1A of study. Forty-five subacute stroke participants would be recruited for the Phase 1B study; the reason being that the same pool of subacute stroke participants would also participate in the Phase 2 study (longitudinal study), and hence this sample size was required (described in greater detail in the next section 4.3.2).

4.3.2 Phase 2 study sample size

Forty-five subacute stroke participants would be recruited for the Phase 2 study. This sample size was determined based on the sample size estimation for longitudinal study design with attrition, as reported by Hedeker et al. (1999), Basagana and Spiegelman (2010) and Basagana et al. (2011). In the Phase 2 study, there were 6 time points of measurement of TIS, SWMFT and upper extremity subsection of the Fugl-Meyer Assessment (FMA) for the participants over a period of 6 months (Figure 4-3). Considering the correlation among the repeated measures ρ=0.5, the attrition rate of 0.05 and medium effect size, a between-groups difference of 0.5 standard deviation at each time point as described by Cohen (1988b), 42 participants are required to achieve a 80% power in a 2-sided 5% test (Hedeker et al. 1999). To allow for further 5% dropout in view of the long period of follow-up of 6 months, it was planned that 45 subacute stroke patients would be recruited for the Phase 2 study.

4.4 Study sites and recruitment process

4.4.1 Phase 1A study

The Phase 1A study was conducted at the Faculty of Health Sciences (Building 45) in the University of Southampton, United Kingdom. Healthy participants were recruited via paper and electronic advertisements (Appendix 9) posted in various faculties of the University. Chronic stroke (>6 months post stroke) participants were screened for eligibility and recruited from the Faculty of Health Sciences' Participant Register and seven local stroke clubs (Southampton, Winchester, Romsey) (Appendix 10) based on the inclusion and exclusion criteria. Section 4.9.2 provides the details with regard to the process of obtaining the informed consent for this study. Refer to the appendices for the invitation letter (Appendix 11), the Participant Information Sheet (PIS) for healthy participants (Appendix 12) and stroke participants (Appendix 13), the participant screening form (Appendix 14 and Appendix 15), reply slip (Appendix 16) and consent form (Appendix 17) for the Phase 1A study.

4.4.2 Phase 1B and Phase 2 studies

In the Phase 1B and Phase 2 studies, all subacute stroke (<6 months post stroke) patients from the inpatient pool at the Rehabilitation Centre of Tan Tock Seng Hospital, Singapore, were screened for medical stability for participation in therapy by the medical doctors. In addition, the doctors would assist the author (SKW) to identify potential participants for the Phase 1B and Phase 2 studies based on the inclusion and exclusion criteria. Once potential participants had been identified, the doctors would mention the study to them and asked if the author could speak to them about the study in greater detail. If they were interested, they could give consent for the doctors to share their name and patient identification number with the author. Upon receiving their names, the author would then approach those patients and discussed with them about the study. They were given one week to discuss with their families, relatives or friends regarding participation. Each potential participant would be provided with an information pack which contains an invitation letter (Appendix 18), the Participant Information Sheet (known as the Informed Consent Form in Singapore) (Appendix 19), reply slip (Appendix 20) and pre-paid envelope. They were reassured that if they decided not to take part or decided later to withdraw from the study, they had no obligation to state their reason(s) and that their current or future healthcare would not be compromised in any way. Section 4.9.2 provides the details and process for obtaining the informed consent for this study.

Another method for recruitment of subacute stroke participants included paper advertisement (Appendix 21) posted on the notice boards and brochure stands in the wards and various clinics within the hospital. Interested participants could contact the author via email or telephone as stated in the paper advertisement. In addition, information packs would be left in the ward and clinics for interested participants to pick up. After receiving the expressions of interest via the reply slip, the author would contact the primary doctor of the participant to verify the medical stability and eligibility for participation in this study, based on the inclusion and exclusion criteria. If the participant was deemed eligible, the author would contact the participant by telephone or email. The telephone communication would offer participants an opportunity to ask any further questions. The author would also perform the initial screening using the participant screening form (Appendix 22) over the

telephone to establish that the inclusion and exclusion criteria were met. If the inclusion and exclusion criteria were met, and the participant agreed to participate, the author would make an appointment with the participant for him/her to attend the first session at the Rehabilitation Centre of Tan Tock Seng Hospital, Singapore.

4.5 Inclusion and exclusion criteria

Inclusion criteria for healthy participants were:

1) aged 18 years or over
2) able to understand the purpose of the study and follow instructions

The following exclusion criteria were set for the healthy participants in view that the presence of neurological or orthopaedic pathology might affect the control and coordination of the trunk and upper extremity movements:

1) history of neurological injury or disease
2) orthopaedic spinal pathology
3) orthopaedic upper extremity pathology

Subacute and chronic stroke participants were recruited if they fulfilled the inclusion criteria:

1) Aged 18 years or over for the Phase 1A study

Aged 21 years or over for the Phase 1B and Phase 2 studies.
Note: The legal age in Singapore is 21 years old. Persons less than 21 years old are considered children and will require additional safeguards (e.g. parental consent) to protect their rights, safety and welfare in research. (www.research.nhg.com.sg/)

2) clinical diagnosis of stroke, as confirmed by computerised tomography scan or functional magnetic resonance imaging

3) (i) between 1 week and 6 months post stroke for subacute stroke participants
   (ii) more than 6 months post stroke for chronic stroke participants

4) able to understand the purpose of the study and follow simple instructions
5) able to sit unsupported for 10 seconds

Exclusion criteria for all stroke participants:

1) Bilateral stroke
2) Brainstem stroke
3) Cerebellar stroke
4) Orthopaedic spinal pathology
5) Orthopaedic upper extremity pathology such as fractures
6) Acute low back pain
7) Severe communication disorders – unable to follow simple instructions
8) Score 0 on the Trunk Impairment Scale (TIS) – unable to sit unsupported for ten seconds (refer to Appendix 23 on TIS)

4.6 Outcome measures

For more details on the selection of outcome measures for the Phase 1 and Phase 2 studies, refer to Chapter 3.

4.6.1 Clinical outcome measures

The participant's trunk and upper extremity function were measured using clinical assessment scales. All the assessments were conducted by the author (SKW) to ensure consistency and standardisation of all assessments in the Phase 1 study and Phase 2 study.

4.6.1.1 Trunk Impairment Scale

The Trunk Impairment Scale (TIS) was used to measure trunk control in the participants (Verheyden et al. 2004) (Appendix 23). The TIS consists of three subscales which assess static sitting balance, dynamic sitting balance, and

trunk coordination on a scale ranging from 0 to 23 points. A higher score indicates better trunk control.

The TIS has no ceiling effect for the subacute and chronic stroke population (Verheyden et al. 2006). Adequate psychometric properties for the TIS in stroke patients have been reported by Verheyden et al. (2004). Verheyden et al. (2005) found that the TIS had the ability to discriminate between stroke patients and healthy individuals. A TIS score of 20 was in the 90th percentile for the stroke patients and in the 10th percentile for the healthy individuals. Based on these findings plus the clinical experience of the author (SKW), it was decided by the author to classify the severity of trunk impairment based on the following cut-off points: TIS score less than 10 as severe trunk impairment; TIS score 11 to 19 as moderate trunk impairment; and TIS score 20 to 23 as mild trunk impairment. In other words, mild, moderate and severe trunk impairment level would imply that participants have good, fair and poor trunk control respectively.

4.6.1.2 Fugl-Meyer Assessment of upper extremity

Post stroke upper extremity motor impairment was measured with the upper extremity subsection of the Fugl-Meyer Assessment (FMA) (Page et al. 2012a) (Appendix 24). Each of the 33 items of FMA was rated on a 3-point scale. The maximum score is 66 points. Participants with FMA score of 0 to 20; 21 to 50; and 51 to 66 were classified as having severe, moderate and mild upper extremity impairment respectively (Velozo & Woodbury 2011).

FMA is widely used in stroke research and has been regarded as the gold standard for measurement of UE impairment (Gladstone et al. 2002; Baker et al. 2011), with well-established psychometric properties (Fugl-Meyer et al. 1975; Duncan et al. 1983; Gladstone et al. 2002; Deakin et al. 2003; Woodbury et al. 2007; Hsieh et al. 2009; Sullivan et al. 2011; Page et al. 2012b; See et al. 2013). In addition, FMA demonstrates a longitudinally stable item difficulty order and is valid for measuring volitional arm motor ability over time (Woodbury et al. 2008). Hence, FMA would be an appropriate outcome

measure for the Phase 2 study, which is a longitudinal study.

FMA can be subdivided into FMA-Shoulder-Elbow subscale (FMA-SE) (Kung et al. 2012; Rundquist et al. 2012) and FMA-Wrist-Hand subscale (FMA-WH) (Page et al. 2012b; Page et al. 2015; Persch et al. 2015; Schulz et al. 2015). The total score for FMA-SE and FMA-WH subscales are 42 and 24 respectively. Analyzing FMA-SE and FMA-WH would provide deeper insights into the recovery of the proximal and distal segments of the upper extremity in the Phase 2 study.

4.6.1.3 Streamlined Wolf Motor Function Test

Post stroke upper extremity motor function was measured with the Streamlined Wolf Motor Function Test (SWMFT) (Bogard et al. 2009). This is a shortened version of the 17-item Wolf Motor Function Test (WMFT) (Wolf et al. 2005), which requires a shorter period of time to administer. The SWMFT has well-established psychometric properties (Wu et al. 2011; Chen et al. 2012). It exhibits comparable responsiveness to WMFT and improved clinical utility (Wu et al. 2011).

For the present studies (Phase 1 and Phase 2), the 8 tasks of SWMFT that were appropriate for subacute and chronic stroke participants included hand to table (front), hand to box (front), reach and retrieve, lift can, lift pencil, fold towel, extend elbow (1-lb weight), and turn key in lock (Appendix 8) (Chen et al. 2014). During performance of the tasks of SWMFT, a stopwatch was used to measure the time taken to complete the tasks. The maximum performance time allowed for the completion of each task was 120 seconds. A time score of 120+ seconds would be assigned to tasks that could not be performed by the participants. The outcome measure would be the mean performance time of the tasks (SWMFT-Time). Normative data for WMFT was reported by Wolf et al. (2006), which can be used to compare and interpret participants' SWMFT-Time (Appendix 25). In addition, there was a 6-point Functional Ability Scale (SWMFT-FAS) that was used to rate the quality of movement during performance of the tasks. SWMFT-FAS has values ranging from 0 (no attempt made to use the more affected upper extremity) to 5 (movement appears to be normal) (Chen et al. 2012).

4.6.2 Kinematic analysis

Kinematic analysis is recognized as a valid, sensitive and objective method for capturing and quantifying improvements in upper extremity impairment and function (Hingtgen et al. 2006; Subramanian et al. 2010; Patterson et al. 2011; Alt Murphy et al. 2013; van Dokkum et al. 2014), trunk control (Messier et al. 2006; Thielman 2013), and scapular movements post stroke (Meskers et al. 2005; Niessen et al. 2008; Niessen et al. 2009; Hardwick & Lang 2011b). Analysis at the kinematic level will enable differentiation between functional gains achieved through compensation versus those achieved through true recovery of motor control (Subramanian et al. 2010; Alt Murphy et al. 2013; Kitago et al. 2013).

The kinematic analysis of trunk, upper extremity and scapular movements during the TIS assessment and task performance during SWMFT were evaluated by the 12-camera motion analysis system (VICON MX T-series; Vicon Motion Systems, Oxford, UK), with a sampling frequency of 100Hz.

The ability for the upper extremity to reach and grasp is required for over 50% of ADL tasks (van der Putten et al. 1999; Ingram et al. 2008). The ‘lift can’ task was chosen for in-depth analysis and discussion because it involves the complex phases of reaching, grasping, lifting up the can close to mouth (simulating an attempt to drink), followed by the return transport phase of putting the can back on the table and ending with the upper extremity returning to the lap. Hence, the ‘lift can’ task provides a good overview of the upper extremity functional ability of the participants. This is supported by Bogard et al. (2009), stating that upper extremity improvement represented by the overall WMFT may best be indicated by the ‘lift can’ task.

The ‘lift can’ task would be analysed and discussed in greater depth for the purpose of this PhD thesis.

To enable kinematic data of the ‘lift can’ task to be analysed in detail, the task was broken down into 4 phases (Table 4-1). Refer to Appendix 26 for the task breakdown of the 8 SWMFT tasks and the parameters used to identify the beginning and end of each phase of tasks. Figure 4-3 shows the events 1 to 5

during the 'lift can' task. Event 1 occurs when the hand leaves the lap; event 2 occurs when hand grasps the can and prepares to lift it; event 3 occurs when the can is lifted to mouth; event 4 occurs when the can is brought back down to table; and event 5 occurs when the hand is returned to the lap.

Kinematic variables captured for analysis included the following:

i) movement duration (seconds): from event 1 to 3

ii) movement smoothness (number of velocity peaks in the ulnar styloid velocity profile): from event 1 to 2

iii) movement straightness (path-line ratio): from event 1 to 2

iv) maximum ulnar styloid velocity: from event 1 to 2

v) average ulnar styloid velocity: from event 1 to 3

vi) range of motion (ROM) of trunk flexion (expressed in degrees of anterior-posterior rotation): from event 1 to 2

vii) ROM of trunk lateral flexion (expressed in degrees of lateral rotation): from event 1 to 2

viii) ROM of trunk rotation (expressed in degrees of axial rotation): from event 1 to 2

ix) ROM of scapular internal rotation (expressed in degrees of internal-external rotation): from event 1 to 2

x) ROM of scapular upward rotation (expressed in degrees of upward-downward rotation): from event 1 to 2

xi)) ROM of scapular posterior tilt (expressed in degrees of anterior-posterior tilt: from event 1 to 2

xii) ROM of shoulder flexion (expressed in degrees): from event 1 to 2

xiii) ROM of elbow extension (expressed in degrees): from event 1 to 2

Table 4-1 Phases of 'lift can' task

Task	Start	Detected by	End	Detected by
'Lift can' task				
i) Reaching (includes grasping)	Hand leaves the lap	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand begins to move the can towards the mouth	Can and ulnar styloid markers move simultaneously: Displacement between the can marker and ulnar styloid marker is constant
ii) Forward transport (bring can to mouth)	Hand begins to move the can towards the mouth	Can and ulnar styloid markers move simultaneously: Displacement between the can marker and ulnar styloid marker is constant	The can is brought close to mouth, without touching lips	Displacement between the can marker and sternal notch (IJ) thorax marker reaches its minimum point
iii) Back transport	Hand begins to move to put the can back to table	Displacement between the can marker and IJ marker increases from the minimum point	Hand releases the can and begins to move back to initial position	Displacement between the can marker and ulnar styloid marker increases beyond 2% of the distance observed whilst the can is grasped
iv) Return hand to initial position	Hand releases the can and begins to move back to initial position	Displacement between the can marker and ulnar styloid marker increases beyond 2% of the distance observed whilst the can is grasped	Hand back on the lap	Ulnar styloid marker velocity returns to 2% of the peak velocity

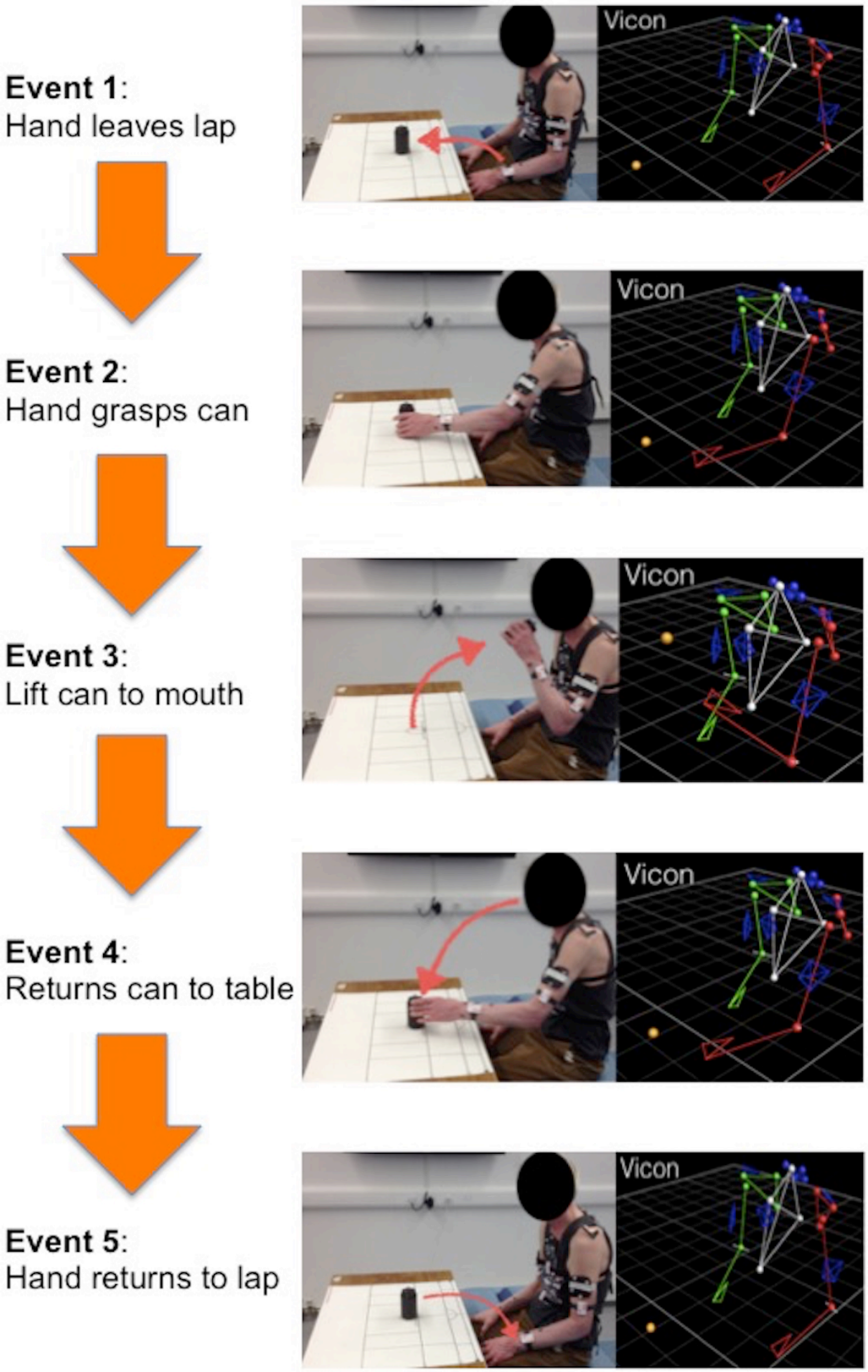


Figure 4-3 Events 1 to 5 of the 'lift can' task

Movement duration was the time taken for the hand to lift up can to the mouth. Movement smoothness was determined by the number of peaks in the ulnar styloid velocity profile during the task. Movement straightness was determined by the path-line ratio. This refers to the ratio of the path length taken by the ulnar styloid marker, to a straight line, as determined by the straight line from ulnar styloid to the final end position of the ulnar styloid prior to picking up the can.

If a participant could not open their hand to grasp the can and lift to their mouth, kinematic data on movement duration and average ulnar styloid velocity could not be computed and were excluded from data analysis. This is because no data were available from event 2 to 3 (lift can to mouth). However, data of all the other kinematic variables (all joint angles, movement smoothness, movement straightness, maximum ulnar styloid velocity) of that participant could be processed and used for analysis.

4.7 Experimental procedure

4.7.1 Phase 1A and Phase 1B studies

All experimental procedures and equipment used were exactly similar for the Phase 1A and Phase 1B studies. Kinematic data capture was only conducted in the Phase 1A study due to availability of the Vicon motion capture system at the University of Southampton. Unfortunately, no motion capture system was available for the Phase 1B study.

The participant was instructed to wear a loose fitting sleeveless T-shirt for the assessments of trunk control and upper extremity function in the research laboratory. He/she was instructed to inform the author when he/she felt tired or experience pain in the upper extremity or the trunk. Rest breaks were allowed in between the assessments. The author conducted all assessments of TIS, FMA, SWMFT-Time and SWMFT-FAS to ensure standardisation in the administration of assessments.

4.7.1.1 Initial assessment

The participant sat unsupported on a height-adjustable plinth with the hips, knees, and ankles at 90 degrees as the starting position. Assessment of the upper extremity impairment was conducted using FMA.

4.7.1.2 Reflective marker positioning

Following FMA assessment, the reflective technical marker sets were placed on the participant's trunk and upper extremity: acromion and scapular spine (Warner et al. 2012; Warner et al. 2015), sternum (Wu et al. 2002), and lateral aspect of humerus (Wu et al. 2005). The "boomerang" shaped technical marker on the acromion is known as the acromion marker cluster (AMC) (Figure 4-4). The AMC is a valid and reliable measurement technique for determining scapular kinematics and it provides continuous data throughout movement, enabling a more comprehensive evaluation of scapular kinematics quasi-static measurements using palpation techniques, and does not require intervention from the investigator during recordings (Warner et al. 2012; Warner et al. 2015). The center of the AMC was placed on the flat portion of the acromion with one section of the AMC pointing anterior to the scapular plane, and the other following the spine of the scapula.

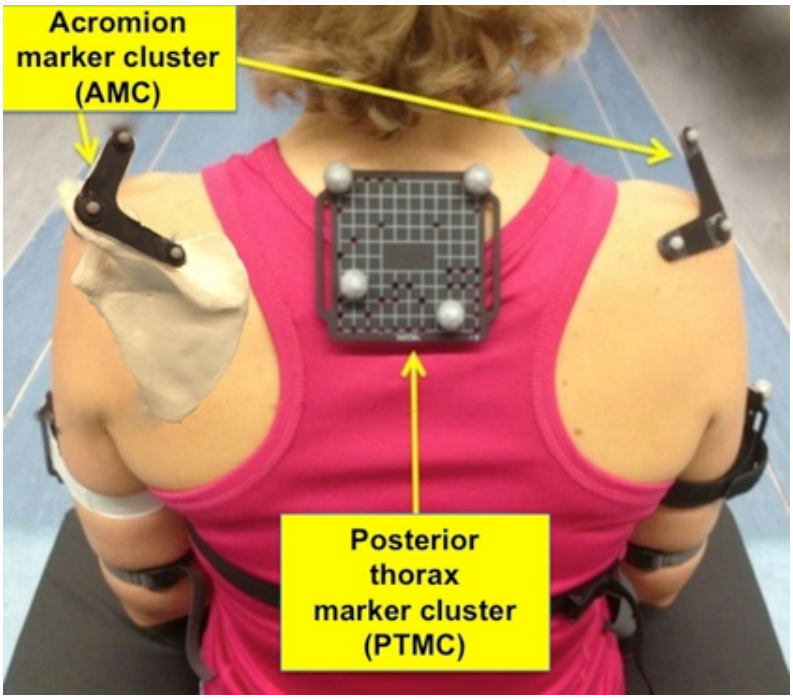


Figure 4-4 Placement of the acromion marker cluster (AMC) and posterior thorax marker cluster (PTMC)

The posterior thorax marker cluster (PTMC) was placed directly below the C7 vertebra spinous process (Figure 4-4). The technical marker on the sternum is known as the sternum marker cluster (SMC). It provides data related to trunk movements (flexion-extension, lateral flexion and rotation) in all three axes. The SMC was placed directly below the suprasternal notch (Figure 4-5). The other technical markers on the humerus are known as the humerus marker clusters (HMC). The HMC provides data related to shoulder flexion-extension, abduction-adduction and lateral-medial rotation, and was placed on the lateral aspect of the mid-humeral shaft (Figure 4-5).

Other reflective markers were placed at the radial styloid (RS), ulnar styloid (US) and along the radial shaft (5cm proximal to the marker on radial styloid) (Figure 4-5). They provide data related to elbow flexion-extension and forearm pronation-supination.

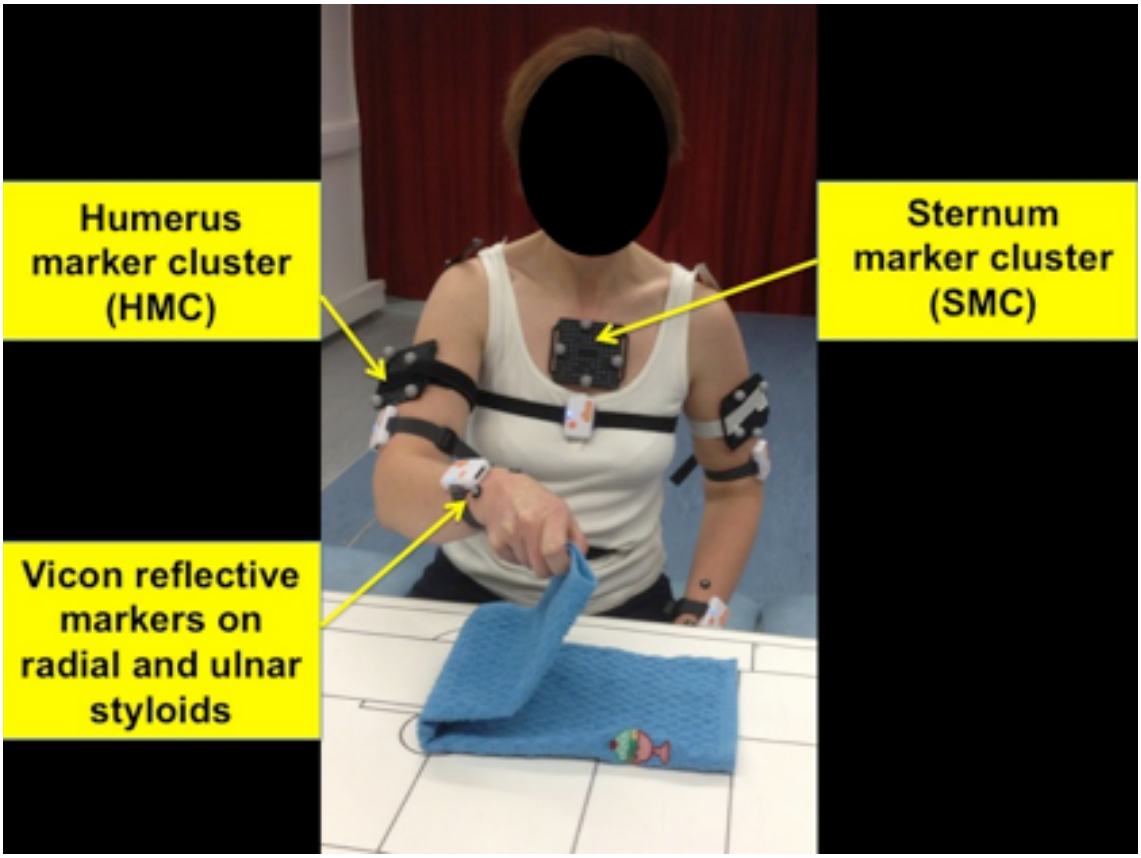


Figure 4-5 Placement of the sternum marker cluster (SMC), humerus marker cluster (HMC) and reflective markers on radial and ulnar styloids

4.7.1.3 Anatomical landmark calibration

Following the attachment of reflective markers, the next step was the anatomical calibration procedure before the Vicon system could capture and process the kinematic data of the trunk and bilateral upper extremity during movement. The tip of a calibration wand (with four reflective markers) (Figure 4-6) was placed at the following anatomical landmarks in a sequential order, based on the standards set by the International Society of Biomechanics (Wu et al. 2005):

1) suprasternal notch (Incisura Jugularis: IJ)

2) xiphoid process (Processus Xiphoideus: PX)

3) 7th cervical vertebra (C7)

4) 8th thoracic vertebra (T8)

5) acromion angle (Angulus Acromialis: AA)

6) medial aspect of scapular spine (Trigonum Spinae Scapulae: TS)

7) inferior angle of scapula (Angulus Inferior: AI)

8) medial epicondyle of humerus (EM)

9) lateral epicondyle of humerus (EL)

The final part of the calibration procedure involved passively moving the upper extremity (in 30 degrees shoulder abduction and elbow fully extended) in a clockwise direction (30 seconds) by the author. The purpose of this procedure was to capture data to determine the glenohumeral (GH) rotation centre; estimated by calculating the pivot point of instantaneous helical axes from abduction, anterior flexion and rotation of the humerus with respect to the thorax using MATLAB (The MathWorks Inc) software (Veeger 2000; van Andel et al. 2008).

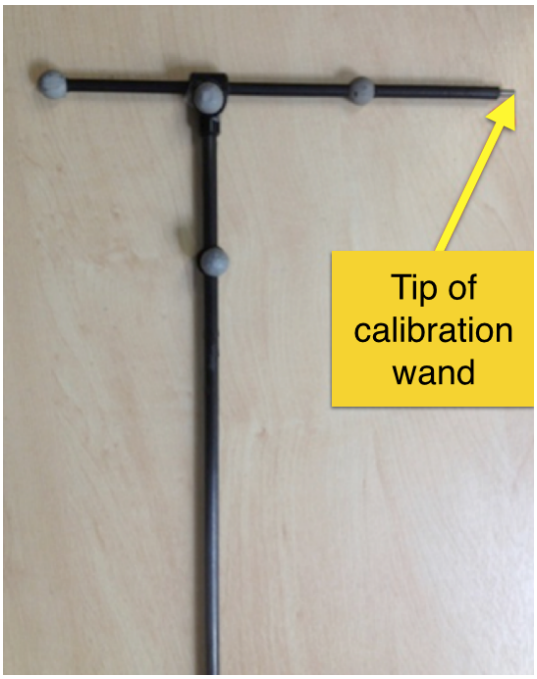


Figure 4-6 Calibration wand of the Vicon motion capture system

4.7.1.4 Clinical assessment

After the calibration procedure, the assessment of trunk control was conducted using TIS; once whilst the participant was seated with no support around the trunk, and once with a high-density foam support around the trunk. Different sizes of the trunk support and accessories were available to suit the body contour and size of the participants (Figure 4-7). The trunk support fitted snugly at the posterior and lateral aspects of the trunk, up to the level of lower thoracic region (between the 10th and 12th thoracic vertebrae). It supported the trunk whilst allowing movement. Thus, the trunk support was not restrictive in nature.

Figure 4-7 Trunk support

The SWMFT-Time and SWMFT-FAS were assessed following TIS assessment. The participant was instructed to perform each SWMFT task as quickly as possible and the performance time was captured with a stopwatch. For the healthy participant, he/she first performed the eight SWMFT tasks with the non-dominant upper extremity, and followed by the dominant upper extremity. Hand dominance was determined by the Edinburgh Handedness Inventory–Short Form (Veale 2014). For the stroke participant, he/she performed the tasks with the less affected upper extremity, followed by the affected upper extremity. Similarly, the assessments would be performed twice, once with no trunk support and once with the trunk support. The order of testing with and without the trunk support was randomized using blocked randomization (Efird 2011), with a block size of four, to avoid possible order bias due to practice or fatigue, while ensuring equal numbers in each order-protocol.

4.7.1.5 Kinematic assessment

During the TIS assessment and task performance of SWMFT, kinematic data were captured by the Vicon system.

4.7.1.6 Kinematic data processing

The kinematic data were transferred to MATLAB (The MathWorks Inc) software for custom-made analysis via the 'PECS' plug-in from Nexus 1.8.5. The 'PECS' plug-in allows the running of MATLAB scripts from within the Nexus environment, removing the need for exporting and importing data between software. The data were filtered with a 10-Hz low pass fourth-order Butterworth filter in both forward and reverse directions resulting in zero-phase distortion.

The bony landmarks incisura jugularis (IJ), processus xiphoideus (PX), 7th cervical vertebra (C7), 8th thoracic vertebra (T8), angulus acromialis (AA), trigonum spinae scapulae (TS), angulus inferior (AI), medial epicondyle (EM), lateral epicondyle (EL), glenohumeral (GH) rotation centre, radial styloid (RS) and ulnar styloid (US) were used to construct local anatomical coordinate systems.

The following sections 4.7.1.6.1 to 4.7.1.6.4 detail the coordinate systems of the thorax, scapula, humerus and forearm.

4.7.1.6.1 Thorax coordinate system

The thorax coordinate system (TCS) was constructed from the reflective markers IJ, PX, C7 and T8 (Figures 4-8, 4-9 and 4-10). Based on the International Society of Biomechanics standardization proposal for the upper extremity (Wu et al. 2005), the origin of TCS, X_t-, Y_t- and Z_t-axis are defined as follows (Figures 4-8, 4-9 and 4-10):

O_t: The origin coincident with IJ

Y_t: The line connecting the midpoint between PX and T8 and the midpoint between IJ and C7, pointing upward

Z_t: The line perpendicular to the plane formed by IJ, C7, and the midpoint between PX and T8, pointing to the left

X_t: The common line perpendicular to the Z_t- and Y_t-axis, pointing forwards

With the TCS, kinematic data of trunk flexion/extension (around Z_t-axis; Figure 4-8), trunk rotation (around Y_t-axis; Figure 4-9) and trunk lateral flexion (around X_t-axis; Figure 4-10) could be processed accordingly.

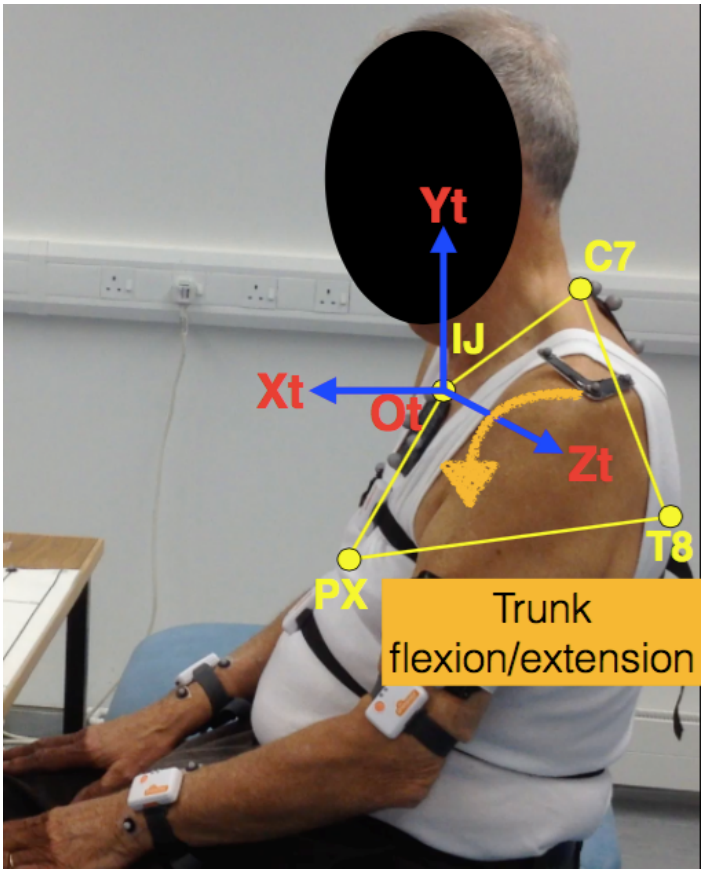


Figure 4-8 Trunk flexion/extension around the Z_t-axis

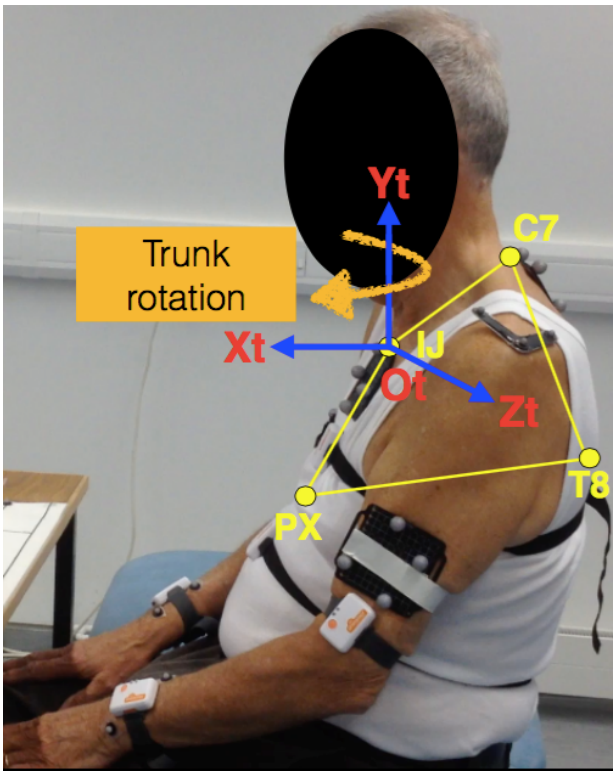


Figure 4-9 Trunk rotation around the Y_t-axis

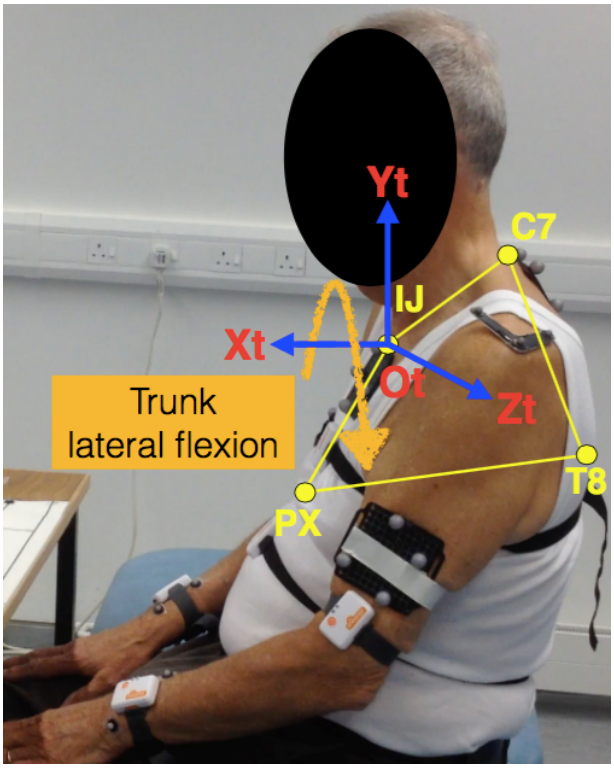


Figure 4-10 Trunk lateral flexion around the X_t-axis

4.7.1.6.2 Scapula coordinate system

The scapula coordinate system (SCS) was constructed from the reflective markers AI, AA, and TS (Figures 4-11, 4-12 and 4-13). Based on the International Society of Biomechanics standardization proposal for the upper extremity (Wu et al. 2005), the origin of SCS, X_S-, Y_S- and Z_S-axis are defined as follows (Figures 4-11, 4-12 and 4-13):

O_S: The origin coincident with AA

Z_S: The line connecting TS and AA, pointing to AA

X_S: The line perpendicular to the plane formed by AI, AA and TS, pointing forward

Y_S: The common line perpendicular to the X_S- and Z_S-axis, pointing upward

With the SCS, kinematic data of scapular internal/external rotation (around Y_S-axis; Figure 4-11), scapular upward/downward rotation (around X_S-axis; Figure 4-12) and scapular anterior/posterior tilt (around Z_S-axis; Figure 4-13) could be processed accordingly.

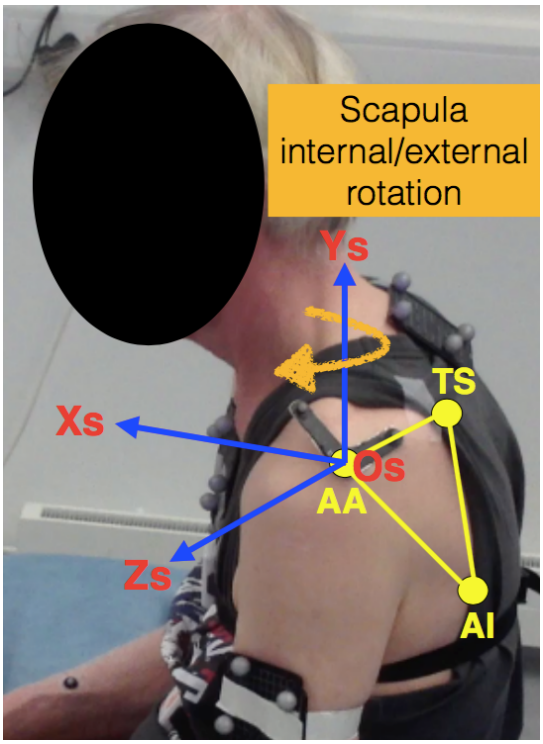


Figure 4-11 Scapular internal/external rotation around Y_S-axis

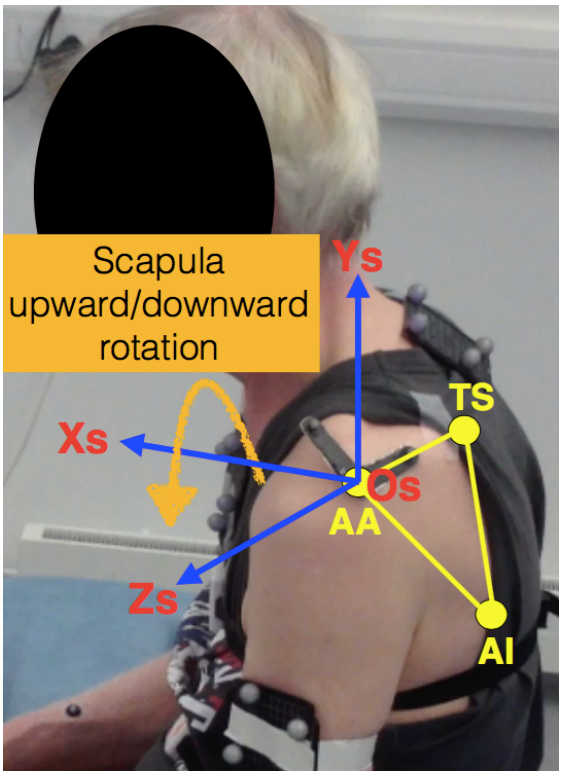


Figure 4-12 Scapular upward/downward rotation around X_s-axis

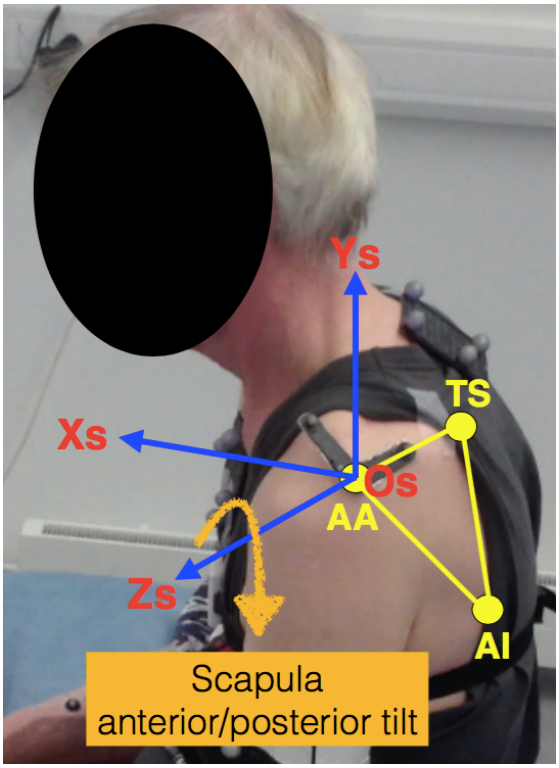


Figure 4-13 Scapular anterior/posterior tilt around the Z_s-axis

4.7.1.6.3 Humerus coordinate system

The humerus coordinate system (HCS) was constructed from anatomical landmarks EL, EM and GH (Figures 4-14). Based on the International Society of Biomechanics standardization proposal for the upper extremity, the second option of humerus coordinate system was chosen for this doctoral study instead of the first option due to possible skin movement artifact from the humerus marker cluster and the high error sensitivity of the direction connecting EL and EM due to the short distance between them (Wu et al. 2005).

The origin of HCS, X_h-, Y_h- and Z_h-axis are defined as follows (Figures 4-14):

O_h: The origin coincident with glenohumeral joint (GH)

Y_h: The line connecting GH and the midpoint of EL and EM, pointing to GH

Z_h: The line perpendicular to the plane formed by Y_h and Y_f (see section 4.7.1.6.4 on forearm coordinate system), pointing to the right

X_h: The common line perpendicular to the Z_h- and Y_h-axis, pointing forward

With the HCS, kinematic data of shoulder flexion (around Z_h-axis; Figure 4-14), could be processed accordingly.

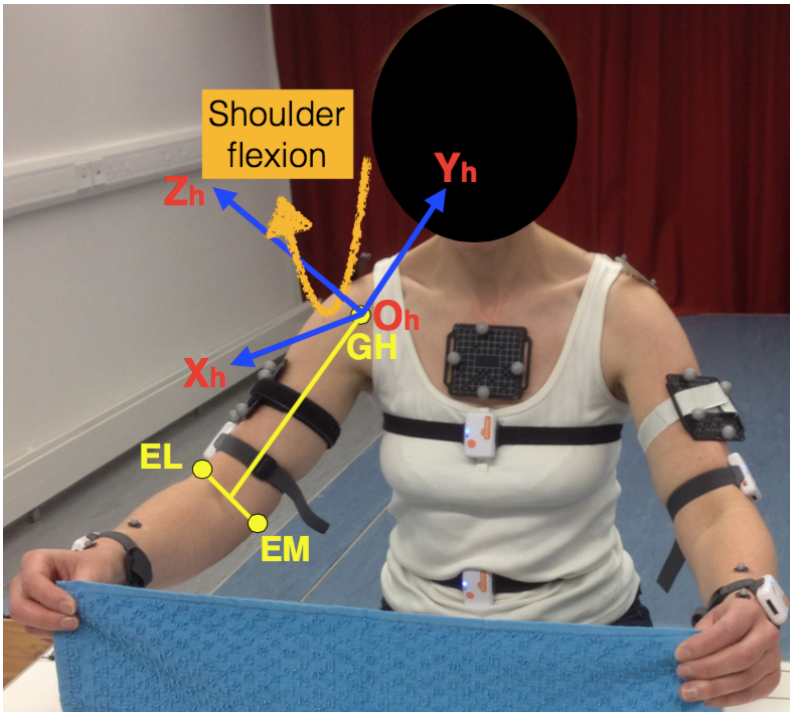


Figure 4-14 Shoulder flexion around the Z_h-axis

4.7.1.6.4 Forearm coordinate system

The forearm coordinate system (FCS) was constructed from anatomical landmarks EL, EM, US and RS (Figures 4-15). Based on the International Society of Biomechanics standardization proposal for the upper extremity (Wu et al. 2005), the origin of FCS, X_f-, Y_f- and Z_f-axis are defined as follows (Figures 4-15):

O_f: The origin coincident with US

Y_f: The line connecting US and the midpoint between EL and EM, pointing proximally

X_f: The line perpendicular to the plane through US, RS, and the midpoint between EL and EM, pointing forward

Z_f: The common line perpendicular to the X_f- and Y_f-axis, pointing to the right

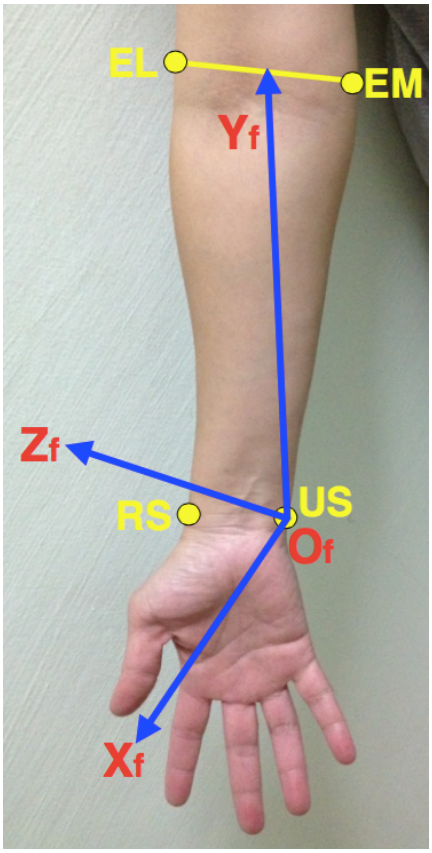


Figure 4-15 Forearm coordinate system

The axis of rotation for the elbow joint (Z_e-axis) is assumed to be parallel to the Z_h-axis of the humerus (Wu et al. 2005; Cutti et al. 2008) (Figure 4-16).

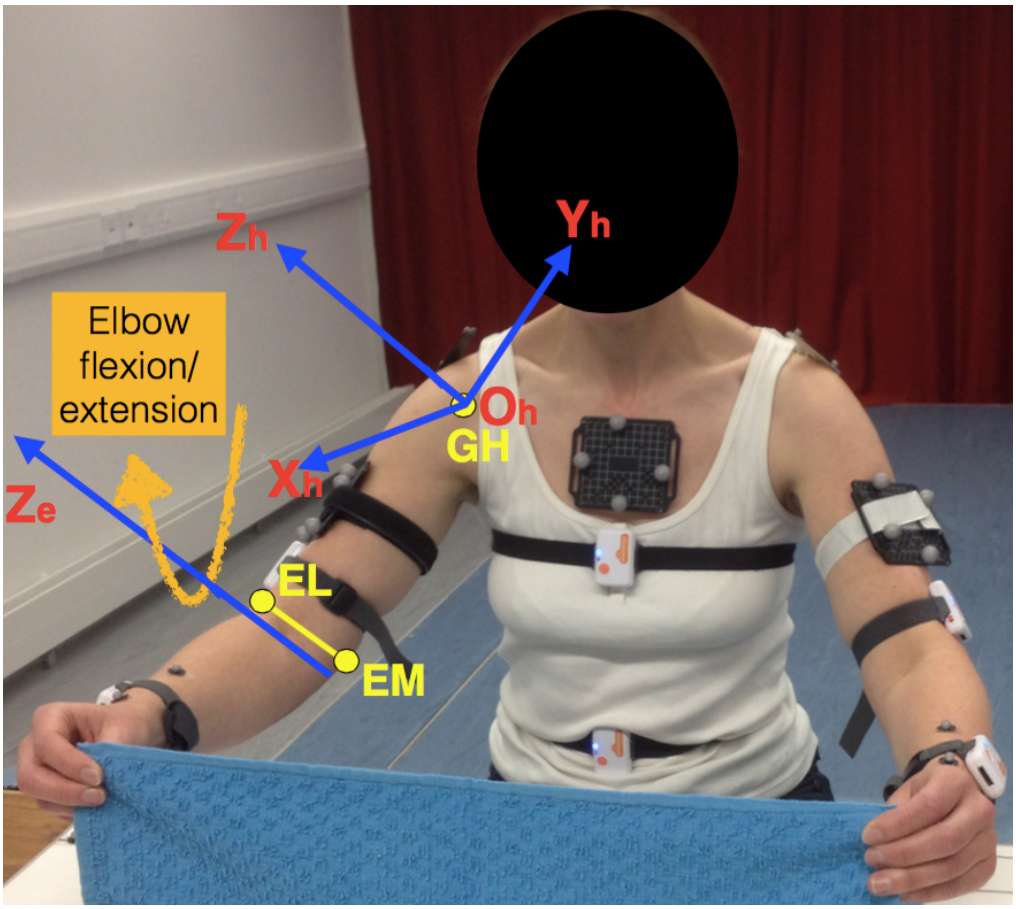


Figure 4-16 Elbow flexion/extension around the Z_e-axis

4.7.1.6.5 Euler angle rotation sequence

A common method for describing three-dimensional joint motion is with the use of Euler angles, which represent three sequential rotations about anatomical axes (Karduna et al. 2000). However, for any given motion, different rotational sequences can result in different angle calculations (Lee et al. 2015a; McCrimmon et al. 2015). Hence, for interpretation of kinematic data, appropriate sequences of Euler angles must be defined to express the relative orientation of coordinate systems in a clinically meaningful manner (Kontaxis et al. 2009).

In this doctoral study, the Euler angle rotation sequences for the thorax, scapula, humerus and elbow are defined as follows:

i) thorax (relative to the global coordinate system): Z_t-X_t-Y_t order (Wu et al. 2005)
ii) scapula (relative to the thorax): Y_s-X_s-Z_s order (Wu et al. 2005)
iii) humerus (relative to the thorax): Z_h-X_h-Y_h order (Kontaxis et al. 2009)
iv) elbow joint (forearm relative to the humerus): Z_f-X_f-Y_f order (Wu et al. 2005)

In summary, the thorax, scapula, humerus and forearm coordinate systems (sections 4.7.1.6.1 to 4.7.1.6.4), and the Euler angle rotation sequences enable the calculation of the trunk, scapula, shoulder and elbow joint angles.

4.7.2 Phase 2 study

The Phase 2 study a longitudinal study conducted with subacute stroke participants. The TIS, FMA and S-WMFT were assessed for each participants once a month for a period of 6 months. The participants were offered a choice of having the follow-up assessments at the Rehabilitation Centre of Tan Tock Seng Hospital or in their own home. This strategy was utilised to minimise the dropout rate of the longitudinal study. All assessments were conducted by the author (SKW) to ensure standardisation in the administration of assessments. In addition, all equipment (wooden stools, height-adjustable table, SWMFT equipment and assessment chart template) were the same set used in both the Rehabilitation Centre and the participant's home to ensure that the administration of the TIS, FMA and SWMFT were standardised throughout the 6 months follow-up.

The Phase 2 study charts the recovery curve of the trunk and upper extremity for the subacute stroke participants, without controlling for the types of therapy that they had received over the 6-month period. There was a therapy log (designed by the author) (Appendix 27) for each participant to record the nature, intensity and frequency of therapy received for the upper extremity. The therapy log would be reviewed and the effect of the duration of therapy on the recovery of the trunk and upper extremity would be analysed.

4.8 Statistical analysis

Data analysis was performed using the IBM SPSS Statistics 22 software. The level of statistical significance was set at $p < 0.05$ for all tests.

4.8.1 Checking for assumption of a normal distribution

All data were tested for normal distribution using the Shapiro-Wilk tests. Parametric tests were applied if data were normally distributed. Otherwise, non-parametric tests would be used for analysis.

4.8.2 Descriptive statistics

The demographic and clinical characteristics of participants would be presented as means, standard deviations and ranges if the data were normally distributed. However, if the data were not normally distributed, the value of the median and interquartile range would be presented.

4.8.3 Statistical analysis for Phase 1A study and Phase 1B study

4.8.3.1 Is there any change in trunk control and upper extremity function when the trunk is stabilised with a trunk support?

To evaluate whether there was any change in trunk control and upper extremity function when the trunk was stabilised with an external trunk support, the TIS, SWMFT-Time and SWMFT-FAS scores with and without trunk support would be compared using the paired t-test or Wilcoxon signed rank test, depending on the normality of data distribution. In addition, the kinematics variables of participants captured by the Vicon motion capture system, with and without trunk support, would be analysed using a paired t-test or Wilcoxon test, depending on whether the kinematic data were parametric or non-parametric. This would inform about any change in the kinematic of the trunk, scapula, shoulder and elbow with the use of trunk support.

4.8.3.2 Relationship between trunk control and upper extremity impairment and function

To evaluate whether there was a relationship between i) trunk control and upper extremity impairment, and ii) trunk control and upper extremity function in subacute and chronic stroke participants, the following correlation coefficients were determined by the Pearson correlation coefficient or Spearman's correlation coefficient, depending on the normality of data distribution:
i) between TIS and FMA;
ii) between TIS and SWMFT-Time; and
iii) between TIS and SWMFT-FAS.

The correlation coefficient would give an indication of the strength of the relationship.

4.8.3.3 Relationship between trunk control and kinematics of the trunk, scapula, shoulder and elbow during 'lift can' task

To evaluate the relationship between trunk control (TIS) and the kinematics of the trunk, scapula, shoulder and elbow during 'lift can' task, the Pearson correlation coefficient or Spearman's correlation coefficient would be calculated to determine the strength of the relationship between TIS and kinematics data, depending on the normality of the data distribution.

4.8.4 Main effect of group and support condition; and interaction effect between group and support condition

In view of the comparison between 3 groups (subacute stroke, chronic stroke and healthy groups) under two support conditions (with and without trunk support), the split plot analysis of variance (SPANOVA) would be used to analyse the results of TIS, SWMFT-Time and kinematic variables as they are interval variables.

4.8.4.1 TIS outcome

Analysis would be conducted for the following:

(i) to compare the TIS scores between the healthy group, subacute and chronic stroke groups, regardless of the support conditions (main effect of group);

(ii) to compare the TIS scores between the two support conditions (with and without trunk support), regardless of the groups that participants were in (main effect of support);

(iii) to compare the TIS scores between the healthy group, subacute and chronic stroke groups according to the support conditions (interaction effect between group and support condition).

4.8.4.2 SWMFT-Time outcome

The SWMFT-Time of the non-dominant upper extremity of healthy participants would be used to compare with the affected upper extremity of stroke participants. This will put the stroke participants with hemiparesis in the non-dominant arm at less of a comparative disadvantage, as recommended by Alt Murphy et al. (2011).

Analysis would be conducted for the following:

(i) to compare the SWMFT-Time between the healthy group, subacute and chronic stroke groups, regardless of the support conditions (main effect of group);

(ii) to compare the SWMFT-Time between the two support conditions (with and without trunk support), regardless of the groups that participants were in (main effect of support);

(iii) to compare the SWMFT-Time between the healthy group, subacute and chronic stroke groups according to the support conditions (interaction effect between group and support condition).

4.8.4.3 SWMFT-FAS outcome

As the SWMFT-FAS is an ordinal variable, the Wilcoxon signed rank test would be used for the following analysis:

(i) to compare the SWMFT-FAS of the healthy participants under the test conditions, with and without trunk support;

(ii) to compare the SWMFT-FAS of the chronic stroke participants under the test conditions, with and without trunk support;

(ii) to compare the SWMFT-FAS of the subacute stroke participants under the test conditions, with and without trunk support.

The Kruskal–Wallis *H* test was used to compare the SWMFT-FAS between the healthy group, subacute stroke and chronic stroke groups. Subsequently, the Mann–Whitney *U* test was conducted as post hoc test to determine whether there was significance difference between subacute stroke participants and healthy participants; between chronic stroke participants and healthy participants; and between subacute stroke participants and chronic stroke participants.

4.8.4.4 Kinematic outcome

Kinematic data were captured only for the healthy and chronic stroke participants in the Phase 1A study. The SPANOVA would be used to analyse the results of all kinematic variables as they are interval variables.

Analysis would be conducted for the following:

(i) to compare the kinematic variables between the healthy group and chronic stroke group, regardless of the support conditions (main effect of group);

(ii) to compare the kinematic variables between the two support conditions (with and without trunk support), regardless of the groups that participants were in (main effect of support);

(iii) to compare the kinematic variables between the healthy group and chronic stroke group according to the support conditions (interaction effect between group and support condition).

4.8.5 Statistical analysis for Phase 2 study

An advanced statistical technique known as individual growth curve (IGC) modelling would be utilised for the analysis of longitudinal data from the Phase 2B study. The IGC modelling technique enables modelling intra-individual systematic change and inter-individual differences in outcomes across different measurement waves over time (Singer & Willett 2003; Shek & Ma 2011; Kozlowski et al. 2013; Hart et al. 2014). The recovery curve for TIS, FMA, SWMFT-Time and SWMFT-FAS would be plotted per participant and the best fit of curve would be determined. The gradient of the slope of the recovery curve would inform about the rate of recovery for each variable. The following statistical analysis would be carried out:

1) Determination of the recovery pattern of TIS, FMA, SWMFT-Time and SWMFT-FAS over the first 6 months post stroke. This would provide valuable information about recovery of trunk control and upper extremity post stroke and aid clinicians in prognostication of outcome and aid in designing of targeted rehabilitation to optimise outcomes.

2) Comparison of the rate of recovery of trunk control (TIS) and the rate of recovery of upper extremity impairment (FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS). This would inform about the relationship between trunk control and recovery of upper extremity function in the subacute stroke patients, which is the overarching aim of this doctoral research.

4.9 Ethical considerations

4.9.1 Ethics approval

For the Phase 1A study, ethics approval was sought from the Faculty of Health Sciences Ethics Committee of the University of Southampton (Ethics number: 7547) (Appendix 28). Ethics approval for the Phase 1B study and Phase 2 study were sought from both the Faculty of Health Sciences Ethics Committee of the University of Southampton (Ethics number: 10647) (Appendix 29) and the Institutional Review Board of National Healthcare Group (NHG) of Singapore (Ethics number: 2014/00229) (Appendix 30).

Phase 1B and Phase 2 studies commenced after ethical approval letters were issued and insurance coverage were approved by the University of Southampton and Tan Tock Seng Hospital of Singapore.

4.9.2 Informed consent

All potential and willing participants were given a full explanation of the research aims and objectives by the author. In addition, the author provided each participant with an information pack that contained an invitation letter (Appendix 11 and Appendix 18), the PIS (Appendix 12, Appendix 13 and Appendix 19), reply slip (Appendix 16 and Appendix 20) and a pre-paid envelope. The PIS details the nature of the research in layperson's language. Any potential risks involved in the study were explained. The rights of the participant to withdraw from the research at any time without compromising their care were reinforced. Channels for providing feedback and complaints about the research were also provided.

Participants were informed about data protection policy of the University (for the Phase 1A study) and Tan Tock Seng Hospital (for the Phase 1B and Phase 2 studies), to maintain strictest confidentiality. They were given one week to consider participation and ask questions when in doubt; a contact number and email address were given in the PIS for the purpose of contacting the author for participation in the research and a platform for participants to ask questions related to the research. After receiving the expressions of interest,

participants were contacted via telephone or email by the author. This communication offered participants an opportunity to ask any further questions. The author would telephone to perform the initial screening using the participant screening form (Appendix 14, Appendix 15 and Appendix 22) to establish whether the inclusion and exclusion criteria (section 4.5) were met. If the inclusion and exclusion criteria were met, and the participant agreed, the author would make an appointment with the participant for him/her to attend a session at:

i) the Faculty of Health Sciences (Building 45), University of Southampton, for the Phase 1A study;

ii) the Rehabilitation Centre of Tan Tock Seng Hospital, Singapore, for the Phase 1B and Phase 2 studies.

Signed, informed consent was obtained from every participant before inclusion in the study. The consent form (Appendix 17 and Appendix 19) would be given when the participant attended the initial outcome measures assessment, and would be signed by the participant in the presence of the author.

4.9.3 Participant confidentiality

All personal details of participants would be kept separately from the research records. All the information collected about participants during the course of this research would be kept strictly confidential and would not be shared with any personnel who were not involved in this research. Any information about participants on research report forms or publications would have their names and addresses removed so that they could not be identified from it.

4.9.4 Data anonymity

Each participant was assigned an unique number that linked the data to each individual. The personal details of participants and the data were kept separately to ensure data anonymity.

4.9.5 Data storage and management

The data recorded, for the purpose of the research study, was 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 for the Phase 1A study and in Tan Tock Seng Hospital for the Phase 1B and Phase 2 studies. Only the author, PhD supervisors and research collaborators from the Faculty of Electronics and Computer Science (ECS) of the University of Southampton, and Tan Tock Seng Hospital would have access to the data.

4.10 Summary of Chapter 4

This Chapter has presented the methodology for this doctoral study, which consisted of the Phase 1 and Phase 2 studies. The Chapter included the aims and objectives of the studies, study design, sample size calculation, recruitment process, outcome measures, experimental procedures and ethical considerations. Methods of statistical analyses were discussed and justified.

The next Chapter will present the detailed results of the Phase 1A and Phase 1B studies.

Chapter 5: Results of Phase 1A and Phase 1B studies (cross-sectional studies)

5. Results of Phase 1A and Phase 1B studies

This Chapter presents the results of the Phase 1A study and Phase 1B study with subacute and chronic stroke participants and healthy participants. The characteristics of the participants, clinical and kinematic outcomes will be detailed. There will be a summary of the main findings at the end of the chapter

The aims of the Phase 1A study and Phase 1B study were to investigate the effect of external trunk support on trunk control and upper extremity function, and to examine the relationship between trunk control and upper extremity function in chronic stroke participants, subacute stroke participants and healthy participants.

5.1 Characteristics of participants

The clinical and demographic characteristics of participants are summarised in Table 5-1. Thirty-four healthy participants, 25 chronic stroke participants and 45 subacute stroke participants were recruited. There was no significant difference in age between the 3 groups of participants.

Table 5-1 Characteristics of participants

Characteristics	Healthy participants (N=34)	Chronic stroke participants (N=25)	Subacute stroke participants (N=45)
Age (years)	60.4 ± 12.4 range 38 – 82	65.3 ± 12.0 range 38 – 84	59.2 ± 11.2 range 34 – 84
Sex			
Male	18	15	26
Female	16	10	19
Time since stroke	N/A	100.4 ± 107.1 months range 12 – 432 months	22.4 ± 15.8 days range 7 – 90 days
Type of stroke	N/A		
Ischaemic		18	29
Haemorrhagic		7	16
Hand dominance			
Right	30	23	40
Left	4	2	5
Affected upper extremity	N/A		
Right		9	21
Left		16	24
Fugl-Meyer Upper Extremity (FMA) score	N/A	41.4 ± 15.3 range 14 – 64	25.5 ± 20.2 range 4 – 61
Number of participants with FMA			
≤ 20 (Severe impairment)		4	22
21-50 (Moderate impairment)		12	17
51-66 (Mild impairment)		9	6
Trunk Impairment Scale (TIS)	22.6 ± 1.0 range 19 – 23	18.0 ± 3.8 range 10 – 23	13.2 ± 4.2 range 3 – 22
Number of participants with TIS			
≤ 10 (poor trunk control)	0	1	13
11-19 (fair trunk control)	1	13	30
≥ 20 (good trunk control)	33	11	2

mean ± standard deviation

5.2 Clinical outcomes in healthy participants

5.2.1 Trunk Impairment Scale (TIS)

The TIS score of the 34 healthy participants ranged from 19 to 23. Twenty-nine participants (85.3%) demonstrated a maximum TIS score of 23. There was only one participant who had a TIS score 19. All the participants were community independent.

There was no significant difference in the median TIS score with and without external trunk support for the healthy participants (Table 5-2).

Table 5-2 Clinical outcome for healthy participants

Outcome measure	Healthy participants (N=34)		95% CI	Effect size *Cohen's d*
	Without trunk support	With trunk support		
TIS (maximum score 23)	22.62 ± 1.02	22.85 ± 0.70	-0.48, 0.01	0.26
SWMFT-Time Dominant UE (seconds)	1.40 ± 0.31**	1.29 ± 0.28**	0.04, 0.15	0.37
SWMFT-Time Non-dominant UE (seconds)	1.46 ± 0.27**	1.36 ± 0.25**	0.07, 0.16	0.38
SWMFT-FAS Dominant UE (maximum score 5)	5	5	–	–
SWMFT-FAS Non-dominant UE (maximum score 5)	5	5	–	–

mean ± standard deviation

CI - confidence interval (CI of difference between the 2 means [without trunk support versus with trunk support])

**Significant difference between no support and with support (p<0.001 on Wilcoxon signed rank test)

*Significant difference between no support and with support (p<0.01 on Wilcoxon signed rank test)

TIS – Trunk Impairment Scale; SWMFT – Streamlined Wolf Motor Function Test; FAS – Functional Ability Scale; UE – upper extremity

5.2.2 Streamlined Wolf Motor Function Test-Time (SWMFT-Time)

The paired-samples t-test demonstrated a significant reduction in the mean SWMFT-Time from 1.40 seconds to 1.29 seconds (p<0.001) for the dominant upper extremity; and from 1.46 seconds to 1.36 seconds (p<0.001) for the non-dominant upper extremity when the trunk was supported (Table 5-2). The effect size was small for both the dominant and non-dominant upper extremity. By convention, effect size (Cohen's *d)* value of 0.2, 0.5, and 0.8 is considered small, moderate, and large effect size respectively (Cohen 1988a).

There was no significant difference in the mean SWMFT-Time between gender, hand dominance and the order of testing with and without trunk support.

5.2.3 Streamlined Wolf Motor Function Test-Functional Ability Scale (SWMFT-FAS)

No significant difference in the SWMFT-FAS scores of the dominant upper extremity and non-dominant upper extremity was demonstrated under the conditions of with and without trunk support for the healthy participants (Table 5-2).

5.3 Clinical outcomes in chronic stroke participants

5.3.1 Fugl-Meyer Upper Extremity (FMA)

Based on the FMA scores, 36%, 48% and 16% of the chronic stroke participants presented with mild, moderate and severe level of upper extremity motor impairment respectively (Table 5-1).

5.3.2 Trunk Impairment Scale (TIS)

The TIS score of the chronic stroke participants ranged from 10 to 23 (Table 5-1). Fourteen of the participants (56%) scored below TIS score of 20 (Table 5-1). There was a statistically significant increase in the mean TIS score with the external trunk support (r=0.69, p<0.05) (Table 5-3).

5.3.3 Streamlined Wolf Motor Function Test-Time (SWMFT-Time)

The Wilcoxon signed rank test demonstrated a statistically significant reduction in the median SWMFT-Time from 2.87 seconds to 2.47 seconds (p<0.001) for the affected upper extremity with the trunk support (Table 5-3). The effect size was large with r = 0.83. The median SWMFT-Time for the less affected upper extremity was significantly reduced from 1.92 seconds to 1.71 seconds (p<0.001) with the trunk support (Table 5-3).

There was no significant difference in the median SWMFT-Time between the order of testing with and without trunk support, gender, hand dominance, stroke type and side of affected upper extremity.

Table 5-3 Clinical outcome for chronic stroke participants

Outcome measure	Chronic stroke participants (N=25)		95% CI	Effect size
	Without trunk support	With trunk support		
TIS	18.00 ± 3.76*	20.00 ± 2.80*	-2.88, -1.12	0.60
SWMFT-Time Affected UE (seconds)	2.87## (IQR 1.75–74.48)	2.47## (IQR 1.63–70.80)	0.05, 0.23	0.83
SWMFT-Time Less affected UE (seconds)	1.92## (IQR 1.61–16.05)	1.71## (IQR 1.42–15.97)	0.04, 0.23	0.77
SWMFT-FAS Affected UE	3.3# (IQR 1.8–4.3)	3.4# (IQR 1.9–4.4)	-0.1, 0.0	0.63
SWMFT-FAS Less affected UE	5	5	–	–

mean ± standard deviation
median (IQR); IQR: interquartile range
CI - confidence interval (CI of difference between the 2 means/medians [without trunk support versus with trunk support])
##Significant difference between no support and with support (p<0.001 on Wilcoxon signed rank test)
#Significant difference between no support and with support (p<0.01 on Wilcoxon signed rank test)
*Significant difference between no support and with support (p<0.001 on paired t test)
TIS: Trunk Impairment Scale; SWMFT: Streamlined Wolf Motor Function Test; FAS: Functional Ability Scale; UE: upper extremity

5.3.4 Streamlined Wolf Motor Function Test-Functional Ability Scale (SWMFT-FAS)

The Wilcoxon signed rank test demonstrated a statistically significant improvement in the median SWMFT-FAS from 3.3 to 3.4 points for the affected upper extremity with the trunk support, with a large effect size (r = 0.63, p<0.01) (Table 5-3). There was no significant difference in the median SWMFT-FAS for the less affected upper extremity with the trunk support (Table 5-3). There was no significant difference in SWMFT-FAS based on the order of testing with and without trunk support, gender, hand dominance and side of affected upper extremity.

5.4 Clinical outcomes in subacute stroke participants

5.4.1 Fugl-Meyer Upper Extremity (FMA)

Based on the FMA scores, 13.3%, 66.7%% and 29% of the subacute stroke participants presented with mild, moderate and severe level of upper extremity motor impairment respectively (Table 5-1).

5.4.2 Trunk Impairment Scale (TIS)

The TIS scores of the 45 subacute stroke participants ranged from 3 to 21 (Table 5-1). The percentage of participants who had poor, fair and good trunk control was 28.9%, 66.7% and 4.4% respectively (Table 5-1). There was a statistically significant increase in the mean TIS score from 13.11 points to 18.33 points with the external trunk support, with a very large effect size (d = 1.49, p<0.001) (Table 5-4).

5.4.3 Streamlined Wolf Motor Function Test-Time (SWMFT-Time)

The Wilcoxon signed rank test demonstrated a significant reduction in the median SWMFT-Time from 90.98 seconds to 90.43 seconds (p<0.001) for the affected upper extremity with the trunk support (Table 5-4). The effect size was large with r = 0.76. The median SWMFT-Time for the less affected upper extremity was significantly reduced from 15.82 seconds to 15.65 seconds

(p<0.001) with the trunk support (Table 5-4). The effect size was large with r = 0.87.

There was no significant difference in the median SWMFT-Time based on the order of testing with and without trunk support, gender, hand dominance, stroke type and side of affected upper extremity.

Table 5-4 Clinical outcome for subacute stroke participants

Outcome measure	Subacute stroke participants (N=45)		95% CI	Effect size
	Without trunk support	With trunk support		
TIS	13.11 ± 4.10[#] range 3–21	18.33 ± 2.79[#] range 13–23	-5.88, -4.48	1.49
SWMFT-Time Affected UE (seconds)	90.98** (IQR 4.12–114.63)	90.43** (IQR 3.78–113.31)	0.01, 0.38	0.76
SWMFT-Time Less affected UE (seconds)	15.82** (IQR 1.60–16.15)	15.65** (IQR 1.42–15.93)	0.10, 0.17	0.87
SWMFT-FAS Affected UE	0.6** (IQR 0.2–2.9)	1.0** (IQR 0.2–3.4)	-0.38, -0.13	0.73
SWMFT-FAS Less affected UE	5	5		–

mean ± standard deviation

median (IQR); IQR: interquartile range

CI - confidence interval (CI of difference between the 2 means/medians [without trunk support versus with trunk support])

[#] Significant difference between no support and with support (p<0.001 on paired t-test)

**Significant difference between no support and with support (p<0.001 on Wilcoxon signed rank test)

TIS: Trunk Impairment Scale; SWMFT: Streamlined Wolf Motor Function Test; FAS: Functional Ability Scale; UE: upper extremity

5.4.4 Streamlined Wolf Motor Function Test-Functional Ability Scale (SWMFT-FAS)

The Wilcoxon signed rank test demonstrated a significant improvement in the median SWMFT-FAS from 0.6 to 1.0 points for the affected upper extremity with the trunk support (r = 0.73, p<0.001) (Table 5-4). There was no significant difference in the median SWMFT-FAS for the less affected upper extremity with the trunk support (Table 5-4). There was no significant difference in SWMFT-FAS based on the order of testing with and without trunk support, gender, hand dominance and side of affected upper extremity.

5.5 Comparison of clinical outcomes (with and without trunk support) between subacute and chronic stroke participants and healthy participants

Comparison of the outcomes between subacute and chronic stroke participants and healthy participants involved selection of appropriate statistical test based on the characteristics of the variables. TIS and SWMFT-Time are interval variables while SWMFT-FAS is an ordinal variable.

In view of the comparison between three groups (subacute stroke, chronic stroke and healthy groups) under two conditions (with and without trunk support), the split plot analysis of variance (SPANOVA) was used to analyse the results of TIS and SWMFT-Time. The Wilcoxon signed rank test was used to compare the SWMFT-FAS under the two support conditions for the three groups. The Kruskal–Wallis H test was then used to analyse the SWMFT-FAS between the three groups.

5.5.1 Outcome of TIS

The outcome of TIS scores is detailed in Table 5-5. Results from the SPANOVA showed significant difference ($F_{(1,101)}$ = 63.48, p<0.001) in the TIS scores between the subacute stroke, chronic stroke and healthy groups, regardless of the support conditions. The partial Eta-squared (η_p^2) was found to be 0.56.

Partial Eta-squared (η_p^2) is a measure of variance that informs what proportion

of the variance in the dependent variable is attributable to the factor in question (Richardson 2011). η_p^2 is therefore a measure of effect size in the analysis of variance (ANOVA). By convention, η_p^2 of 0.01, 0.06, and 0.14 is considered small, medium, and large effect size respectively (Cohen 1998; Richardson 2011). Hence, there was a significant difference in the TIS scores between the three groups, regardless of the support conditions, with a very large effect size; subacute stroke participants had lower TIS scores than chronic stroke participants and healthy participants.

The difference in the TIS score between the two support conditions (with and without trunk support), regardless of the groups, was significant ($F_{(1,101)}$ = 166.09, p<0.001) with η_p^2 of 0.62, implying a very large efect size with the trunk support (Table 5-5).

Further analysis also revealed a statistically significant interaction effect between group and support condition ($F_{(1,101)}$ = 68.41, p<0.001, η_p^2 = 0.58) (Table 5-5). The effect size was very large. Figure 5-1 illustrates that the TIS score increased significantly more with the trunk support in the subacute stroke group as compared to the chronic stroke and healthy group, as observed from the steeper slope of the graph for the subacute stroke group.

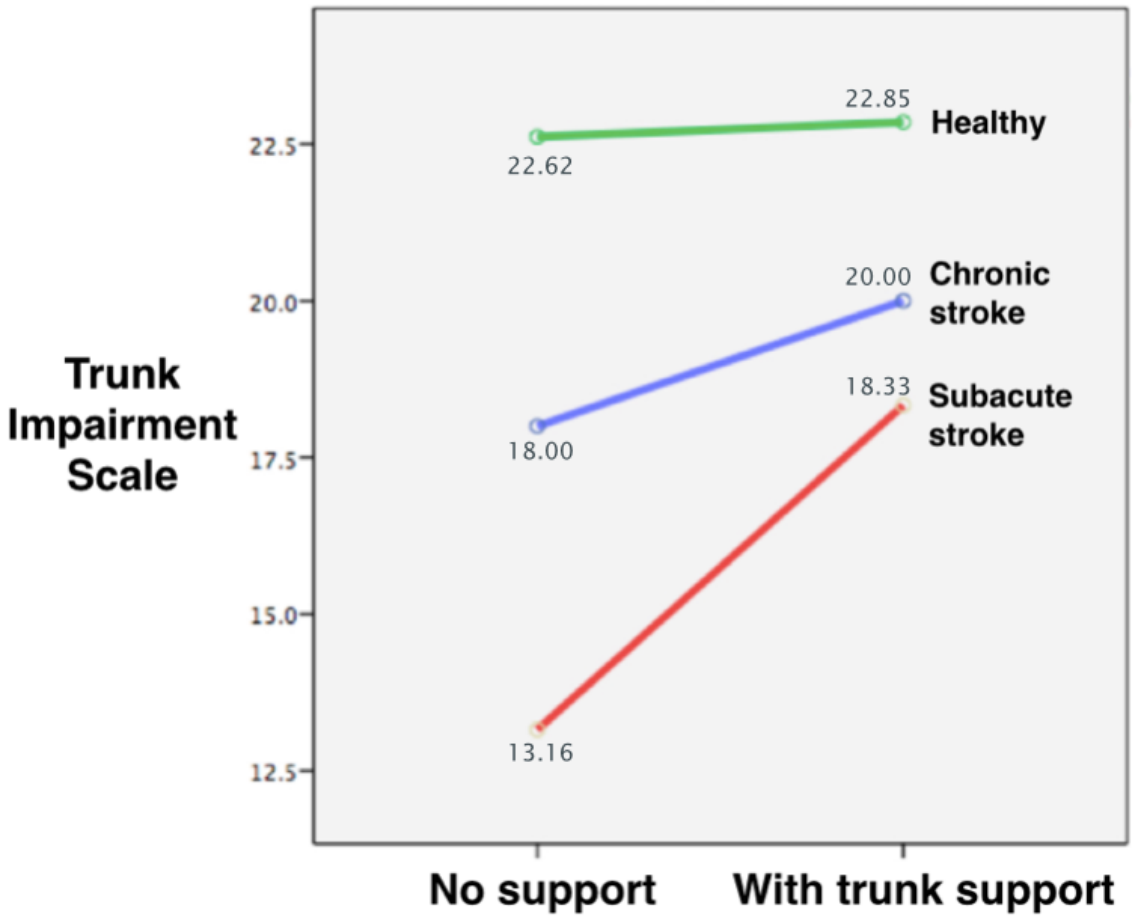


Figure 5-1 Large significant interaction effect between group and support condition ($F_{(1,101)}$ = 68.41, p<0.001; η_p^2 = 0.58)

As there were significant differences in the TIS scores between the three groups, post hoc tests were necessary to determine which groups differ from each other. The Tukey-Kramer post hoc test (Table 5-6) was conducted due to the unequal group sizes (Kleinbaum et al, 1997). Post hoc test results demonstrated statistically significant differences between subacute stroke group and healthy group (p<0.001); between subacute stroke group and chronic stroke group (p<0.001); and between chronic stroke group and healthy group (p<0.001) (Table 5-6). The healthy group's mean TIS score was 6.99 points higher than the subacute stroke group; this mean difference being the largest amongst the three groups (Table 5-6). The chronic stroke group exhibited a TIS score of 3.26 points higher than the subacute stroke group; implying a better trunk control in the chronic stroke group (Table 5-6).

Table 5-5 SPANOVA results of TIS and SWMFT-Time for subacute and chronic stroke participants and healthy participants

Clinical outcome	Group	Without support	With support	95% CI	Effect	F value	*p* value	Partial Eta-squared (η_p^2)
TIS	Subacute stroke	13.16 ± 4.18	18.33 ± 2.79	-5.88, -4.48	Group	63.48	0.001	0.56
	Chronic stroke	18.00 ± 3.76	20.00 ± 2.80	-2.88, -1.12	Support	166.09	0.001	0.62
	Healthy	22.62 ± 1.02	22.85 ± 0.70	-0.48, 0.01	Support x Group	68.41	0.001	0.58
SWMFT-Time (seconds) Affected UE for stroke Non-dominant UE for healthy	Subacute stroke	66.37 ± 49.24	64.36 ± 49.86	0.01, 0.38	Group	28.49	0.001	0.36
	Chronic stroke	29.39 ± 39.24	27.99 ± 37.73	0.05, 0.23	Support	9.14	0.01	0.08
	Healthy	1.46 ± 0.27	1.37 ± 0.25	0.07, 0.16	Support x Group	2.45	0.09	0.05
SWMFT-Time (seconds) Less affected UE for stroke Dominant UE for healthy	Subacute stroke	10.46 ± 7.01	9.89 ± 7.08	0.10, 0.17	Group	23.87	0.001	0.32
	Chronic stroke	6.35 ± 6.86	5.71 ± 6.60	0.04, 0.23	Support	6.37	0.01	0.06
	Healthy	1.40 ± 0.31	1.29 ± 0.28	0.04, 0.15	Support x Group	0.90	0.41	0.02

mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means [without trunk support versus with trunk support])
Support x Group : interaction effect
η_p^2 : 0.01 small effect size; 0.06 medium effect size; 0.14 large effect size
TIS: Trunk Impairment Scale; SWMFT: Streamlined Wolf Motor Function Test; FAS: Functional Ability Scale; UE: upper extremity

Table 5-6 Tukey-Kramer post hoc test for TIS scores

Group (a)	Group (b)	Mean difference (a-b)	*p* value	95% Confidence Interval	
				Lower bound	Upper bound
Healthy	Subacute stroke	6.99	0.001	5.51	8.47
	Chronic stroke	3.74	0.001	2.02	5.45
Subacute stroke	Chronic stroke	-3.26	0.001	-4.88	-1.63
	Healthy	-6.99	0.001	-8.47	-5.51

5.5.2 Outcome of SWMFT-Time

The outcome of SWMFT-Time of both the affected and less affected upper extremity is detailed in Table 5-5.

5.5.2.1 SWMFT-Time of the affected upper extremity

With regard to the affected UE of the subacute and chronic stroke participants, the SPANOVA showed significant difference ($F_{(1,101)}$ = 28.49, p<0.001) in the SWMFT-Time between the subacute stroke, chronic stroke and the healthy groups, regardless of the support conditions (Table 5-5). The effect size was very large (η_p^2 = 0.36).

The difference in the SWMFT-Time between the two support conditions (with and without trunk support), regardless of the groups, was significant ($F_{(1,101)}$ = 9.14, p<0.01) with η_p^2 of 0.08, implying a medium efect size with the trunk support (Table 5-5). There was no significant interaction effect between group and support condition ($F_{(1,101)}$ = 2.45, p>0.05; η_p^2 = 0.05) (Table 5-5).

The Tukey-Kramer post hoc test (Table 5-7) demonstrated significant differences between subacute stroke group and healthy group (p<0.001); between chronic stroke group and healthy group (p<0.05); and between subacute stroke group and chronic stroke group (p<0.001) (Table 5-7). The largest mean difference in SWMFT-Time for the affected upper extremity was 63.95 seconds between the subacute stroke group and healthy group; performance time was shorter for the healthy group (Table 5-7). On average, the subacute stroke participants took 36.68 seconds longer to perform the SWMFT tasks compared with the chronic stroke participants (Table 5-7).

Table 5-7 Tukey-Kramer post hoc test for SWMFT-Time of the affected upper extremity

Group (a)	Group (b)	Mean difference (a-b)	p value	95% Confidence Interval	
				Lower bound	Upper bound
Healthy	Subacute stroke	-63.95	0.001	-84.30	-43.59
	Chronic stroke	-27.27	0.05	-50.87	-3.68
Subacute stroke	Chronic stroke	36.68	0.001	14.33	59.01
	Healthy	63.95	0.001	43.59	84.30

5.5.2.2 SWMFT-Time of the less affected upper extremity

The SPANOVA showed significant difference ($F_{(1,101)}$ = 23.87, p<0.001) in the SWMFT-Time between the subacute stroke, chronic stroke and the healthy groups, regardless of the support conditions (Table 5-5). The effect size was very large (η_p^2 = 0.32).

The difference in the SWMFT-Time between the two support conditions (with and without trunk support), regardless of the groups, was significant ($F_{(1,101)}$ = 6.37, p<0.01) with η_p^2 of 0.06, implying a medium efect size with the trunk support (Table 5-5). There was no significant interaction effect between group and support condition ($F_{(1,101)}$ = 0.90, p>0.05; η_p^2 = 0.02).

The Tukey-Kramer post hoc test (Table 5-8) demonstrated significant differences between subacute stroke group and healthy group (p<0.001); between chronic stroke group and healthy group (p<0.01); and between subacute stroke group and chronic stroke group (p<0.01) (Table 5-8). The largest mean difference in SWMFT-Time for the less affected upper extremity was 8.83 seconds between the subacute stroke group and healthy group; performance time was shorter for the healthy group (Table 5-8). On average, the subacute stroke participants took 4.15 seconds longer to perform the SWMFT tasks compared with the chronic stroke participants (Table 5-8).

Table 5-8 Tukey-Kramer post hoc test for SWMFT-Time of the less affected upper extremity

Group (a)	Group (b)	Mean difference (a-b)	*p* value	95% Confidence Interval	
				Lower bound	Upper bound
Healthy	Subacute stroke	-8.83	0.001	-11.87	-5.79
	Chronic stroke	-4.68	0.01	-8.21	-1.15
Subacute stroke	Chronic stroke	4.15	0.01	0.81	7.49
	Healthy	8.83	0.001	5.79	11.87

5.5.3 **Outcome of SWMFT-FAS** of the affected upper extremity

The Wilcoxon signed rank test demonstrated a significant improvement in the median SWMFT-FAS from 3.3 points to 3.6 points with the trunk support (r = 0.56, p<0.001), regardless of groups.

The Kruskal–Wallis H test was used to compare the SWMFT-FAS between the healthy group, subacute stroke and chronic stroke groups. Subsequently, the Mann–Whitney U test was conducted as post hoc test to determine the actual significance difference between subacute stroke participants and healthy participants; between chronic stroke participants and healthy participants; and between subacute stroke participants and chronic stroke participants. If a number of Mann–Whitney U tests were used, the procedures will inflate the Type I error rate (Field, 2009). Hence, a Bonferroni correction was applied (i.e. p value of 0.05 divided by three tests) so that all effects were reported at a 0.0167 level of significance.

Table 5-9 details the SWMFT-FAS for the healthy group, subacute stroke and chronic stroke groups. The Kruskal–Wallis H test demonstrated statistical significant improvement in SWMFT-FAS with the trunk support (H(2)=72.07, p<0.001). The Mann–Whitney U test results (Table 5-10) demonstrated significant differences between subacute stroke group and healthy group (r = 0.89, p<0.001); between chronic stroke group and healthy group (r = 0.86, p<0.001); and between subacute stroke group and chronic stroke group (r = 0.40, p<0.001). The chronic stroke participants exhibited a higher median SWMFT-FAS of 3.4 points compared to 1.0 point in the subacute stroke participants (Table 5-10).

Table 5-9 SWMFT-FAS of the affected upper extremity

Clinical outcome	Group	Without support	With support	95% CI	*p* value	Effect size *r*
SWMFT-FAS	Subacute stroke	0.6 (IQR 0.2-2.9)	1.0 (IQR 0.2-3.4)	-0.38, -0.13	0.001	0.73
	Chronic stroke	3.3 (IQR 1.8-4.3)	3.4 (IQR 1.9-4.4)	-0.1, 0.0	0.01	0.62
	Healthy	5	5	–	–	–

CI - confidence interval (CI of difference between the 2 medians [without trunk support versus with trunk support])

Table 5-10 Mann-Whitney test for SWMFT-FAS of the affected upper extremity

Group (a)	Group (b)	Mann-Whitney *U* test	*p* value	Effect size *r*
Healthy	Subacute stroke	0.00	0.001	0.89
	Chronic stroke	51.00	0.001	0.86
Subacute stroke	Chronic stroke	288.00	0.001	0.40
	Healthy	0.00	0.001	0.89

5.6 Association between TIS and clinical variables of the affected upper extremity of subacute and chronic stroke participants

Evaluation of the normality of the data was conducted with the Shapiro-Wilk test. The Shapiro-Wilk test provides better power than the Kolmogorov-Smirnov test even after the Lilliefors correction (Steinskog et al. 2007). Researchers have recommended the Shapiro-Wilk test as the best choice for testing the normality of data (Ghasemi & Zahediasl 2012).

The Shapiro-Wilk test showed that only the TIS data was normally distributed while the FMA, FMA-Shoulder-Elbow (FMA-SE) and FMA-Wrist-Hand (FMA-WH), SWMFT-Time and SWMFT-FAS were not normally distributed. Therefore, the Spearman's correlation coefficient would be used to determine the relationship between TIS and FMA, FMA-SE and FMA-WH, SWMFT-Time and SWMFT-FAS (Table 5-11).

There was significant strong correlation between TIS and FMA (Spearman's ρ = 0.71, p<0.001); TIS and FMA-SE (ρ = 0.70, p<0.001); TIS and FMA-WH (ρ = 0.67, p<0.001) (Table 5-11). Strong correlations were found between TIS and SWMFT-Time (ρ = -0.67, p<0.001); and between TIS and SWMFT-FAS (ρ = 0.68, p<0.001) (Table 5-11). FMA was found to correlate strongly with SWMFT-Time (ρ = -0.96, p<0.001); and SWMFT-FAS (ρ = 0.97, p<0.001) (Table 5-11).

Table 5-11 Association between TIS, FMA, FMA-SE and FMA-WH in subacute and chronic stroke participants (Spearman's ρ)

	TIS	FMA	FMA-SE	FMA-WH
TIS	–	0.71*	0.70*	0.67*
FMA	0.71*	–	0.99*	0.97*
FMA-SE	0.70*	0.99*	–	0.92*
FMA-WH	0.67*	0.97*	0.92*	–
SWMFT-Time	-0.67*	-0.96*	-0.95*	-0.93*
SWMFT-FAS	0.68*	0.97*	0.95*	0.94*

*p<0.001

5.7 Kinematic outcomes (with and without trunk support) in healthy participants

5.7.1 Kinematic analysis of the 'lift can' task

As there was no significant difference in SWMFT-Time and SWMFT-FAS of the dominant upper extremity and non-dominant upper extremity in healthy participants, with and without trunk support, it was decided that the kinematic data of the non-dominant arm would be chosen for the healthy participants' group statistics. This will put the stroke participants with hemiparesis in the non-dominant arm at less of a comparative disadvantage, as recommended by Alt Murphy et al. (2011).

5.7.2 Checking for normal distribution of kinematic data

All the kinematic data were checked for normal distribution prior to any further statistical analysis. Visual inspection of the histograms and the Shapiro-Wilk test were used to ascertain the normality of the data distribution. Analysis showed that the data for movement duration, movement smoothness, trunk flexion, trunk lateral flexion, scapular upward rotation, scapular posterior tilt and elbow extension were not normally distributed. The data for movement straightness, maximum ulnar styloid velocity, average ulnar styloid velocity, trunk rotation, scapular internal rotation and shoulder flexion were normally distributed. Hence, the appropriate parametric and non-parametric tests were used for further analysis based on the normality of data distribution.

5.7.3 Movement duration, movement smoothness, movement straightness and ulnar styloid velocity

The paired-samples t-test demonstrated a statistically significant reduction (p<0.001) in the mean maximum ulnar styloid velocity from 1031.24 mm/s to 846.93 mm/s with the trunk support. The average ulnar styloid velocity was also significantly reduced (p<0.01) from 251.31mm/s to 228.74 mm/s (Table 5-12).

The Wilcoxon signed rank test showed significant improvement (p<0.05) in movement smoothness, i.e., reduction in number of velocity peaks, with trunk

support (Table 5-12). There was no significant difference in movement duration of the non-dominant upper extremity in healthy participants, with and without trunk support.

Table 5-12 Movement duration, movement smoothness, movement straightness and ulnar styloid velocity in healthy participants

Kinematic variable	Without trunk support	With trunk support	95% CI	Effect size
Movement duration (seconds)	1.39 (IQR 1.17 – 1.57)	1.29 (IQR 1.17 – 1.64)	-0.07, 0.19	0.30
Movement smoothness (number of velocity peaks)	2# (IQR 2-3)	2# (IQR 1.5-2)	0, 1	0.37
Movement straightness (path-line ratio)	1.37 ± 0.16	1.40 ± 0.15	-0.10, 0.03	0.19
Maximum ulnar styloid velocity (mm/second)	1031.24 ± 297.41**	846.93 ±261.73**	104.71,263.92	0.66
Average ulnar styloid velocity (mm/second)	251.31 ± 72.46*	228.74 ± 69.49*	3.61, 41.52	0.32

median (IQR); IQR: interquartile range

mean ± standard deviation

CI - confidence interval (CI of difference between the 2 means/medians [without trunk support versus with trunk support])

#p < 0.05; * p < 0.01; **p < 0.001

5.7.4 Kinematic analysis of trunk, scapula, shoulder flexion and elbow extension

The range of motion (ROM) of the trunk, scapula, shoulder flexion and elbow extension that occurred from event 1(hand leaves lap) to event 2 (hand grasps can) are presented in Table 5-13.

The paired-samples t-test showed statistically significant reduction (p<0.01) in the ROM of scapular internal rotation with trunk support. There was no significant difference in the ROM of trunk rotation and shoulder flexion, with and without trunk support (Table 5-13).

The Wilcoxon signed rank test showed statistically significant reduction in the ROM of trunk lateral flexion (p<0.05), scapular upward rotation (p<0.001), and scapular internal rotation (p<0.01) with trunk support (Table 5-13). The ROM of elbow extension (p<0.01) was significantly increased with trunk support (Table 5-13). No significant differences were found for the ROM of trunk flexion and scapular posterior tilt, with and without trunk support (Table 5-13).

Table 5-13 Kinematic data (range of motion) of the trunk, scapula and upper extremity of the healthy participants

Kinematic variable	Without trunk support	With trunk support	95% CI	Effect size
Trunk flexion	3.81° (IQR 2.32° – 5.26°)	3.11° (IQR 2.29° – 4.97°)	-0.93, 0.78	0.02
Trunk rotation (rotation away from the tested side)	11.49° ± 4.11°	10.98° ± 4.27°	-0.44, 1.46	0.12
Trunk lateral flexion (opposite to the tested side)	3.20° * (IQR 2.16° – 4.32°)	2.93° * (IQR 1.43° – 3.60°)	0.09, 0.96	0.34
Scapular internal rotation	9.03° ± 3.00° #	8.01° ± 2.77° #	0.22, 1.81	0.45
Scapular upward rotation	7.37° *** (IQR 6.22° – 9.61°)	5.03° *** (IQR 4.25° – 7.78°)	1.02, 2.81	0.67
Scapular posterior tilt	5.68° (IQR 3.19° – 6.60°)	5.36° (IQR 3.80° – 6.84°)	-0.65, 0.64	0.08
Shoulder flexion	50.34° ± 5.94°	49.51° ± 6.14°	-1.80, 3.45	0.14
Elbow extension	56.96° ** (IQR 52.20° – 64.01°)	58.80° ** (IQR 55.43° – 66.89°)	-6.50, -0.29	0.35

median (IQR); IQR: interquartile range
mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means/medians [without trunk support versus with trunk support])
***Significant difference between no support and with support (p<0.001 on Wilcoxon signed rank test)
**Significant difference between no support and with support (p<0.01 on Wilcoxon signed rank test)
*Significant difference between no support and with support (p<0.05 on Wilcoxon signed rank test)
Significant difference between no support and with support (p<0.01 on paired t test)

The means of the average segment angles with one standard deviation of the 'lift can' task are presented in Figures 5-2, 5-3 and 5-4. The movement patterns were generally similar comparing with and without trunk support for the trunk, scapula, shoulder flexion and elbow flexion. In other words, the shape of the waveforms which depict the movement patterns of the various body segments (Figures 5-2, 5-3 and 5-4) are similar under trunk supported and trunk unsupported conditions from the beginning of 'lift can' task (0%) to completion of task (100%).

Table 5-14 presents the maximum angles of kinematic variables that occurred at the respective percentage of the 'lift can' task under trunk supported and trunk unsupported conditions. When comparing the trunk supported condition to the unsupported condition, the maximum angle occurred at the same point (percentage of task) during the 'lift can' task for each joint (Table 5.14). This result is supported by the non-significant Wilcoxon signed rank test when comparing support conditions. This suggests that the participants adopt a similar movement pattern between the trunk supported condition versus the unsupported condition.

Table 5-14 Maximum angles of kinematic variables during the 'lift can' task in healthy participants

Kinematic variable	Without trunk support		With trunk support	
	Maximum angle	Percentage of task (%)	Maximum angle	Percentage of task (%)
Trunk flexion	11.25º ± 6.50º	57	10.41º ± 7.47º	60
Trunk lateral flexion	3.34º ± 2.59º	52	2.25º ± 1.45º	52
Trunk rotation	12.14º ± 4.61º	51	12.01º ± 4.29º	52
Scapular internal rotation	39.30º ± 6.09º	48	40.42º ± 5.62º	50
Scapular upward rotation	12.06º ± 7.41º	100	11.78º ± 7.30º	100
Scapular posterior tilt	12.93º ± 4.87º	11	11.74º ± 6.80º	11
Shoulder flexion	55.13º ± 10.59º	100	52.04º ± 9.17º	100
Elbow extension	130.10º ± 6.22º	46	126.37º ± 9.50º	46
Elbow flexion	126.40º ± 6.40º	100	126.40º ± 5.40º	100

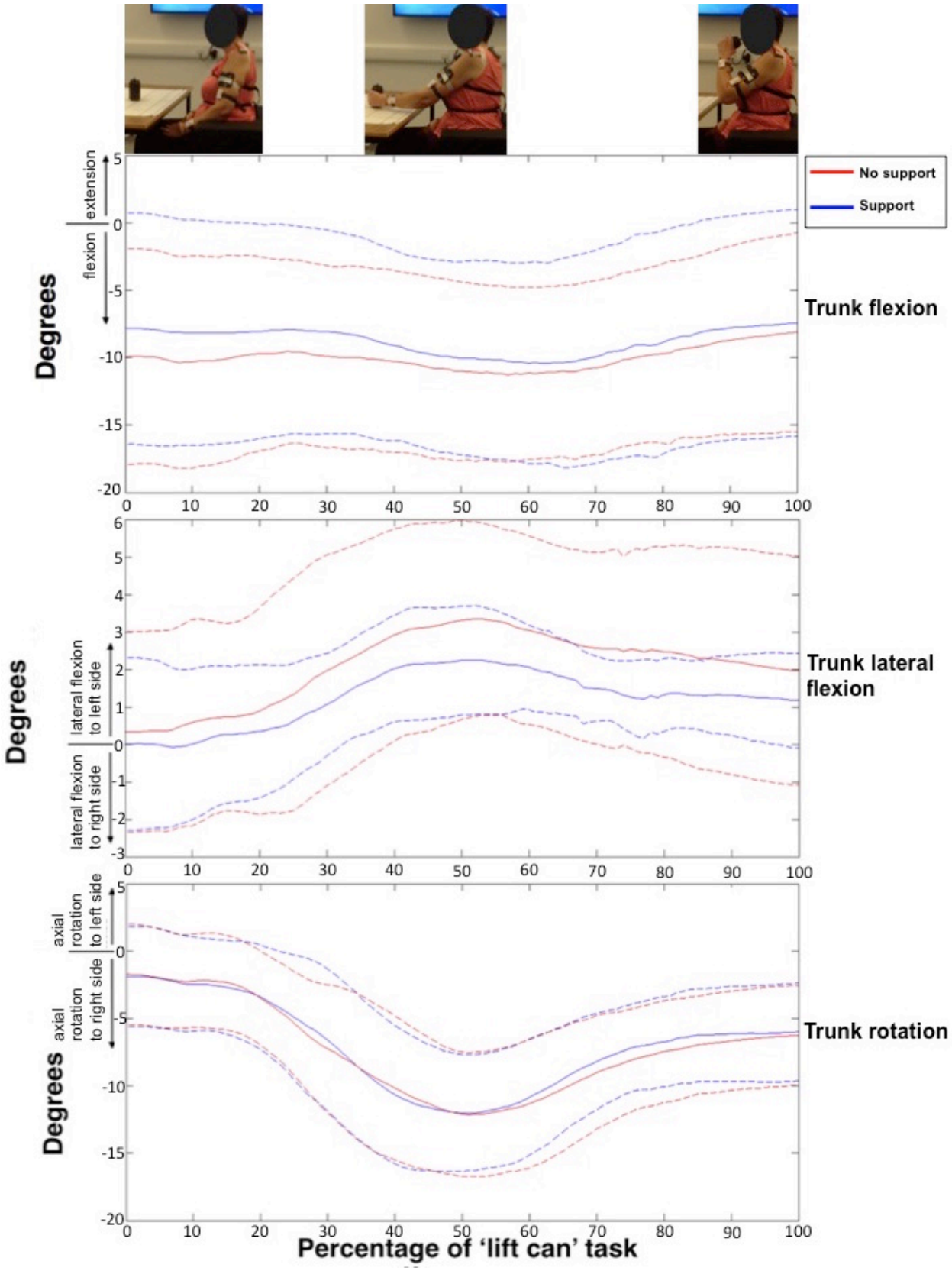


Figure 5-2 Average trunk segment angles (solid lines) ± one standard deviation (dashed lines) during the 'lift can' task in healthy participants

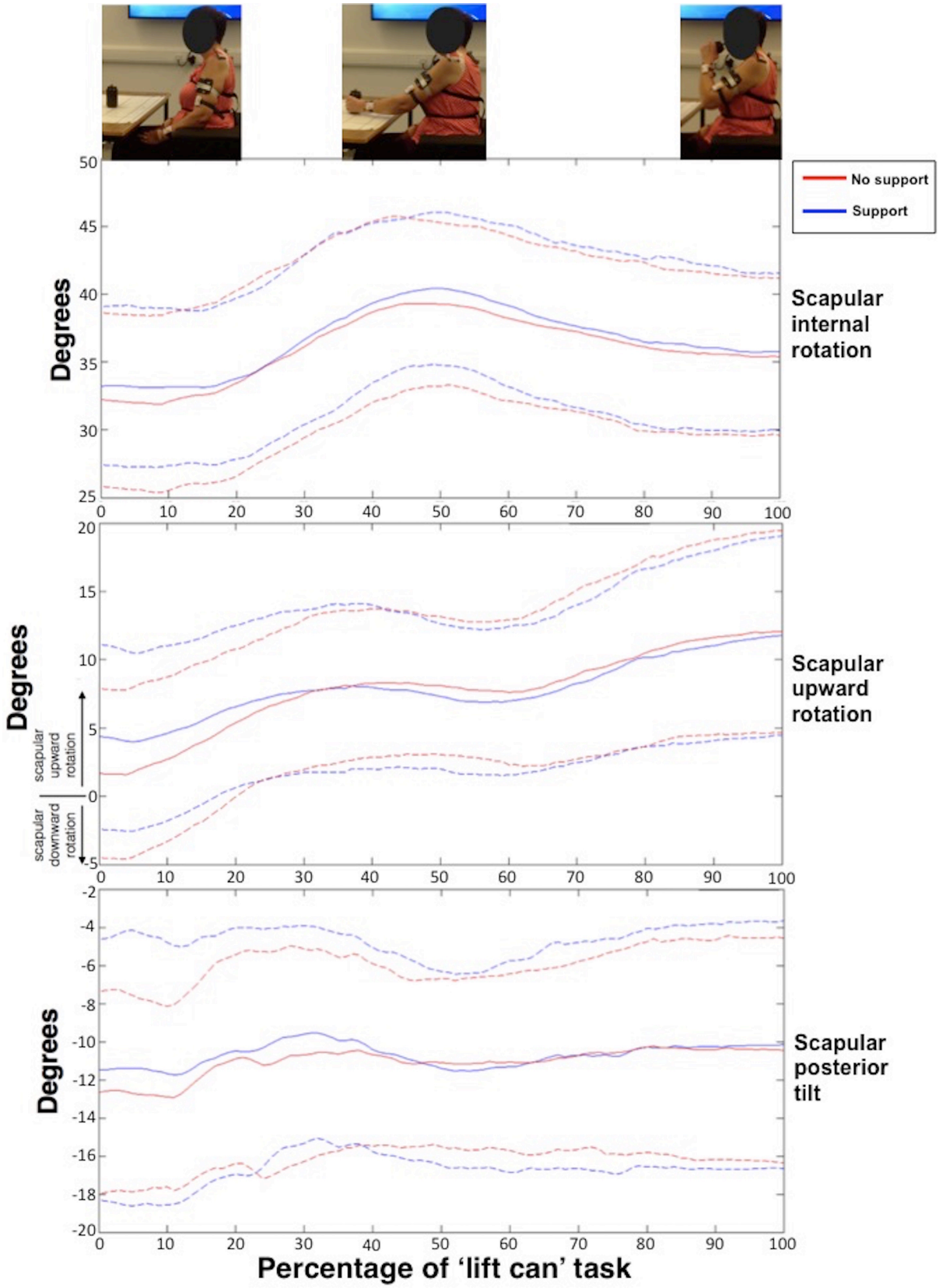


Figure 5-3 Average scapula segment angles (solid lines) ± one standard deviation (dashed lines) during the 'lift can' task in healthy participants

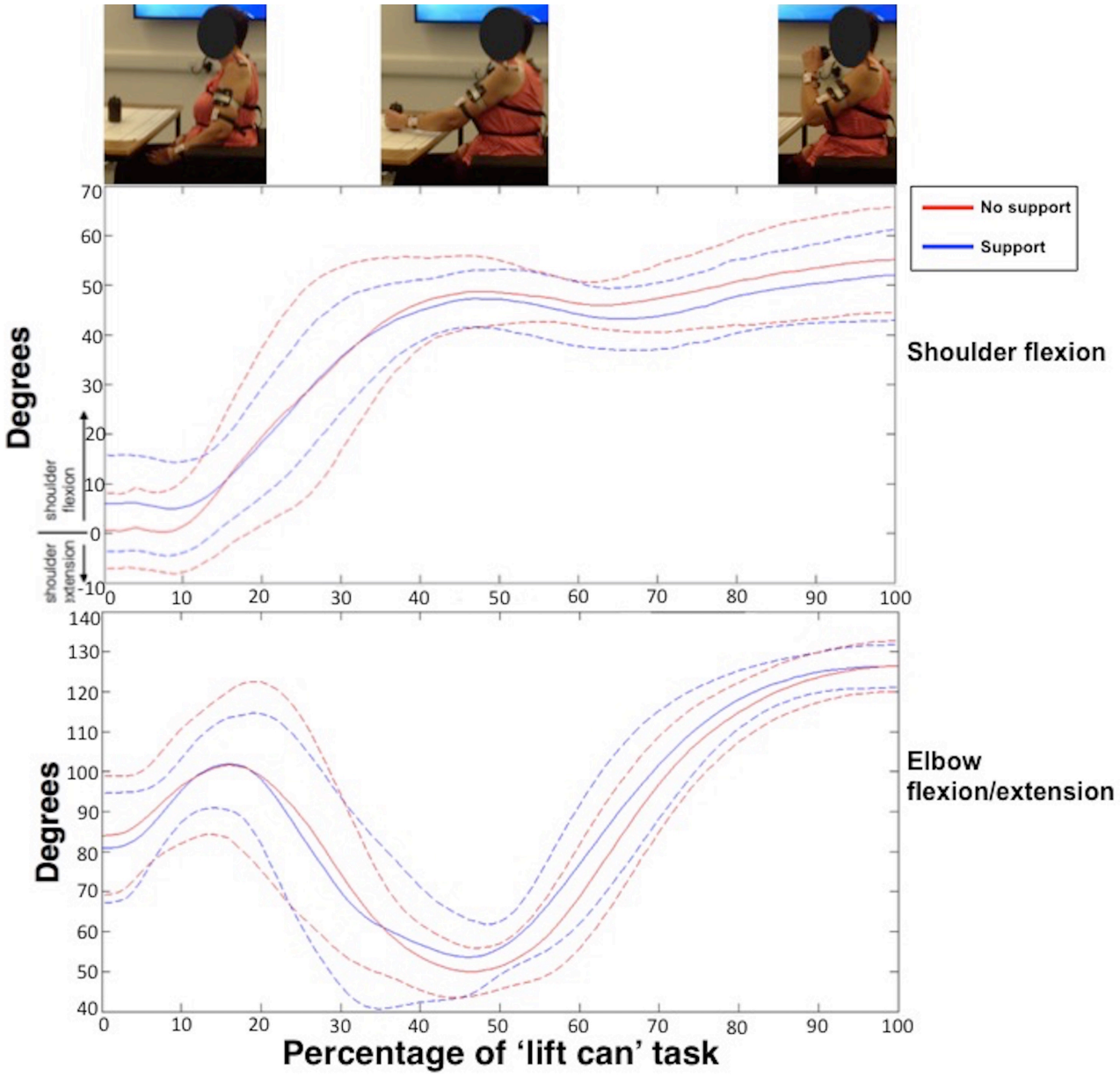


Figure 5-4 Average shoulder and elbow segment angles (solid lines) ± one standard deviation (dashed lines) during the 'lift can' task in healthy participants

5.8 Kinematic outcomes (with and without trunk support) in chronic stroke participants

5.8.1 Checking for normal distribution of kinematic data

The Shapiro-Wilk test showed that the data for movement duration, movement smoothness, movement straightness, trunk flexion and scapular upward rotation were not normally distributed. The data for maximum ulnar styloid velocity, average ulnar styloid velocity, trunk lateral flexion, trunk rotation, scapular internal rotation, scapular posterior tilt, shoulder flexion and elbow extension were normally distributed. Hence, the appropriate parametric and non-parametric tests were used for further analysis based on the normality of data distribution.

5.8.2 Movement duration, movement smoothness, movement straightness and ulnar styloid velocity

As seven of the chronic stroke participants could not complete the whole task of lifting can to the mouth due to poor hand dexterity, data from 18 participants were used in the analysis for movement duration and average ulnar styloid velocity. Analysis of all other kinematic variables were made for all the 25 chronic stroke participants.

The Wilcoxon signed rank test showed statistically significant reduction in movement duration ($p<0.05$) and improvement in movement smoothness ($p<0.01$) with trunk support. There was no significant difference in movement straightness, with and without trunk support (Table 5-15).

The paired-samples t-test demonstrated no significant difference in the maximum and average ulnar styloid velocity, with and without trunk support (Table 5-15).

5.8.3 Kinematic analysis of the trunk, scapula, shoulder flexion and elbow extension

The range of motion (ROM) of the trunk, scapula, shoulder flexion and elbow extension that occurred from event 1 (hand leaves lap) to event 2 (hand grasps can) are presented in Table 5-16.

The paired-samples t-test demonstrated no significant difference in the degree of trunk lateral flexion, trunk rotation, scapular internal rotation, scapular posterior tilt, shoulder flexion and elbow extension, with and without trunk support (Table 5-16).

The Wilcoxon signed rank test showed statistically significant reduction in the range of motion of scapular upward rotation (p<0.01) with trunk support. No significant difference was found for trunk flexion, with and without trunk support (Table 5-16).

Table 5-15 Movement duration, movement smoothness, movement straightness and ulnar styloid velocity in chronic stroke participants

Kinematic variable	Without trunk support	With trunk support	95% CI	Effect size
Movement duration (seconds)	2.89* (IQR 2.04–120.00)	2.44* (IQR 1.87–120.00)	0, 0.25	0.46
Movement smoothness (number of velocity peaks)	5** (IQR 3-10)	4** (IQR 3-6)	0, 2	0.55
Movement straightness (path-line ratio)	1.65 (IQR 1.46–1.86)	1.61 (IQR 1.48–1.88)	-0.16, 0.17	0.02
Maximum ulnar styloid velocity (mm/second)	814.46 ± 266.59	734.69 ± 302.37	-21.29, 180.81	0.66
Average ulnar styloid velocity (mm/second)	175.71 ± 79.15	171.16 ± 73.01	-16.88, 25.98	0.32

median (IQR); IQR: interquartile range; *p < 0.05; **p < 0.01
mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means/medians [without trunk support versus with trunk support])

Table 5-16 Kinematic data (range of motion) of the trunk, scapula and upper extremity of the chronic stroke participants

Kinematic variable	Without trunk support	With trunk support	95% CI	Effect size
Trunk flexion	9.47º (IQR 4.50º – 14.64º)	10.27º (IQR 5.32º – 21.16º)	-2.54, 0.19	0.33
Trunk rotation (rotation away from the tested side)	13.47º ± 5.42º	13.79º ± 4.71º	-1.75, 1.11	0.06
Trunk lateral flexion (opposite to the tested side)	8.45º ± 4.50º	8.09º ± 4.84º	-1.27, 1.98	0.08
Scapular internal rotation	8.89º ± 2.83º	9.24º ± 2.61º	-1.42, 0.71	0.13
Scapular upward rotation	11.52º ** (IQR 7.96º – 15.40º)	8.58º ** (IQR 5.26º – 14.71º)	0.05, 4.00	0.52
Scapular posterior tilt	6.16º ± 2.58º	5.65º ± 2.49º	-0.48, 1.50	0.20
Shoulder flexion	43.31º ± 14.79º	40.31º ± 14.57º	-0.70, 6.69	0.20
Elbow extension	38.47º ± 20.46º	40.40º ± 20.77º	-5.21, 1.34	0.09

median (IQR); IQR: interquartile range
mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means/medians [without trunk support versus with trunk support])

**Significant difference between no support and with support (p<0.01 on Wilcoxon signed rank test)

The means of the average segment angles with one standard deviation of the 'lift can' task are presented in Figures 5-5, 5-6 and 5-7. The movement patterns were generally similar comparing with and without trunk support for the trunk, scapula, shoulder flexion and elbow flexion. In other words, the shape of the waveforms which depict the movement patterns of the various body segments (Figures 5-5, 5-6 and 5-7) are similar under trunk supported and trunk unsupported conditions from the beginning of 'lift can' task (0%) to completion

of task (100%). The only exception was an increased in scapular upward rotation in the first 30% of the 'lift can' task under the trunk supported condition (Figure 5-6).

Table 5-17 presents the maximum angles of kinematic variables that occurred at the respective percentage of the 'lift can' task under trunk supported and trunk unsupported conditions. When comparing the trunk supported condition to the unsupported condition, the maximum angle occurred at the almost the same point (percentage of task) during the 'lift can' task for each joint (Table 5.17). This result is supported by the non-significant Wilcoxon signed rank test when comparing support conditions. This suggests that the participants adopt a similar movement pattern between the trunk supported condition versus the unsupported condition.

Table 5-17 Maximum angles of kinematic variables during the 'lift can' task in chronic stroke participants

Kinematic variable	Without trunk support		With trunk support	
	Maximum angle	Percentage of task (%)	Maximum angle	Percentage of task (%)
Trunk flexion	13.12º ± 7.47º	69	14.49º ± 9.07º	71
Trunk lateral flexion	2.93º ± 6.92º	24	1.06º ± 6.39º	22
Trunk rotation	5.72º ± 10.60º	50	5.72º ± 10.82º	57
Scapular internal rotation	41.12º ± 8.02º	51	41.12º ± 7.22º	53
Scapular upward rotation	10.86º ± 8.32º	100	11.17º ± 7.75º	100
Scapular posterior tilt	17.03º ± 7.58º	2	16.12º ± 6.17º	8
Shoulder flexion	44.47º±16.36º	100	42.99º±16.76º	100
Elbow extension	104.25º±25.85º	43	100.84º±25.54º	36
Elbow flexion	117.50º±18.60º	100	115.10º±18.70º	100

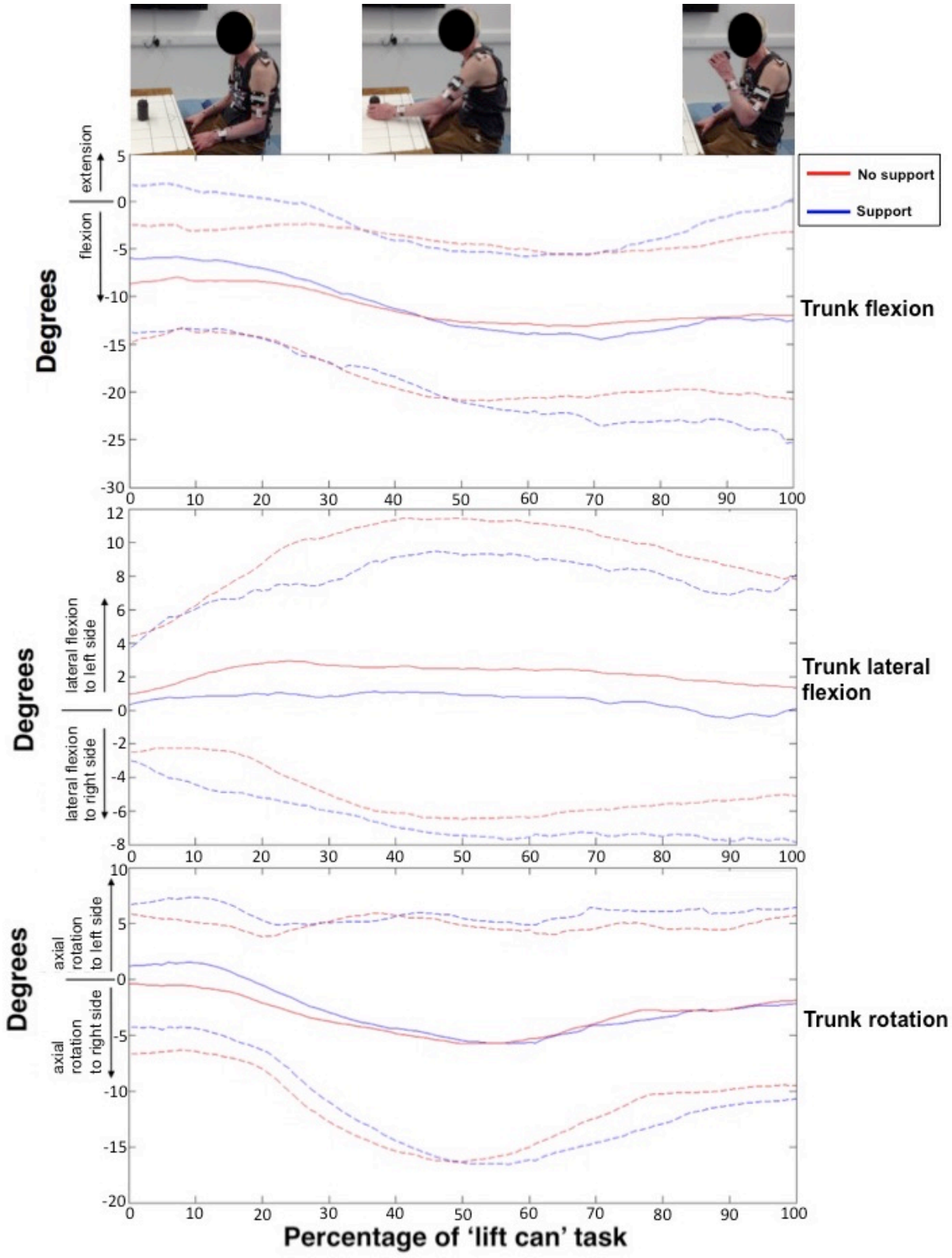


Figure 5-5 Average trunk segment angles (solid lines) ± one standard deviation (dashed lines) during the 'lift can' task in chronic stroke participants

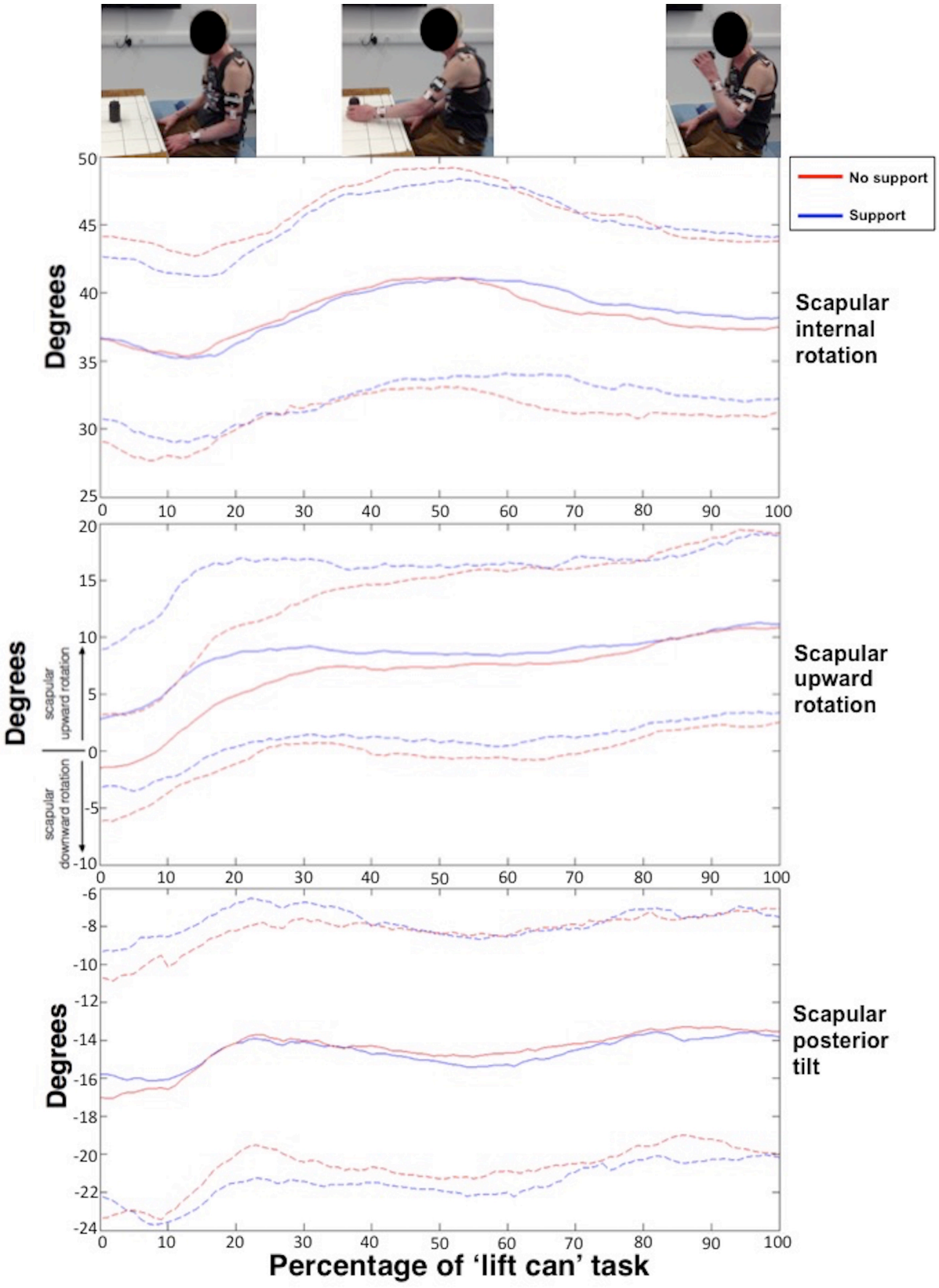


Figure 5-6 Average scapula segment angles (solid lines) ± one standard deviation (dashed lines) during the 'lift can' task in chronic stroke participants

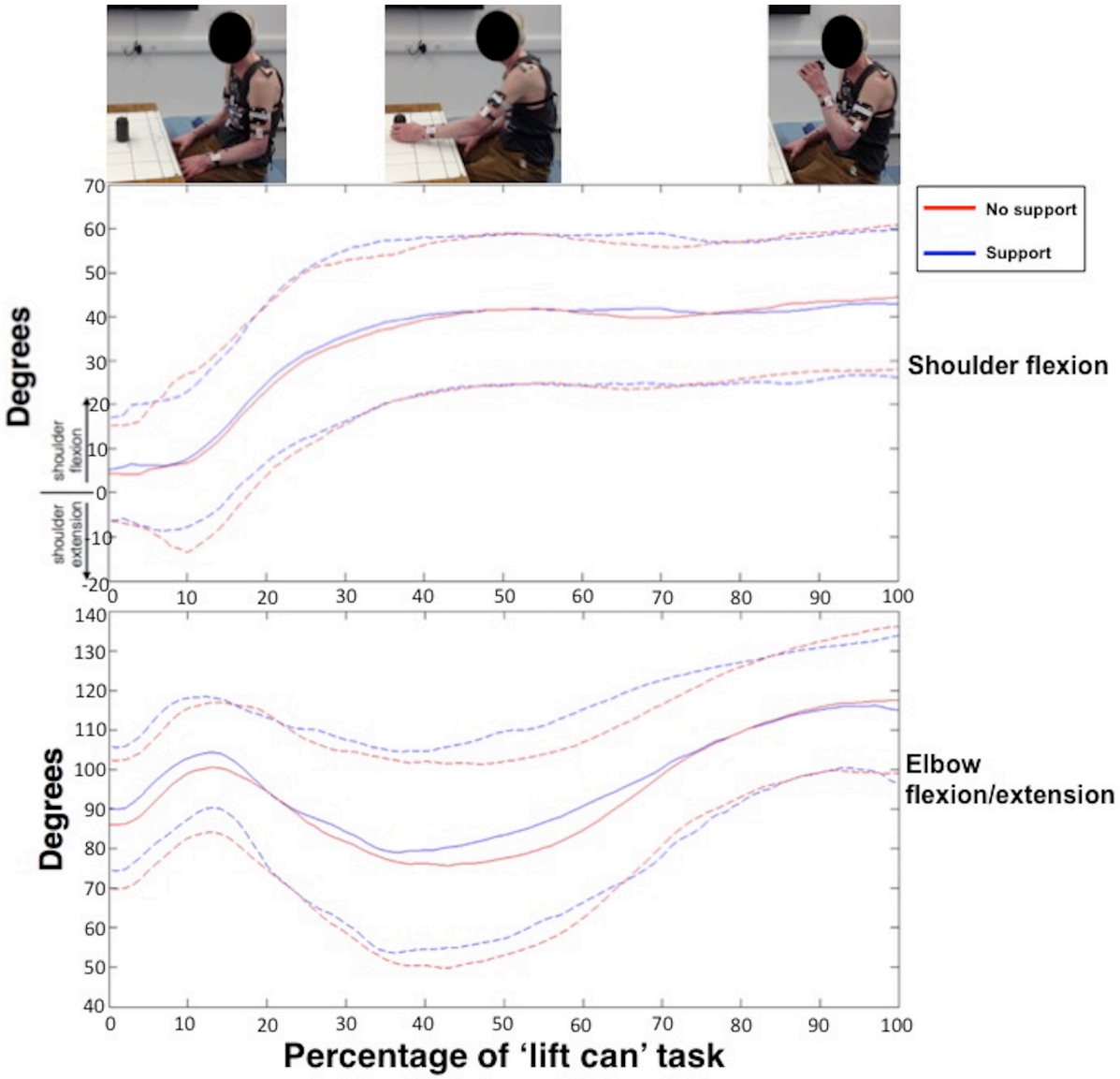


Figure 5-7 Average shoulder and elbow segment angles (solid lines) ± one standard deviation (dashed lines) during the 'lift can' task in chronic stroke participants

5.9 Trunk and scapular kinematics based on the severity of upper extremity impairment in chronic stroke participants

Several studies (Michaelsen et al. 2006; Woodbury et al. 2009; Wu et al. 2012a; Wu et al. 2012b; Massie et al. 2014) have demonstrated excessive compensatory trunk movements (anterior trunk displacement) during reaching in stroke patients. Therefore, sub-analysis was conducted in the present study to evaluate trunk and scapular kinematics in the chronic stroke participants based on the severity of their upper extremity impairment, and examine the presence of any compensatory movement of the trunk and scapula during reaching. As the sample size of the chronic stroke participants was small, those participants with moderate level (FMA score 21-50) (Velozo & Woodbury 2011) and severe level (FMA score ≤20) (Velozo & Woodbury 2011) of upper extremity impairment were grouped together for sub-analysis. Those participants with FMA score 51-66 had mild upper impairment level (Velozo & Woodbury 2011).

The trunk and scapular kinematics (ROM) (without trunk support) based on the severity of upper extremity impairment in the stroke participants are presented in Table 5-18.

In comparison with healthy participants, the stroke participants with moderate-to-severe upper extremity impairment (FMA ≤50) exhibited significantly more ROM of trunk flexion (p<0.001), trunk lateral flexion (p<0.001), and scapular upward rotation (p<0.001) during reaching. The ROM of trunk flexion, trunk lateral flexion, and scapular upward rotation were 3.75 times, 3.16 times, and 1.80 times more than the healthy participants respectively (Table 5-18).

The stroke participants with mild upper extremity impairment (FMA >50) demonstrated significantly more ROM of trunk lateral flexion (p<0.01) when compared to the healthy participants. The ROM of trunk lateral flexion was 1.83 times more than the healthy participants (Table 5-18).

Table 5-18 Trunk and scapular kinematic (without the external trunk support) based on the severity of upper extremity impairment

Kinematic variable	Chronic stroke participants		Healthy participants (N=34)
	Mild upper extremity impairment (FMA score >50) (N=9)	Moderate-to-severe upper extremity impairment (FMA score ≤50) (N=16)	
Trunk flexion	3.91° (IQR 3.18° – 5.69°)	14.30°♦♦ (IQR 9.12° – 17.24°)	3.81° (IQR 2.32° – 5.26°)
Trunk rotation (rotation away from the tested side)	12.35° ± 3.68°	14.11° ± 6.22° *	11.49° ± 4.11°
Trunk lateral flexion (opposite to the tested side)	5.87°♦ (IQR 3.90° – 9.05°)	10.11°♦♦ (IQR 5.18° – 13.62°)	3.20° (IQR 2.16° – 4.32°)
Scapular internal rotation	9.00° ± 3.12°	8.82° ± 2.77°	9.03° ± 3.00°
Scapular upward rotation	9.91° (IQR 7.09° – 12.42°)	13.27°♦♦ (IQR 7.72° – 17.94°)	7.37° (IQR 6.22° – 9.61°)
Scapular posterior tilt	6.35° (IQR 5.29° – 9.45°)	5.56° (IQR 3.56° – 7.60°)	5.68° (IQR 3.19° – 6.60°)

Note: the range of motion of each variable are presented
median (IQR); IQR: interquartile range
mean ± standard deviation
♦Significant difference when compared with healthy participants (p<0.01 on Mann-Whitney test)
♦♦Significant difference when compared with healthy participants (p<0.001 on Mann-Whitney test)

5.10 Comparison of kinematic outcomes between chronic stroke participants and healthy participants

In view of the comparison between two groups (chronic stroke group and healthy group) under two conditions (with and without trunk support), the split plot analysis of variance (SPANOVA) was used to analyse the results of all kinematic variables. The SPANOVA results are detailed in Table 5-19.

Results from the SPANOVA showed significant differences between the chronic stroke and healthy groups, regardless of the support conditions, for the following variables (Table 5-19): movement duration ($F_{(1,57)}$ = 15.67, p<0.001), movement smoothness ($F_{(1,57)}$ = 17.23, p<0.001), movement straightness ($F_{(1,57)}$ = 15.90, p<0.001), maximum ulnar styloid velocity ($F_{(1,57)}$ = 5.83, p<0.05), average ulnar styloid velocity ($F_{(1,57)}$ = 13.52, p<0.001), ROM of trunk flexion ($F_{(1,57)}$ = 24.63, p<0.001), trunk rotation ($F_{(1,57)}$ = 4.35, p<0.05), trunk lateral flexion ($F_{(1,57)}$ = 33.05, p<0.001), scapular upward rotation ($F_{(1,57)}$ = 15.90, p<0.001), shoulder flexion ($F_{(1,57)}$ = 9.67, p<0.01), and elbow extension ($F_{(1,57)}$ = 26.08, p<0.001). The partial Eta-squared (η_p^2) ranged from 0.07 (medium effect size) to 0.77 (large effect size).

A statistically significant main effect of support (Table 5-19) was found for movement duration ($F_{(1,57)}$ = 6.22, p<0.05), movement smoothness ($F_{(1,57)}$ = 11.93, p<0.001), maximum ulnar styloid velocity ($F_{(1,57)}$ = 18.21, p<0.001), ROM of scapular upward rotation ($F_{(1,57)}$ = 20.85, p<0.001), and elbow extension ($F_{(1,57)}$ = 5.12, p<0.05). The value of η_p^2 ranged from 0.08 (medium effect size) to 0.27 (large effect size). There was a significant interaction effect for movement smoothness ($F_{(1,57)}$ = 6.27, p<0.05), with medium effect size of 0.10 (Figure 5-8).

Figures 5-9, 5-10, 5-11 and 5-12 present samples of the velocity profile of the affected upper extremity of a stroke participant (CS13) and non-dominant upper extremity of a healthy participant (H24), with and without trunk support. These velocity profiles were meant to illustrate how the movement smoothness of 'lift can' task changed when the trunk was supported. The number of velocity peaks was reduced with trunk support, hence implying improvement in movement smoothness.

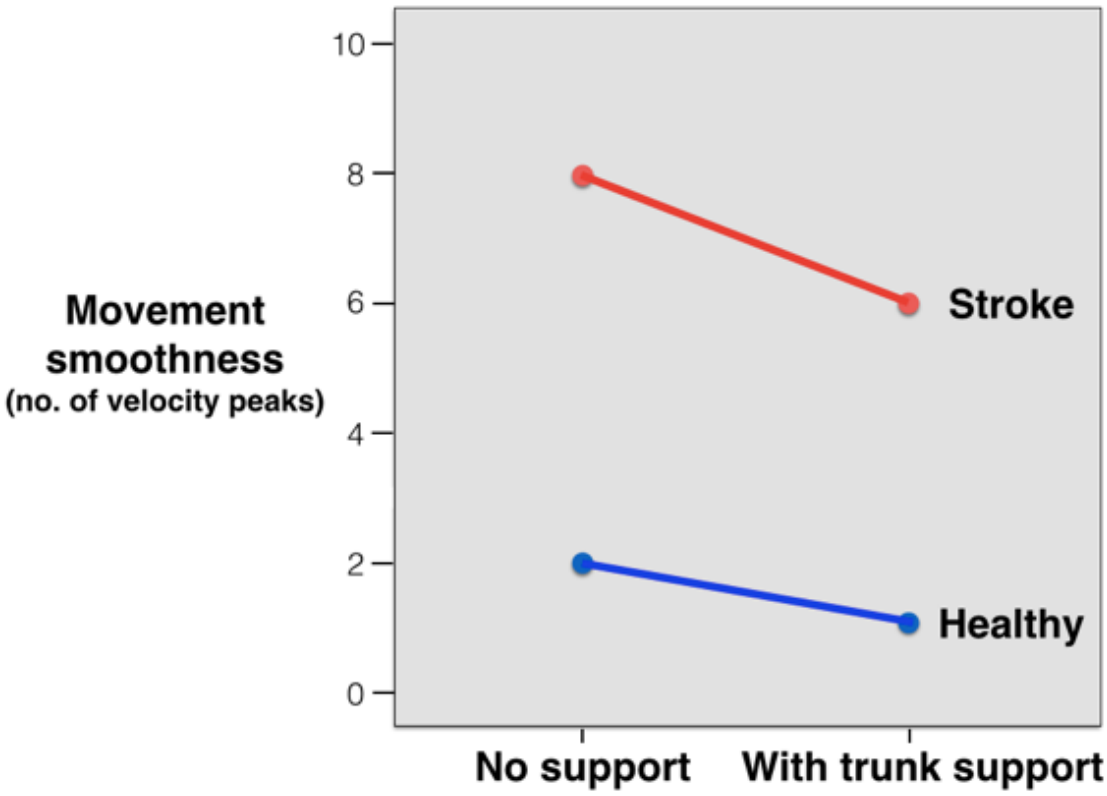


Figure 5-8 Moderate significant interaction effect between group and support condition for movement smoothness ($F_{(1,57)} = 6.27$, $p<0.05$; $\eta_p^2 = 0.10$)

Figure 5-9 to Figure 5-12 illustrate the ulnar styloid velocity profiles of a stroke participant (CS13) and a healthy participant (H24) from event 1(hand leaves the lap) to event 2 (hand grasps the can), with and without trunk support. The sampling rate is 100 frames per second. The velocity peaks are related to a change in direction in the ulnar styloid velocity profile.

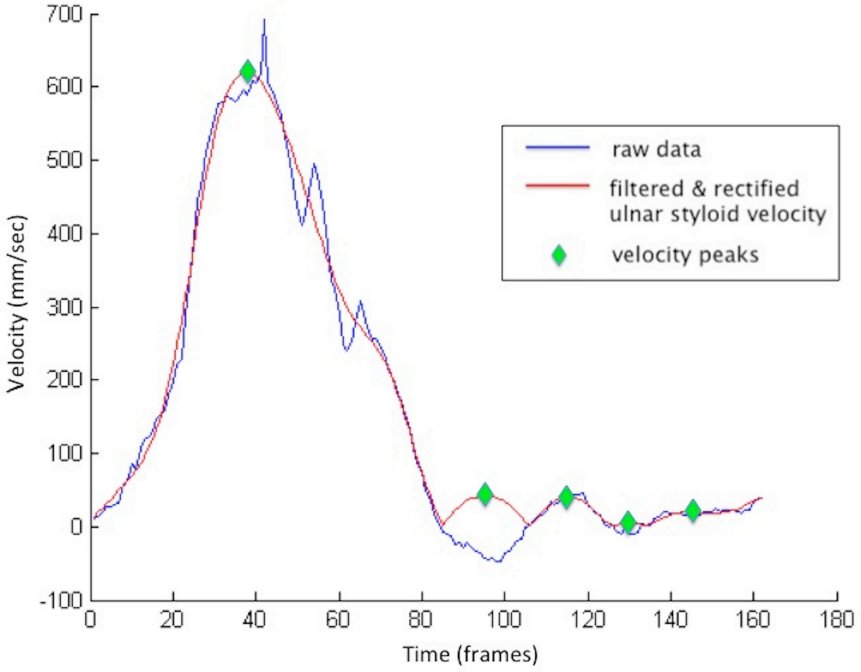


Figure 5-9 Velocity profile of the affected upper extremity of a stroke participant (CS13) without trunk support

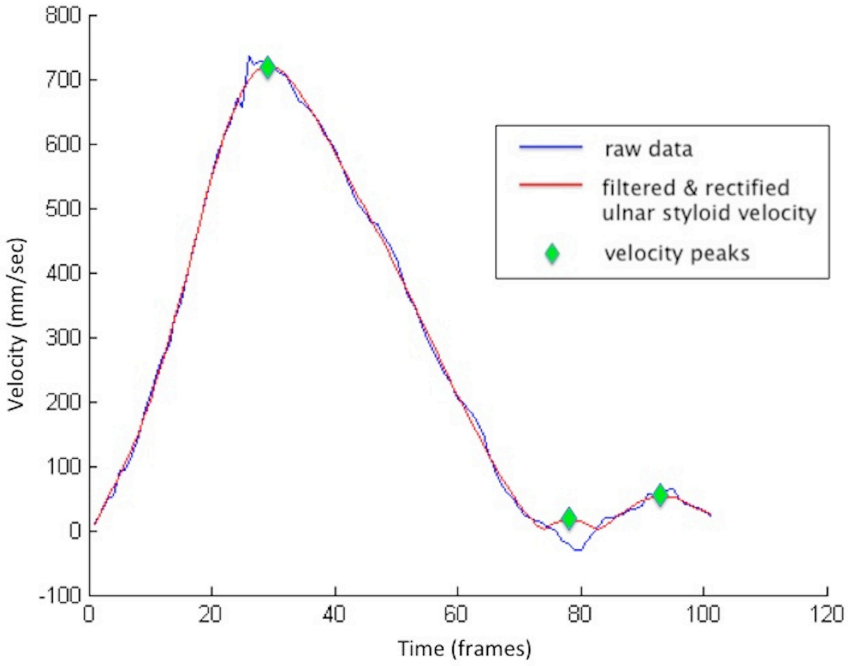


Figure 5-10 Velocity profile of the affected upper extremity of a stroke participant (CS13) with trunk support

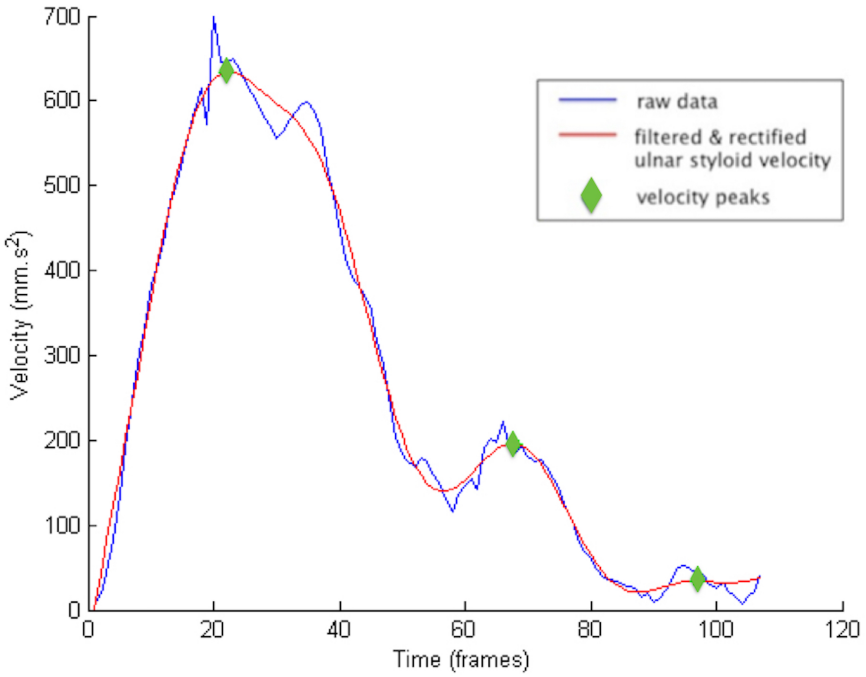


Figure 5-11 Velocity profile of the non-dominant upper extremity of a healthy participant (H24) without trunk support

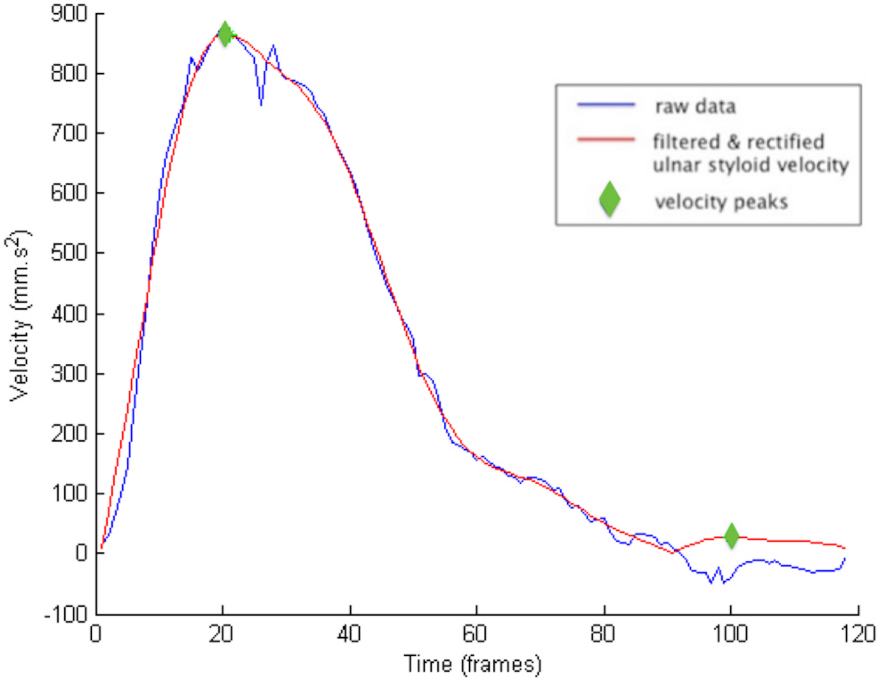


Figure 5-12 Velocity profile of the non-dominant upper extremity of a healthy participant (H24) with trunk support

Table 5-19 SPANOVA results of kinematic variables of chronic stroke participants and healthy participants

Kinematic outcome	Group	Without support	With support	95% CI	Effect	F value	*p* value	Partial Eta-squared (η_p^2)
Movement duration (seconds)	Chronic stroke	40.03 ± 55.99	39.87 ± 56.10	-0.04, 0.36	Group	15.67	0.001	0.22
					Support	6.22	0.02	0.10
	Healthy	1.50 ± 0.57	1.39 ± 0.34	-0.01, 0.24	Support x Group	0.14	0.71	0.002
Movement smoothness (number of velocity peaks)	Chronic stroke	8.24 ± 8.50	5.96 ± 5.02	0.52, 4.05	Group	17.23	0.001	0.24
					Support	11.93	0.001	0.18
	Healthy	2.42 ± 1.25	2.06 ± 0.90	0.03, 0.69	Support x Group	6.27	0.02	0.10
Movement straightness (path-line ratio)	Chronic stroke	1.72 ± 4.46	1.81 ± 0.82	-0.43, 0.25	Group	15.90	0.001	0.22
					Support	0.72	0.40	0.01
	Healthy	1.37 ± 0.16	1.40 ± 0.15	-0.10, 0.03	Support x Group	0.17	0.69	0.003

mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means [without trunk support versus with trunk support])
Support x Group : interaction effect
η_p^2 : 0.01 small effect size; 0.06 medium effect size; 0.14 large effect size

Table 5-19 (Continued) SPANOVA results of kinematic variables of chronic stroke participants and healthy participants

Kinematic outcome	Group	Without support	With support	95% CI	Effect	F value	*p* value	Partial Eta-squared (η_p^2)
Maximum ulnar styloid velocity (mm/second)	Chronic stroke	814.46 ± 266.59	734.69 ± 302.37	-21.29, 180.81	Group	5.83	0.02	0.09
					Support	18.21	0.001	0.25
	Healthy	1031.24 ± 297.41	846.93 ± 261.73	104.71, 263.92	Support x Group	2.85	0.10	0.05
Average ulnar styloid velocity (mm/second)	Chronic stroke	175.71 ± 79.15	171.16 ± 73.01	-16.88, 25.98	Group	13.52	0.001	0.19
					Support	3.75	0.06	0.06
	Healthy	251.31 ± 72.46	228.74 ± 69.49	3.61, 41.52	Support x Group	1.66	0.20	0.03

mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means [without trunk support versus with trunk support])
Support x Group : interaction effect

η_p^2 : 0.01 small effect size; 0.06 medium effect size; 0.14 large effect size

Table 5-19 (Continued) SPANOVA results of kinematic variables of chronic stroke participants and healthy participants

Kinematic outcome	Group	Without support	With support	95% CI	Effect	F value	*p* value	Partial Eta-squared (η_p^2)
Trunk flexion (degrees)	Chronic stroke	11.27 ± 9.74	12.76 ± 9.28	-3.64, 0.67	Group	24.63	0.001	0.31
					Support	1.66	0.20	0.03
	Healthy	3.99 ± 2.20	3.78 ± 2.22	-0.48, 0.91	Support x Group	2.96	0.09	0.05
Trunk lateral flexion (degrees)	Chronic stroke	8.45 ± 4.50	8.09 ± 4.84	-1.27, 1.98	Group	33.05	0.001	0.77
					Support	1.47	0.23	0.03
	Healthy	3.61 ± 2.47	3.07 ± 2.14	0.04, 1.05	Support x Group	0.07	0.80	0.001
Trunk rotation (degrees)	Chronic stroke	13.47 ± 5.42	13.79 ± 4.71	-1.75, 1.11	Group	4.35	0.04	0.07
					Support	0.06	0.82	0.001
	Healthy	11.49 ± 4.11	10.98 ± 4.27	-0.44, 1.46	Support x Group	1.05	0.31	0.02

mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means [without trunk support versus with trunk support])
Support x Group : interaction effect

η_p^2 : 0.01 small effect size; 0.06 medium effect size; 0.14 large effect size

Table 5-19 (Continued) SPANOVA results of kinematic variables of chronic stroke participants and healthy participants

Kinematic outcome	Group	Without support	With support	95% CI	Effect	F value	*p* value	Partial Eta-squared (η_p^2)
Scapular internal rotation (degrees)	Chronic stroke	8.89 ± 2.83	9.24 ± 3.61	-1.43, 0.71	Group	0.54	0.47	0.01
	Healthy	9.03 ± 2.99	8.01 ± 2.77	0.22, 1.81	Support	1.08	0.30	0.02
					Support x Group	4.65	0.04	0.08
Scapular upward rotation (degrees)	Chronic stroke	12.65 ± 6.36	10.47 ± 6.39	0.52, 3.86	Group	15.90	0.001	0.22
	Healthy	7.96 ± 2.88	6.00 ± 2.56	0.94, 2.98	Support	20.85	0.001	0.27
					Support x Group	0.06	0.80	0.001
Scapular posterior tilt (degrees)	Chronic stroke	6.16 ± 2.58	5.65 ± 2.49	-0.48, 1.50	Group	0.10	0.75	0.002
	Healthy	5.73 ± 2.12	5.69 ± 2.68	-0.63, 0.71	Support	0.97	0.33	0.02
					Support x Group	0.71	0.40	0.01

mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means [without trunk support versus with trunk support])
Support x Group : interaction effect

η_p^2 : 0.01 small effect size; 0.06 medium effect size; 0.14 large effect size

Table 5-19 (Continued) SPANOVA results of kinematic variables of chronic stroke participants and healthy participants

Kinematic outcome	Group	Without support	With support	95% CI	Effect	F value	*p* value	Partial Eta-squared (η_p^2)
Shoulder flexion (degrees)	Chronic stroke	43.31 ± 14.79	40.31 ± 14.57	-0.70, 6.69	Group	9.67	0.01	0.15
					Support	3.16	0.08	0.05
	Healthy	50.34 ± 5.94	49.51 ± 6.14	-1.80, 3.45	Support x Group	1.02	0.32	0.02
Elbow extension (degrees)	Chronic stroke	38.47 ± 20.46	40.40 ± 20.77	-5.21, 1.34	Group	26.08	0.001	0.32
					Support	5.12	0.03	0.08
	Healthy	59.34 ± 11.37	61.66 ± 11.11	-4.56, -0.06	Support x Group	0.04	0.84	0.001

mean ± standard deviation
CI - confidence interval (CI of difference between the 2 means [without trunk support versus with trunk support])
Support x Group : interaction effect

η_p^2 : 0.01 small effect size; 0.06 medium effect size; 0.14 large effect size

5.11 Comparison of movement patterns of 'lift can' task between chronic stroke participants and healthy participants

Figures 5-13, 5-14 and 5-15 present the movement patterns of the trunk, scapula, shoulder and elbow in chronic stroke participants and healthy participants during the 'lift can' task. Generally, the movement patterns were similar from the start to end of task between the two groups. However, under the unsupported condition, the values of the maximum angle (Table 5-14 and Table 5-17) of trunk rotation, shoulder flexion, elbow extension and elbow flexion were higher in the healthy participants compared to chronic stroke participants; these differences were not statistically significant (p>0.05). The maximum angle of scapular posterior tilt was higher in the chronic stroke participants compared to healthy participants; however, the difference was not statistically significant (p>0.05) (Table 5-14 and Table 5-17).

Under the unsupported condition, maximum trunk flexion occurred at the later phase of 'lift can' task in the chronic stroke participants compared to healthy participants (stroke 69% versus healthy 57% of task) (Table 5-14 and Table 5-17; Figure 5-13). Maximum trunk lateral flexion occurred earlier in the phase of 'lift can' task in the chronic stroke participants (stroke 24% versus healthy 52% of task) (Tables 5-14 and 5-17; Figure 5-13). Maximum scapular posterior tilt occurred earlier in the phase of 'lift can' task in the chronic stroke participants (stroke 2% versus healthy 11% of task) (Tables 5-14 and 5-17; Figure 5-14). The maximum angle of trunk rotation, scapular internal rotation, scapular upward rotation, shoulder flexion, elbow flexion and elbow extension occurred at similar phase of the 'lift can' task (Table 5-14 and Table 5-17; Figures 5-13, 5-14 and 5-15).

The standard deviations for trunk lateral flexion, trunk rotation, scapular upward rotation, scapular posterior tilt, shoulder flexion and elbow flexion/extension were larger in the chronic stroke participants compared to the healthy participants; thus, implying larger variability in these kinematic variables during execution of 'lift can' task in the chronic stroke participants.

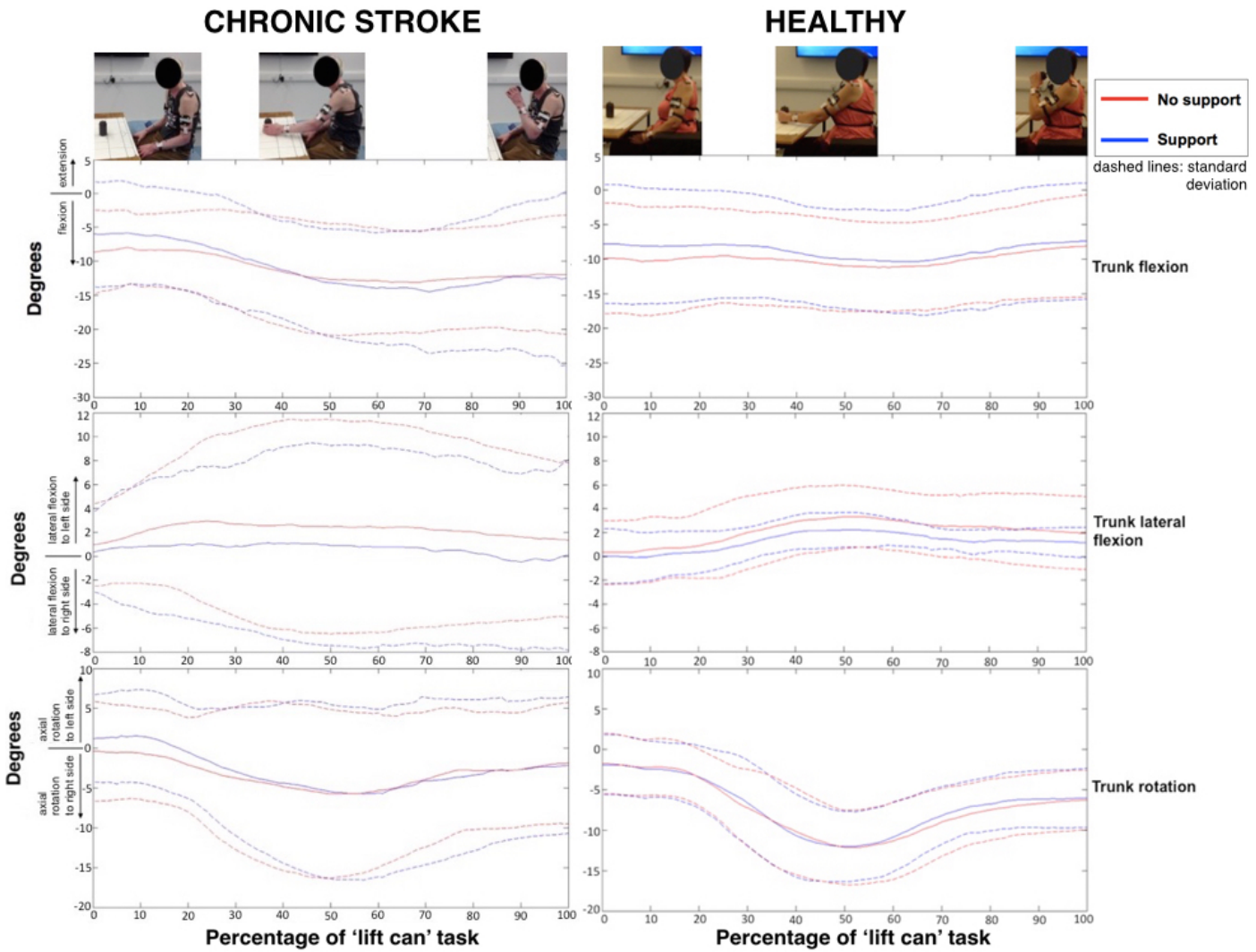


Figure 5-13 Comparison of the trunk movement patterns between chronic stroke participants and healthy participants

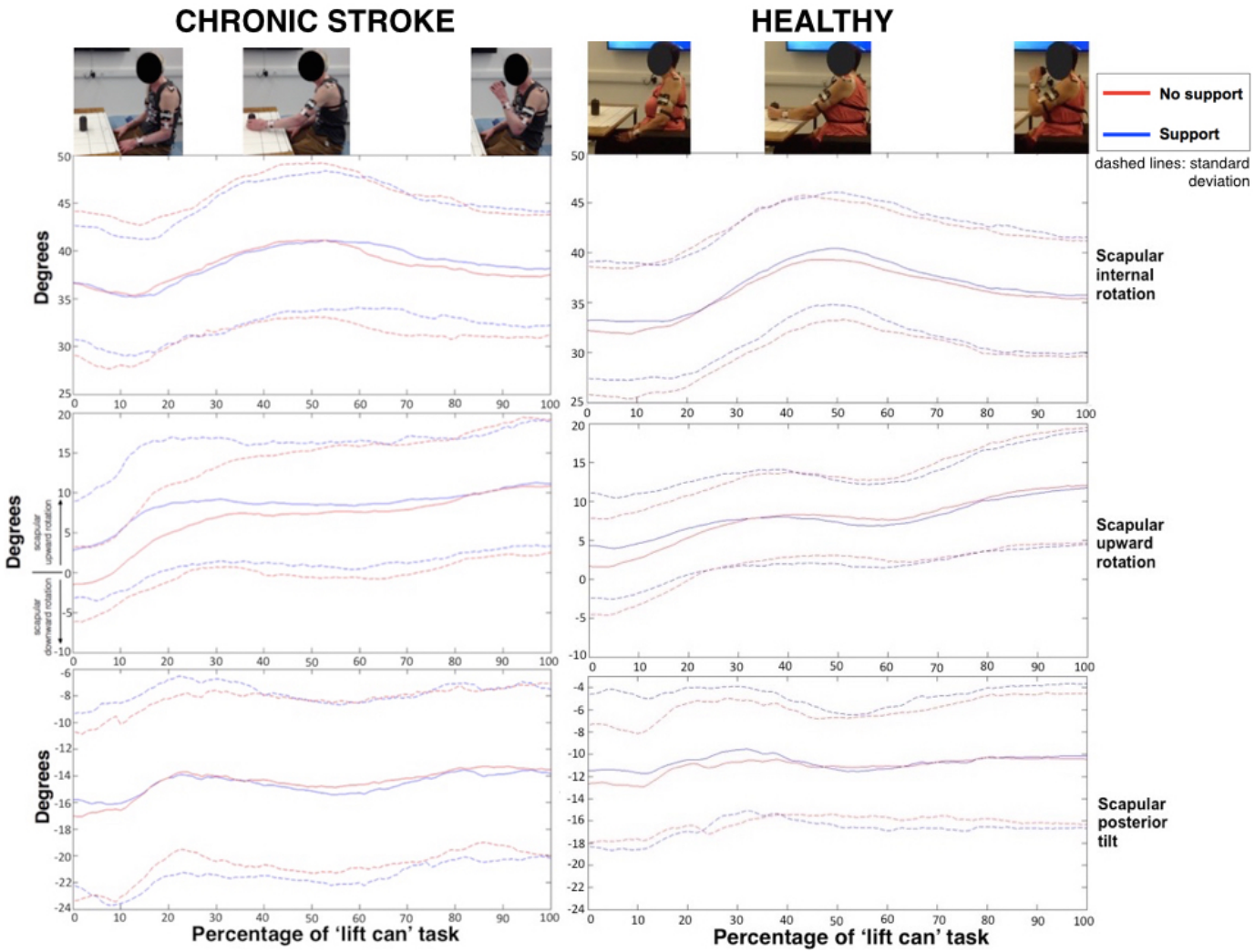


Figure 5-14 Comparison of the scapular movement patterns between chronic stroke participants and healthy participants

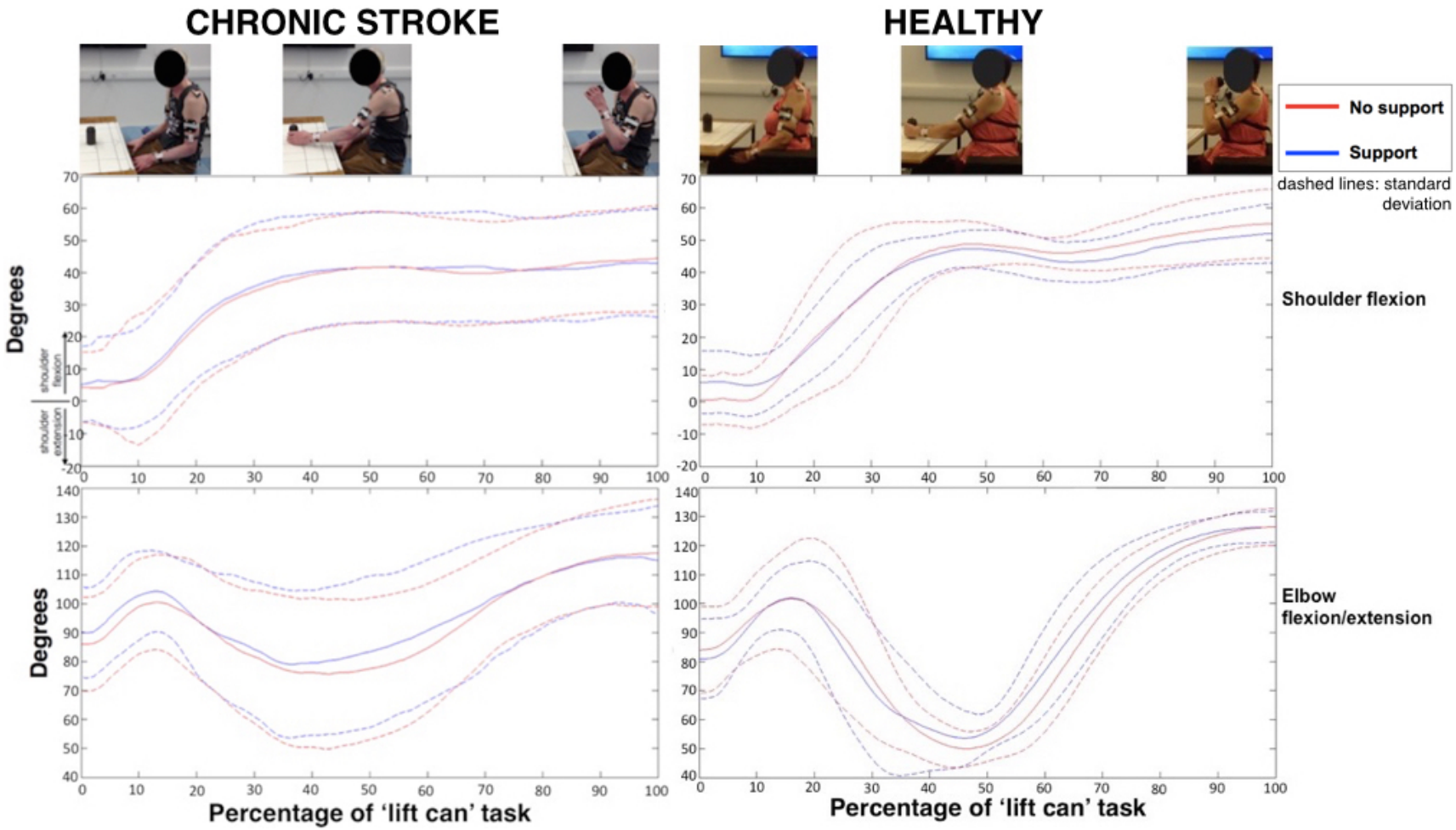


Figure 5-15 Comparison of the shoulder and elbow movement patterns between chronic stroke participants and healthy participants

5.12 Association between TIS, FMA and kinematic variables of chronic stroke participants and healthy participants

There was significant moderate correlation between TIS and movement duration, movement smoothness, movement straightness and trunk lateral flexion (Table 5-20). Weak correlations were found between TIS and trunk flexion, scapular upward rotation, shoulder flexion and elbow extension.

FMA was found to correlate strongly with movement duration, movement smoothness, trunk flexion and elbow extension (Table 5-20).

Table 5-20 Association between TIS, FMA and the clinical and kinematic variables for chronic stroke and healthy participants (Spearman's rho)

	TIS	FMA-UE (Total)	FMA shoulder-elbow subscore	FMA wrist-hand subscore
Movement duration	-0.55**	-0.78**	-0.79**	-0.70**
Movement smoothness	-0.60**	-0.63**	-0.67**	-0.47#
Movement straightness	-0.49**	-0.22	-0.17	-0.22
Maximum ulnar styloid velocity	0.30#	0.38	0.40#	0.36
Average ulnar styloid velocity	0.38*	0.45#	0.51*	0.26
Trunk flexion	-0.43**	-0.79**	-0.71**	-0.67**
Trunk lateral flexion	-0.53**	-0.44#	-0.51*	-0.24
Trunk rotation	-0.03	0.09	0.04	0.16
Scapular internal rotation	0.06	-0.17	0.01	-0.01
Scapular upward rotation	-0.30#	-0.19	-0.14	-0.18
Scapular posterior tilt	0.02	0.52*	0.49*	0.51*
Shoulder flexion	0.41**	0.40#	0.47#	0.21
Elbow extension	0.37*	0.76**	0.79**	0.63**

**p<0.001; *p<0.01; #p<0.05

5.13 Additional analysis

5.13.1 Comparability of the timing of 'lift can' task captured by a stopwatch and the Vicon motion capture system

All the assessments of SWMFT-Time were conducted by the author. Therefore, there could be an element of observer bias. The Bland-Altman plot was used to analyse the comparability of the timing of 'lift can' task captured by a stopwatch and the Vicon system. This method of plot is appropriate to assess the agreement between two measurement tools (Sedgwick 2013) . The Bland-Altman plot is illustrated in Figure 5-16. The results showed that the mean difference between the time measured with the stopwatch and the Vicon system was 0.01 seconds. In addition, all the time readings between the stopwatch and the Vicon system fall within the limits of agreement except one outlier. The limits of agreement were calculated based on two standard deviations of the mean difference in time. This interval was between -0.40 to 0.42 seconds, and is represented by the broken red lines (Figure 5-16). Hence, there was good agreement between the time measured with a stopwatch and the Vicon system. The spread of the data did not appear skewed in either direction. Taken together, this implies that a stopwatch remains a suitable tool for measurement of the SWMFT tasks. More importantly, these results assist to eliminate the element of observer bias partially.

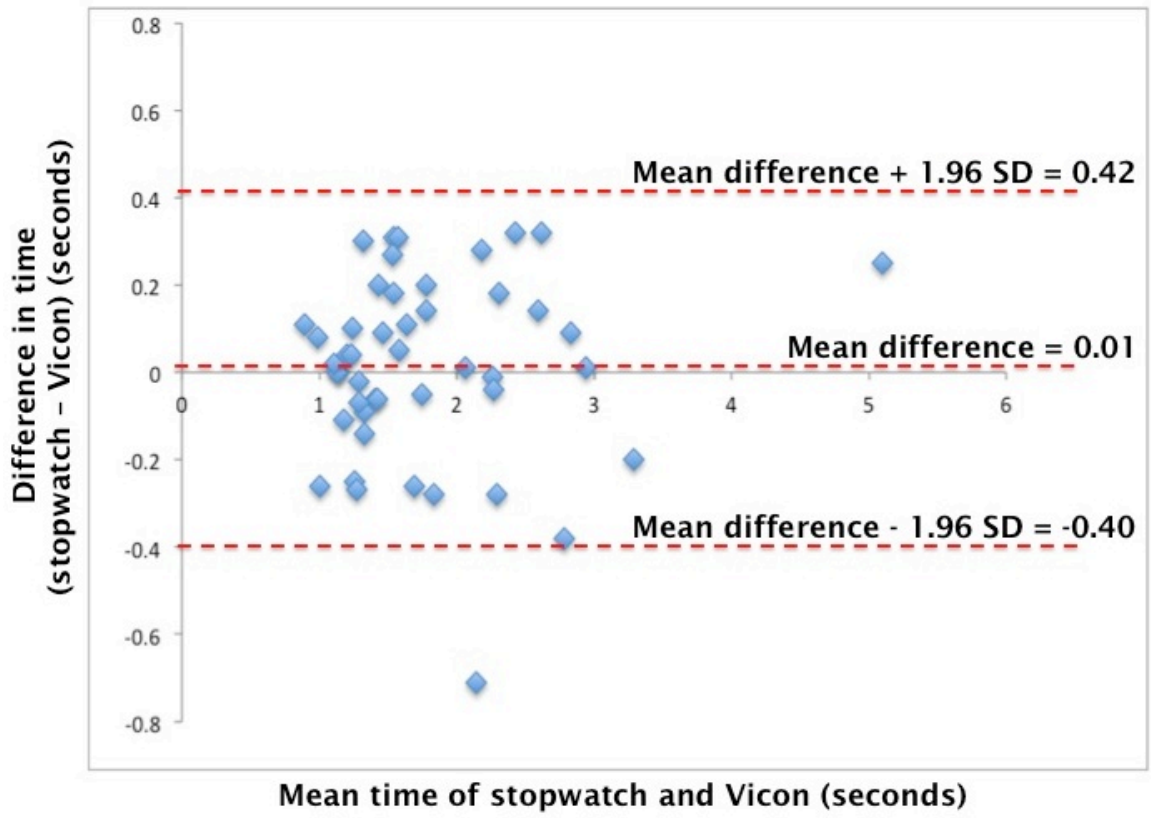


Figure 5-13 Bland-Altman plot of the difference in time measured with a stopwatch and the Vicon system against the mean time of the stopwatch and the Vicon system

5.14 Summary of Chapter 5

This Chapter has presented the clinical results of the subacute and chronic stroke participants and healthy participants from Phase 1A and Phase 1B studies. In addition, the kinematic (lift can task) results for the chronic stroke participants and healthy participants are presented. The key findings from the Phase 1A and Phase 1B studies are summarised below. Discussion of these findings in relation to previous research and clinical practice will be presented in Chapter 7.

5.14.1 Healthy participants

1) There was a statistically significant reduction in SWMFT-Time for the dominant upper extremity and the non-dominant upper extremity with trunk support.

2) There was a significant reduction in maximum ulnar styloid velocity, average ulnar styloid velocity, trunk lateral flexion, scapular internal rotation and scapular upward rotation with trunk support.

3) Significant improvements in movement smoothness and elbow extension were found for the trunk support condition.

4) The movement patterns of the trunk, scapula, shoulder and elbow during the 'lift can' task were similar with and without trunk support.

5.14.2 Chronic stroke participants

1) There was a statistically significant reduction in SWMFT-Time for both the affected upper extremity and less affected upper extremity with trunk support.

2) There was a statistically significant increase in TIS and SWMFT-FAS scores for the affected upper extremity with trunk support.

3) Significant improvement in movement smoothness and reduction in movement duration were found for the trunk support condition.

4) There was significant reduction in scapular upward rotation with trunk support.

5) The movement patterns of the trunk, scapula, shoulder and elbow during the 'lift can' task were similar with and without trunk support.

5.14.3 Subacute stroke participants

1) There was a statistically significant reduction in SWMFT-Time for both the affected upper extremity and less affected upper extremity with trunk support.

2) There was a statistically significant increase in TIS and SWMFT-FAS scores for the affected upper extremity with trunk support.

5.14.4 Comparison of clinical outcomes between subacute and chronic stroke participants and healthy participants

1) Main effect of group: significant difference in TIS scores between subacute and chronic stroke and healthy groups. Subacute stroke participants had lower TIS scores than chronic stroke participants and healthy participants.

2) Main effect of group: significant difference in SWMFT-Time between the three groups. Subacute stroke participants had longer SWMFT-time than chronic stroke participants and healthy participants.

3) Main effect of trunk support: the difference in TIS scores between the three groups were significant with large efect size.

4) Main effect of trunk support: the difference in SWMFT-Time between the three groups were significant with medium efect size.

5) There was a statistically significant interaction effect between group and support condition for TIS scores; effect size was very large. The TIS score increased significantly more with trunk support in the subacute stroke group as compared to the chronic stroke and healthy groups.

6) The chronic stroke participants exhibited a higher SWMFT-FAS than subacute stroke participants.

5.14.5 Comparison of kinematic outcomes between chronic stroke participants and healthy participants

1) Main effect of group: significant differences between the chronic stroke and healthy groups demonstrated for movement duration, movement smoothness, movement straightness, maximum ulnar styloid velocity, average ulnar styloid velocity, trunk flexion, trunk rotation, trunk lateral flexion, scapular upward rotation, shoulder flexion and elbow extension.

2) Main effect of trunk support: significant differences demonstrated for movement duration, movement smoothness, maximum ulnar styloid velocity, scapular upward rotation and elbow extension.

3) There was a statistically significant interaction effect between group and support condition for movement smoothness, with medium effect size. Movement smoothness improved significantly more with trunk support in the chronic stroke group compared to the healthy group.

4) The movement patterns of the trunk, scapula, shoulder and elbow during the 'lift can' task were similar for the chronic stroke participants and healthy participants.

5.14.6 Association between TIS, FMA and clinical variables

1) Significant strong correlation were found between TIS and FMA; FMA-shoulder-elbow; and FMA-wrist-hand.

2) There were strong correlation between TIS and SWMFT-Time; and between TIS and SWMFT-FAS.

3) FMA was found to correlate strongly with SWMFT-Time and SWMFT-FAS.

5.14.7 Association between TIS, FMA and kinematic variables

1) There was significant moderate correlation between TIS and movement duration; movement smoothness; movement straightness; and trunk lateral flexion.

2) Weak correlations were found between TIS and trunk flexion; scapular upward rotation; shoulder flexion; and elbow extension.

3) FMA was found to correlate strongly with movement duration; movement smoothness; trunk flexion; and elbow extension.

The results of the Phase 1A and Phase 1B studies will be discussed in greater depth in relation to the existing literature in Chapter 7 after reviewing the results of the Phase 2 study (longitudinal study) in the next Chapter.

Chapter 6: Results of Phase 2 study (longitudinal study)

6. Results of Phase 2 study

This Chapter presents the results of the Phase 2 study on subacute stroke participants. The Phase 2 study was a longitudinal study with the aims to examine the recovery pattern of trunk control and upper extremity impairment and function over the first six months post stroke, and to evaluate the impact of trunk control on the recovery pattern of upper extremity impairment and function.

This Chapter begins with the introduction of the concept of using an advanced statistical technique known as individual growth curve (IGC) modelling for the analysis of longitudinal data in the Phase 2 study. As IGC modelling is a very complex process, sections 6.1 to 6.3 are dedicated to explaining the whole process of creating models for the longitudinal data systematically so that the reader can comprehend the presentation of the results of Phase 2 study.

The results of Phase 2 study are presented from sections 6.4 to 6.10. The characteristics of the participants, clinical outcomes and the recovery trajectories of the trunk and upper extremity will be detailed. There will be a summary of the main findings at the end of the Chapter

6.1 Advantages of individual growth curve (IGC) modelling

This section highlights the advantages of IGC modelling and the justification for utilizing the technique to analyse the longitudinal data for the Phase 2 study.

IGC modelling is an advanced statistical technique for modelling intra-individual systematic change and inter-individual differences in outcomes over time (Rogosa et al. 1982; Rogosa & Willett 1983; Willett 1994; Willett 1997; McCoach & Kaniskan 2010; Shek & Ma 2011). IGC modelling is known by different names in different research literature; the more common ones are latent growth curve analysis (Voelkle 2007), hierarchical linear modelling (Warschausky et al. 2001; Woltman et al. 2012), mixed-effect modelling (Gibbons et al. 2010; Shek & Ma 2011; Yen et al. 2015), random effects modelling (DeLucia & Pitts 2006), and multilevel modelling (Field 2009; Peugh

2010; Shek & Ma 2011; Kozlowski et al. 2013).

IGC modelling has been demonstrated to offer additional advantages over traditional statistical analysis techniques in the analysis of longitudinal data (Field 2009; Peugh 2010; Shek & Ma 2011). Traditional statistical analysis techniques used for examining changes over time include repeated measures analysis of variance (ANOVA), multivariate ANOVA (MANOVA) and analysis of covariance (ANCOVA) (Shek & Ma 2011). These techniques focus on estimation of group mean trends across time but do not consider individual changes across time (Gibbons et al. 2010; Kozlowski & Heinemann 2013). In contrast, IGC modelling can be used to examine the unique trajectories of individuals, in addition to group analysis, in repeated measures data (Chen & Cohen 2006). IGC modelling would therefore capture a more comprehensive understanding of the changes in status of individuals across time. In the context of clinical practice, a better insight into the patterns of change and the effects at both the individual and group levels would provide valuable information to clinicians for the purpose of treatment recommendations, treatment planning and prediction of outcomes for patients.

For the traditional methods of analyses, there is an assumption of independence of observations (Field 2009). In addition, there is an assumption that the variances and covariances of the dependent variable across time are equal (Gibbons et al. 2010). In the longitudinal study design, multiple observations are nested within individuals. Observations from the same individual will typically be correlated by sharing the same characteristics and are therefore not independent (Cheng et al. 2010). Measures taken close together in time are more highly correlated than measures taken far apart in time (Littell et al. 2000). Thus, there is violation of the independence assumption required by traditional statistical analyses such as ANOVA. If traditional analysis techniques are used for longitudinal data analysis, they can produce excessive Type I errors and biased parameter estimates (Singer & Willett 2003; Peugh 2010; Shek & Ma 2011). The repeated measure ANOVA and MANOVA requires balanced data, i.e., equal sample size, equal time interval for measurement, with all individuals. IGC modelling has the advantage that it is immune to the “unbalancedness” (Gibbons et al. 2010) and

does not require balanced data across different waves of data (Shek & Ma 2011).

The other critical issue to address is missing data. Missing data is inevitable in longitudinal studies (Twisk & de Vente 2002; Engels 2003; Singer & Willett 2003; DeLucia & Pitts 2006; Donders et al. 2006; Field 2009; Baraldi & Enders 2010; Gibbons et al. 2010). There are various reasons to the cause of missing data. For example, some subjects are not available to be measured at all time points resulting in nonmonotone missing data patterns (Ibrahim & Molenberghs 2009); some subjects may achieve the full benefit of the study early on and discontinue the study because they feel that their continued participation will provide no added benefit (Gibbons et al. 2010). Therefore, such data present a considerable modelling challenge. MANOVA only includes individuals with complete data set across time (Gibbons et al. 2010). This implies that individuals with missing data are excluded from the analysis, hence losing valuable information. On the other hand, IGC modelling is able to accommodate outcome data missing at random without excluding individuals with incomplete data for analysis (DeLucia & Pitts 2006; Shek & Ma 2011; Kozlowski et al. 2013).

The IGC modelling simultaneously uses data on all individuals at every time point to concurrently investigate within- and between-individual change, with concomitant improvements in precision and power (Lenzenweger et al. 2004). The use of multiple data points can confirm linear change or expose curvilinear or nonlinear trends in the data, allowing for more precise delineation of the impact of separate factors on different aspects of recovery (Kozlowski et al. 2013; Pretz et al. 2013). In addition, IGC modelling is more powerful than ANOVA and MANOVA in examining the effects associated with repeated measures as it models the covariance matrix (Shek & Ma 2011). In other words, IGC modelling fits the true covariance structure to the data rather than imposing a certain structure commonly used in traditional statistical techniques. By selecting the appropriate covariance structure for the model, it will capture the true pattern of change over time and enable better interpretation of the results.

Taken together, IGC modelling can incorporate time factor, address correlations between measurement points, factor in both individual and group

changes across time and accommodate missing data so that the best model can be constructed to fit the longitudinal data set. Recent publications have demonstrated that IGC modelling is an appropriate statistical technique to examine recovery trajectories of patients over time (Kozlowski & Heinemann 2013; Kozlowski et al. 2013; Hart et al. 2014). Modelling recovery as individual and average group trajectories permits the interpretation of outcome as an evolving event rather than the state at a single time point (Kozlowski & Heinemann 2013). In addition, modelling individual trajectories will facilitate the development of prognostic tools to support clinical and administrative planning, and may provide a basis to examine disparities and effectiveness of clinical interventions (Kozlowski & Heinemann 2013). Hence, IGC modelling would be used to examine the recovery pattern of trunk control and upper extremity impairment and function over a period of six months in the Phase 2 study.

The next section details the systematic framework for building the IGC model for longitudinal data analysis. This will provide evidence that the final model has the best fit to the data prior to drawing inferences from the results.

6.2 Systematic framework for building individual growth curve modelling

6.2.1 Setting up the SPSS data file

Before performing IGC analysis, a "person-period data, one record for each period" (univariate format) set is required (Singer & Willett 2003). The SPSS file was restructured such that each row represents a single measurement at one point in time for an individual. Each column represents a different outcome variable (Figure 6-1). The restructured file is termed as the SPSS long format. The long format enables longitudinal data analysis using the "*Linear Mixed Model"* function in SPSS.

	ID	Sex	Age	Time_since_stroke_days	Stroke_type	Hand_Dominance	Affected_UL	UL_impairment	Trunk_Impairment	TIME	TIS	FMA
1	1	1	44	21	1	1	1	2	2	1	19	50
2	1	1	44	21	1	1	1	2	2	2	20	56
3	1	1	44	21	1	1	1	2	2	3	23	64
4	1	1	44	21	1	1	1	2	2	4	23	65
5	1	1	44	21	1	1	1	2	2	5	23	65
6	1	1	44	21	1	1	1	2	2	6	23	66
7	2	1	47	29	1	1	2	3	2	1	12	4
8	2	1	47	29	1	1	2	3	2	2	12	4
9	2	1	47	29	1	1	2	3	2	3	16	6
10	2	1	47	29	1	1	2	3	2	4	19	14
11	2	1	47	29	1	1	2	3	2	5	19	14
12	2	1	47	29	1	1	2	3	2	6	20	14
13	3	2	55	25	1	1	1	2	2	1	19	49
14	3	2	55	25	1	1	1	2	2	2	20	54
15	3	2	55	25	1	1	1	2	2	3	22	59
16	3	2	55	25	1	1	1	2	2	4	23	60
17	3	2	55	25	1	1	1	2	2	5	23	63
18	3	2	55	25	1	1	1	2	2	6	23	64

Figure 6-1 Sample of the long format in SPSS

6.2.2 Selection of an appropriate estimation method for IGC modelling

In SPSS, there are two methods for estimation of parameter values, namely, maximum likelihood (ML) and restricted maximum likelihood (REML). To compare models that differ both in regression coefficient and variance component estimates, ML estimation is more appropriate because REML only allows for tests of models that differ in their variances (Peugh 2010). Hence, ML would be used for estimation of parameter values for this doctoral study.

6.2.3 Testing of model fit

To test for model fit to the data of this study, the deviance statistic would be used. The term “likelihood ratio test” is used interchangeably with “deviance statistic” in the literature (Cheng et al. 2010; Curran et al. 2010; Peugh 2010). Firstly, it is important to note that the likelihood function captures “the probability of observing the sample data as a function of the model’s unknown parameters” (Singer & Willett 2003). The deviance statistic is equal to -2 multiplied by the natural log of the likelihood ratio, which then yield a value called a deviance (-2Log Likelihood [-2LL]) that can be used to compare the relative fit of two competing models (Cheng et al. 2010). Deviance is a measure of the badness of fit of a given model. It describes how much worse

the specified model is compared to the best possible model (Singer & Willett 2003).

The difference in the deviance statistics between the models is approximately chi-square distributed with degrees of freedom equal to the difference in the number of estimated parameters between the models (McCoach & Kaniskan 2010; Peugh 2010). If the resulting value of the deviance statistics is significant, then the model with the lower deviance value fits the data significantly better (Peugh 2010).

As different models in this study were constructed systematically, the deviance statistic would be examined until a final model was established. Peugh (2010) reported that a deviance statistic could be used to test models that differ only in regression coefficient estimates or to test models that differ in variance estimates. Hence, the deviance statistic would also be used when predictor variables of interest were added to the model to examine their significance and contribution to the model in this doctoral study.

6.2.4 Model building

6.2.4.1 Model 1: Unconditional means model (UMM)

The first step in IGC modelling was to create an unconditional means model (UMM), which is identical to a one-way ANOVA with random effects. No predictors were included in UMM. UMM serves as a baseline model to examine individual variation in the outcome variable without regard to time (Singer & Willett 2003). Cillessen and Borch (2006) stated that the goal of the UMM is to test whether there is sufficient variability in individuals' average scores on the dependent variable (averaged over time) for the analyses to proceed. Thus, the intraclass correlation coefficient (ICC) can be calculated from UMM. ICC describes the amount of variance in the outcome that is attributed to interindividual differences. If ICC ≥ 0.25, IGC modelling is required (Shek & Ma 2011). The formula for calculation of ICC:

$$\text{ICC} = (\text{Intercept variance})/(\text{Residual} + \text{Intercept variance})$$

The deviance statistic was used to compare subsequent models.

6.2.4.2 Model 2: Unconditional linear growth curve model

Once it was established that ICC ≥ 0.25 for this study, the next step was to build the unconditional linear growth curve model. This was a crucial step in building any growth model to identify the optimal functional form of the trajectory over time (Curran et al. 2010). In other words, establishing exactly how the repeated measures change as a function of time is critical. If the incorrect functional form is used as the basis for the initial growth model, then expanding this model to include complexities such as predictors of growth or multiple group analysis will likely lead to biased results (Curran et al. 2010).

The goal of the unconditional linear growth curve model is to test whether there is sufficient variability in the data over time (Cillessen & Borch 2006). This is the baseline growth curve model that examines individual variation of the growth rates, i.e., any significant variations in individual trajectory changes over time. In addition, the model also examines individual changes over time, i.e., how each person's rate of change deviates from the true rate of change of the population (Singer & Willett 2003; Peugh 2010).

There are two levels of IGC modelling. The level 1 model is commonly referred to as the intra-individual change model. The level 1 model estimates the average of the intra-individual initial status and rate of change over time. No predictors are included in this model. "*TIME*" was added as the linear growth.

$$\text{Level 1:} \quad Y_{ij} = b_{0i} + b_{1i}(TIME_{ij}) + \varepsilon_{ij} \qquad \text{[Equation 1]}$$

Y_{ij} : outcome variable i : person

b_0 : intercept j : measurement occasion

b_1 : slope

ε_{ij} : residual

The errors (residual ε_{ij}) are assumed to be independent and normally distributed with mean zero, and the variance is equal across individuals (Woodhouse et al. 1996; van Dommelen et al. 2005). A small residual value is an indication of a good estimation of the growth parameters.

The level 2 model is commonly referred to as the inter-individual change model. The level 2 model captures inter-individual variability in the growth rates.

$$\text{Level 2:} \quad b_{0i} = \beta_{00} + r_{0i}$$

$$b_{1i} = \beta_{10} + r_{1i}$$

Hence, the composite equation for Level 1 and Level 2:

$$Y_{ij} = (\beta_{00} + r_{0i}) + [(\beta_{10} + r_{1i})(TIME_{ij})] + \varepsilon_{ij} \qquad \text{[Equation 2]}$$

$\boldsymbol{\beta_{00}}$: intercept (population estimates)

$\boldsymbol{r_{0i}}$: individual's deviation from the population intercept

$\boldsymbol{\beta_{10}}$: slope (population estimates)

$\boldsymbol{r_{1i}}$: individual's deviation from the population slope

The individual deviations, r_{0i} and $r_{1i,}$ are the level 2 residuals, which are considered as the random effects. It is the estimation of these deviations of individuals from the population curve that puts the "individual" in IGC modelling (DeLucia & Pitts 2006).

The deviance statistic was used to compare the unconditional linear growth model and the unconditional means model to examine which model has a better fit to the data. If the effect of linear growth (*TIME*, b_1) is not statistically significant, there is no need to perform further growth curve modelling analysis.

6.2.4.3 Model 3: Quadratic growth curve model

Based on the stroke recovery patterns reported in previous studies (Duncan et al. 1994; Kwakkel et al. 2004; Kwakkel et al. 2006; Verheyden et al. 2008; Kwakkel & Kollen 2013; Lee et al. 2015b), it is clear that the stroke recovery trajectories are nonlinear over time. Researchers frequently assume a linear functional form in growth curve when higher-order polynomials may better model the data (Singer & Willett 2003). Any inferences that a researcher makes

about inter-individual differences in growth that are based on incorrect assumptions or specifications about the shape of that growth may be incorrect (McCoach & Kaniskan 2010). Hence, it was reasonable, as the next step, to build the quadratic growth curve model to assess the quadratic trend, i.e., rate of change, and examine the acceleration and deceleration of the trajectories over time. A model with quadratic time (i.e.,$TIME^2$) was examined by adding quadratic parameter ($TIME^2$) in the previous model.

$$\text{Level 1:} \quad Y_{ij} = b_{0i} + b_{1i}(TIME_{ij}) + b_{2i}(TIME_{ij})^2 + \varepsilon_{ij} \qquad \text{[Equation 3]}$$

Similarly, the deviance statistic was used to compare the unconditional linear growth curve model and the quadratic growth curve model. If the -2 Log Likelihood (-2LL) difference is not statistically significant, the linear growth curve model will be retained as the final model. If the -2LL difference is significant, the cubic growth curve model will be built and reassessed for fit.

6.2.4.4 Model 4: Cubic growth curve model

The purpose of this model was to examine whether the cubic trend fits the data better than the quadratic trend. To build a cubic growth curve model, the cubic parameter ($TIME^3$) was added in the previous model.

$$\text{Level 1:} \quad Y_{ij} = b_{0i} + b_{1i}(TIME_{ij}) + b_{2i}(TIME_{ij})^2 + b_{3i}(TIME_{ij})^3 + \varepsilon_{ij} \qquad \text{[Equation 4]}$$

The deviance statistic was used to compare the quadratic growth curve model and the cubic growth curve model. If the -2LL difference is not statistically significant, the quadratic growth curve model will be retained as the final model.

6.2.4.5 Examination of the covariance structure

In longitudinal studies, observations from the same individual will typically be correlated by sharing the same characteristics (Cheng et al, 2010). A key step in the analysis of correlated data is to determine the appropriate covariance structure, which describes the form or structure of the correlation among data points within clusters (Fitzmaurice et al. 2004). Covariance is a measure of

how changes in one variable are associated with changes in a second variable. Covariance structures between the repeated measures have an important effect on the estimates to be made (Ser 2012). Ignoring covariance structure may result in erroneous inference, and avoiding it may result in inefficient inference (Littell et al, 2000).

SPSS has 17 different covariance structures that can be used (Peugh & Enders 2005; Field 2009). In the present study, the three commonly used covariance structures, namely, compound symmetry, first-order autoregressive [AR(1)] and heterogeneous first-order autoregressive [AR(1)heterogeneous] (Wolfinger 1996; Singer 1998; Singer & Willett 2003; Wittekind et al. 2009; Ser 2012) would be examined. The goodness-of-fit index, -2LL, would be used to assess which covariance structure improves the fit of the model. The smaller the value of -2LL, the better is the fit to the model.

6.2.4.5.1 Model 5: Compound symmetry covariance structure

In the compound symmetry covariance structure, the variances are homogeneous. There is a correlation between two separate measurements, but it is assumed that the correlation is constant regardless of how far apart the measurements are (Littell et al, 2000).

6.2.4.5.2 Model 6: First-order autoregressive covariance structure

In the first-order autoregressive [AR(1)] covariance structure, the variances are assumed to be homogeneous and correlations decline exponentially with distance. It means that data from measurement waves lying close to one another correlate more highly than data from more distant measurement waves (Wittekind et al, 2009).

6.2.4.5.3 Model 7: Heterogeneous first-order autoregressive covariance structure

In the heterogeneous first-order autoregressive [AR(1)heterogeneous], the variances are assumed to be heterogeneous. Similar to AR(1), the correlations decline exponentially with distance, i.e., two measurements taken farther apart in time would be less correlated. The AR(1)heterogeneous structure is often

used in growth curve modelling (Field, 2009).

Following the comparison of the three covariance structures, the one with the lowest -2LL value was retained for the next step of model building.

6.2.4.6 Model 8: Addition of predictors (covariates)

The next step in the model building process was to add predictor variables at level 1. The purpose was to examine whether baseline variables (eg. Trunk Impairment Scale) were predictive of change in outcome variable (eg. SWMFT-Time) over time. The inclusion of predictors, also known as covariates, in the model results in what is called a conditional growth model because the fixed and random effects are now "conditioned on" the predictors (Curran et al, 2010). In other words, the addition of 1 or more covariates to explain variance of the growth parameters will produce models that are conditional on the specific associations between the covariate(s) and the growth parameters that are included (Kozlowski et al, 2013).

There are two types of covariates, namely time-invariant covariates (TIC) and time-varying covariates (TVC). TIC do not change in value as a function of time (Stoel & van den Wittenboer 2004; Curran et al. 2010). Examples of TIC are gender, type of stroke and hand dominance. TVC can change as a function of time (Curran et al, 2010; McCoach & Kaniskan, 2010). Examples of TVC are Trunk Impairment Scale, Fugl-Meyer Assessment and SWMFT-Time.

TIC evaluates whether characteristics of the individual, e.g., gender, affected side of upper extremity, are predictive of higher or lower initial status (intercept) or steeper or less steep rates of change (slope) over time (Curran et al, 2010). TVC directly predicts the repeated measures while controlling for the influence of the growth factors. Thus, any given repeated measure is jointly determined by the underlying growth factors and the impact of the TVC at that time period (Curran et al, 2010). TVC can influence the overall shape of growth trajectories (Rojas & Iglesias 2013).

In the analysis for this study, separate models would be fitted with each TIC and TVC by adding the predictor (value at baseline) and an interaction term (predictor × time) to the unconditional growth model. To which growth curve model (linear, quadratic or cubic trend) to add the predictors would depend on

the deviance statistic to determine which of these models has the best fit to the data. The interaction term was included to examine whether the proposed predictor variable predicted change in outcome variable over time. After testing each predictor individually, all significant predictors would be included in the final model in order to determine which predictors accounted for unique variance in the outcome variable. Results are considered significant at $p<0.05$.

6.3 Summary of IGC modelling

Sections 6.1 to 6.3 detailed the advantages and robustness of using IGC modelling for the longitudinal data analysis for the Phase 2 study. The systematic approach to building the best IGC model to fit the data was also presented. The basic unconditional means model was first built to serve as a baseline model for comparison with subsequent models. The next critical step was to determine the form of trajectory that best fit the data by testing the relative significance of linear, quadratic, and cubic trajectories (unconditional growth curve models). Following that, the common covariance structures used in longitudinal studies were examined to identify the best structure to fit the model to the data. Finally, predictors were added to the model to evaluate their contribution in explaining the intra-individual and inter-individual differences in trajectories and outcome variables.

The subsequent sections 6.4 to 6.10 present the results of Phase 2 study.

6.4 Results of Phase 2 study

6.4.1 Characteristics of subacute stroke participants

Consecutive 216 subacute stroke participants who were admitted to the Rehabilitation Centre of Tan Tock Seng Hospital, Singapore, from May 2015 to September 2015, were screened for eligibility for this study (Figure 6-2). Forty-five stroke participants (mean age 59.2 years) who met the inclusion criteria, provided informed consent and were recruited. Forty-three stroke participants were recruited at ≤1-month post stroke; one participant was recruited at 2-month post stroke; and one participant was recruited at 3-month post stroke.

The clinical and demographic characteristics of participants are summarised in Table 6-1. At recruitment, 86.7% of the stroke participants had moderate to severe impairment of the upper extremity and 95.6% of the participants had poor to fair trunk control. Each participant was on follow-up once a month till 6 months post stroke. Data related to the participant's TIS, FMA, SWMFT-Time and SWMFT-FAS were gathered during the follow-up period.

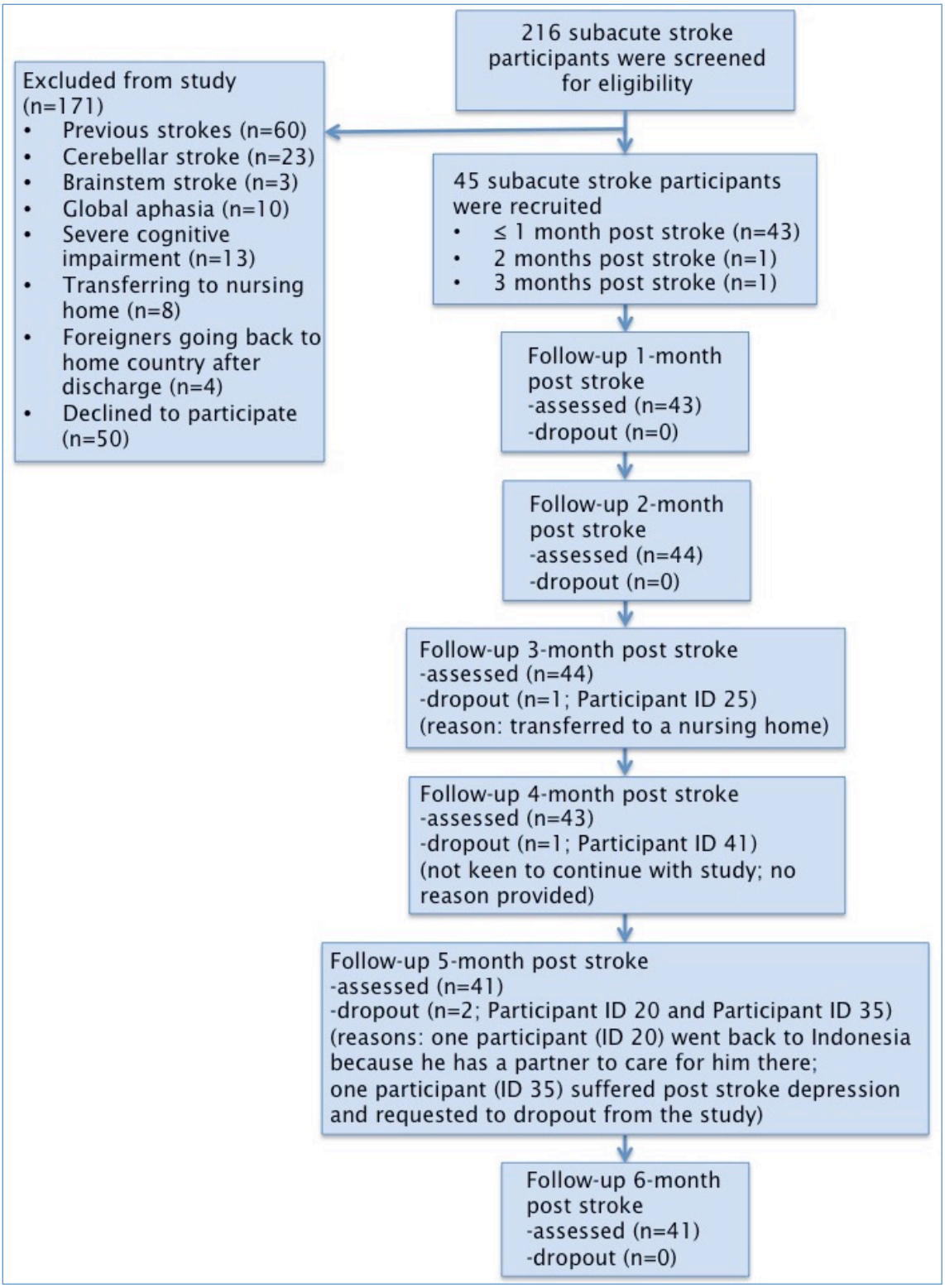


Figure 6-2 Flowchart of recruitment process and completion of the Phase 2 study

Table 6-1 Characteristics of subacute stroke participants

Characteristics	Subacute stroke participants (N=45)
Age (years)	59.2 ± 11.2 range 34 – 84
Sex - Male Female	26 19
Time since stroke (days)	22.4 ± 15.8 range 7 – 90
Type of stroke – Ischaemic Haemorrhagic	29 16
Hand dominance – Right Left	40 5
Affected upper extremity – Right Left	21 24
Fugl-Meyer Upper Extremity (FMA) score Number of participants with FMA ≤ 20 (Severe impairment) 21-50 (Moderate impairment) 51-66 (Mild impairment)	25.5 ± 20.2 range 4 – 61 22 17 6
Trunk Impairment Scale (TIS) score Number of participants with TIS ≤ 10 (poor trunk control) 11-19 (fair trunk control) ≥ 20 (good trunk control)	13.2 ± 4.2 range 3 – 22 13 30 2

mean ± standard deviation

6.4.2 Dropout and missing data

Over the entire data collection period from May 2014 to February 2015, four participants dropped out at different time points due to various reasons (Table 6-2 and Figure 6-2). All the missing data were classified as "missing completely at random" (MCAR) because the reasons for dropout were totally unrelated to the measured variables and outcomes. Little and Rubin (2002) classified data as MCAR when the probability of missing data on a variable *X* is unrelated to other measured variables and to the values of *X* itself. Due to the dropout, the total number of measurement data was 256 instead of 267. Despite some missing data in this study, the IGC modelling technique is robust enough to accommodate outcome data missing at random without excluding individuals with incomplete data for analysis (Delucia & Pitts, 2006; Shek & Ma, 2011; Kozlowski et al, 2013).

Table 6-2 Reasons for drop-out from the study

	Number of participants	Number of drop-out	Reason for drop-out
Time point 1: 1st month	43	0	
Time point 2: 2nd month	44	0	
Time point 3: 3rd month	44	1	Participant was transferred to a nursing home.
Time point 4: 4th month	43	1	Participant was not keen to continue with study. No reason provided.
Time point 5: 5th month	41	2	One participant went back to Indonesia because he has a partner to care for him there. One participant suffered post stroke depression and requested to dropout from the study.
Time point 6: 6th month	41	0	

6.4.3 Duration of therapy received during the first 6 months post stroke

The participants were requested to log the average duration per day spent on upper extremity exercises and interventions on the therapy log sheets and hand them over to the author (SKW) during the assessment sessions at 6 time points. The types of therapy exercises that the participants engaged in consisted of stretching and strengthening exercises; passive, active-assisted and active exercises; functional electrical stimulation; functional task training; acupuncture; acupressure; and traditional Chinese medicine massage. Post discharge from the inpatient rehabilitation centre, 53.3% participants chose to attend therapy at day rehabilitation centres or outpatient therapy clinics; 8.9% received home-based therapy; and 37.8% chose to do self exercises at home. All the therapy log data were self-reported. Different combinations of upper extremity exercises and interventions were received per participant based on the individual's preference and financial resources to pay for the interventions. The author could only present the mean duration of therapy time spent on the upper extremity per day at each time point (Table 6-3) to provide an estimated overview of upper extremity rehabilitation over the first 6 months post stroke. The mean duration of therapy time includes both supervised and unsupervised therapy sessions.

Table 6-3 Mean duration of therapy received per day at each time point

Time post stroke	Therapy time (minutes)
1st month	81.31 ± 12.55
2nd month	82.19 ± 19.27
3rd month	80.88 ± 30.38
4th month	89.05 ± 42.96
5th month	89.67 ± 48.89
6th month	91.24 ± 48.24

mean ± standard deviation

6.4.4 Individual growth curve models for TIS, FMA, SWMFT-Time and SWMFT-FAS

The subsequent sections detail the results of model building and the identification of appropriate predictors of the models for the 4 outcome variables: the Trunk Impairment Scale (TIS), Fugl-Meyer Upper Extremity score (FMA), SWMFT-Time and SWMFT-FAS. The FMA can be subdivided into FMA-Shoulder-Elbow subscale (FMA-SE) (Kung et al. 2012; Rundquist et al. 2012) and FMA-Wrist-Hand subscale (FMA-WH) (Page et al. 2012b; Page et al. 2015; Persch et al. 2015; Schulz et al. 2015). The results of FMA-SE and FMA-WH will be presented to provide insights into the proximal and distal recovery of the upper extremity.

Tables 6-4, 6-9, 6-14, 6-19, 6-24 and 6-29 present the results of fitting the unconditional linear, quadratic and cubic growth model for TIS, FMA, FMA-SE and FMA-WH respectively. The Tables also detail the estimates of the intercept (initial status) and slope (rate of change) for each growth model. In addition, each table also presents the variances of the intercepts and slopes.

6.4.4.1 Trunk Impairment Scale (TIS)

The results demonstrated that the quadratic model (Model 3 – shaded in grey) improved model fit over the linear model (Model 2) based on the -2 log likelihood test ($x^2(1) = 1085.47 - 989.77 = 95.70$, $p<0.001$) (Table 6-4). However, the cubic model (Model 4) did not further improve model fit ($x^2(1) = 989.77 - 987.46 = 2.31$, $p>0.05$). Therefore, the quadratic change of TIS (Model 3) was modelled in all subsequent analyses.

Analysis of the different covariance structures showed that the heterogeneous first-order autoregressive [AR(1) heterogeneous] covariance structure yield the lowest -2LL value (Table 6-5). Hence, the final decision was to use AR(1) heterogeneous structure for subsequent analysis because the -2LL value is lowest and the assumption of the correlation is sound, i.e., the correlations between repeated measurements get smaller over time; and the covariance structure is often used in growth curve modelling (Field, 2009).

Table 6-4 Comparison of growth curve model parameter estimates for TIS

	Model 1 Unconditional means model	**Model 2** Unconditional Linear Model	**Model 3** Unconditional quadratic model	**Model 4** Unconditional cubic model
FIXED EFFECTS				
Initial status				
Intercept	19.61***	16.56***	15.45***	15.36***
Rate of change				
Linear slope		1.24***	2.76***	3.14***
Quadratic slope			-0.29***	-0.50***
Cubic slope				0.03
RANDOM EFFECTS				
Level 1 intra-individual:				
Residual variance	7.65***	2.03***	0.93***	0.91***
Level 2 inter-individual:				
Variance of intercept	3.95***	8.35***	12.93***	13.02***
Variance of slope		0.17	0.39***	0.40***
GOODNESS-OF-FIT				
-2LL	1303.66	1085.47	989.77	987.46
No. of parameters	3	5	6	7
x^2		218.19***	95.70***	2.31
Degrees of freedom		2	1	1

***p<0.001; **p<0.01; *p<0.05
-2LL: -2 Log Likelihood
x^2: chi-square
critical value $x^2(1) = 10.83$ $p < 0.001$
$x^2(1) = 6.64$ $p < 0.01$
$x^2(1) = 3.84$ $p < 0.05$

The column shaded in grey represents the best model fit.

Table 6-5 Covariance structure models for TIS

Covariance structure	-2 Log Likelihood -2LL
Compound symmetry	1075.29
AR(1)	1075.29
AR(1) heterogeneous	890.25

6.4.4.1.1 Shape of TIS recovery curve

Table 6-6 illustrates the impact of each predictor when it was added to the quadratic model. The significant predictors of TIS were stroke type, time post stroke, severity of upper extremity (UE) impairment and severity of trunk impairment. This implies that these predictors have an influence on the overall shape of TIS recovery curve. The combination of significant predictors in a conditional multivariable model is presented in Table 6-7. Finally, the most parsimonious multivariable model was determined based on the model with the largest reduction in the proportional variance (pseudo R^2) as compared to the quadratic model with no predictors.

The formula to calculate pseudo R^2 :

$$\text{Pseudo } R^2 = \frac{(\text{Residual Variance}_{\text{baseline}} - \text{Residual Variance}_{\text{predictor}})}{\text{Residual Variance}_{\text{baseline}}}$$

Table 6-6 Effect of predictors on the TIS model

Predictors	Conditional quadratic model	
	F statistic	p value
Age	0.13	0.721
Age x TIME (linear slope)	1.62	0.205
Age x TIME x TIME (quadratic slope)	2.74	0.100
Gender	0.001	0.974
Gender x TIME	0.29	0.591
Gender x TIME x TIME	0.35	0.557
Hand dominance	0.02	0.898
Hand dominance x TIME	0.003	0.960
Hand dominance x TIME x TIME	0.001	0.997
Affected UE	0.78	0.383
Affected UE x TIME	0.10	0.751
Affected UE x TIME x TIME	0.01	0.923
Time post stroke	38.55***	0.001
Time post stroke x TIME	27.42***	0.001
Time post stroke x TIME x TIME	9.45**	0.002
Stroke type	7.08*	0.011
Stroke type x TIME	32.46***	0.001
Stroke type x TIME x TIME	26.53***	0.001
Severity of UE impairment	22.12***	0.001
Severity of UE impairment x TIME	10.08**	0.002
Severity of UE impairment x TIME x TIME	2.12	0.147
Severity of trunk impairment	26.02***	0.001
Severity of trunk impairment x TIME	34.62***	0.001
Severity of trunk impairment x TIME x TIME	19.02***	0.001
Therapy Time	0.20	0.659
Therapy Time x TIME	0.03	0.869
Therapy Time x TIME x TIME	0.06	0.811

***p<0.001; **p<0.01; *p<0.05

Table 6-7 TIS: Combination of predictors and pseudo R^2

Predictors	-2LL	df	Deviance statistics	*p* value	Residual variance	Proportional variance reduction Pseudo R^2
Stroke type x Time post stroke x UE impairment x Trunk impairment x TIME²	820.11	10	70.14	0.001	0.76	16.4%
Stroke type x UE impairment x Trunk impairment x TIME²	842.94	10	47.31	0.001	0.79	13.2%
Stroke type x UE impairment x TIME²	854.54	10	35.71	0.001	0.82	9.9%
UE impairment x Trunk impairment x TIME²	853.28	10	36.97	0.001	0.87	4.4%
Time post stroke x stroke type x TIME²	841.46	10	48.82	0.001	0.80	12.1%
Time post stroke x UE impairment x TIME²	841.20	10	49.05	0.001	0.85	6.6%
Time post stroke x Trunk impairment x TIME²	826.56	10	63.69	0.001	0.79	13.2%
Time post stroke x Stroke type x Trunk impairment x TIME²	821.99	10	68.26	0.001	0.75	17.6%
Time post stroke x UE impairment x Trunk impairment x TIME²	814.72	10	75.53	0.001	0.80	12.1%
Stroke type x Time post stroke x UE impairment x TIME²	834.62	10	55.63	0.001	0.79	13.2%

Note: the baseline quadratic curve: -2LL = 890.25
df = 7
Residual = 0.91

critical value $x^2(3) = 16.27$ $p < 0.001$
$x^2(3) = 11.35$ $p < 0.01$
$x^2(3) = 7.82$ $p < 0.05$

The row shaded in grey represents the model with the largest pseudo R^2.

Table 6-7 showed that the combined predictors, i.e., (Time post stroke x stroke type x Severity of trunk impairment x TIME^2) (shaded in grey), demonstrated the largest pseudo R^2 of 17.6%. Hence, the full equation for the estimated model for TIS is:

Trunk Impairment Scale = 20.10 + (1.37 x TIME) + (-0.15 x TIME^2) + (-0.06 x Time post stroke x Stroke type x Severity of trunk impairment) + (0.02 x Time post stroke x Stroke type x Severity of trunk impairment x TIME) + (-0.002 x Time post stroke x Stroke type x Severity of trunk impairment x TIME^2)

This equation was used to plot the predicted TIS against the observed TIS (Figure 6-3). The R^2 value was 62.8%.

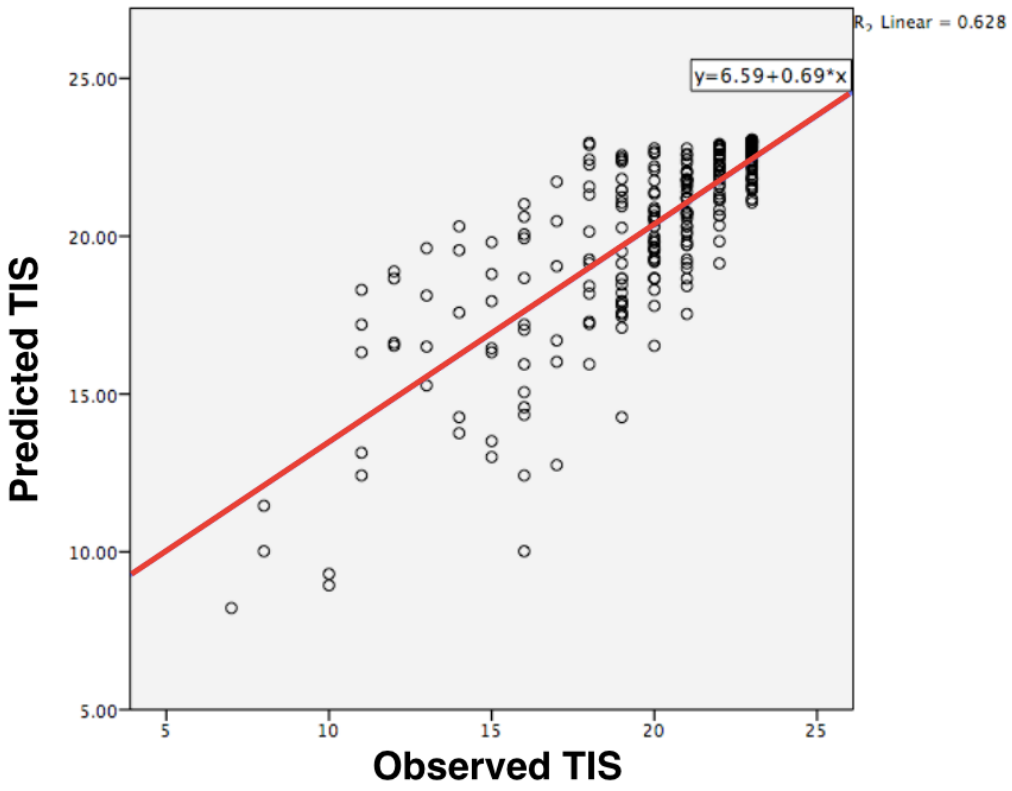


Figure 6-3 Plot of the predicted TIS against the observed TIS

Figure 6-4 illustrates the individual TIS recovery curves for the group of 45 subacute stroke participants. Figure 6-5 illustrates the prototypical plot of the TIS recovery curve derived from the equation of the estimated model. The curve showed that the most rapid recovery of TIS occurred in the first 3 months post stroke and then the rate of recovery decreased from 3rd to 6th month period. This finding is supported by the SPSS analysis of the instantaneous rate of change (slope) for the TIS recovery curve at each time point (Table 6-8 and Figure 6-6). The instantaneous rate of change refers to the rate of change of the curve, i.e., tangent to the curve, at a specific point in time.

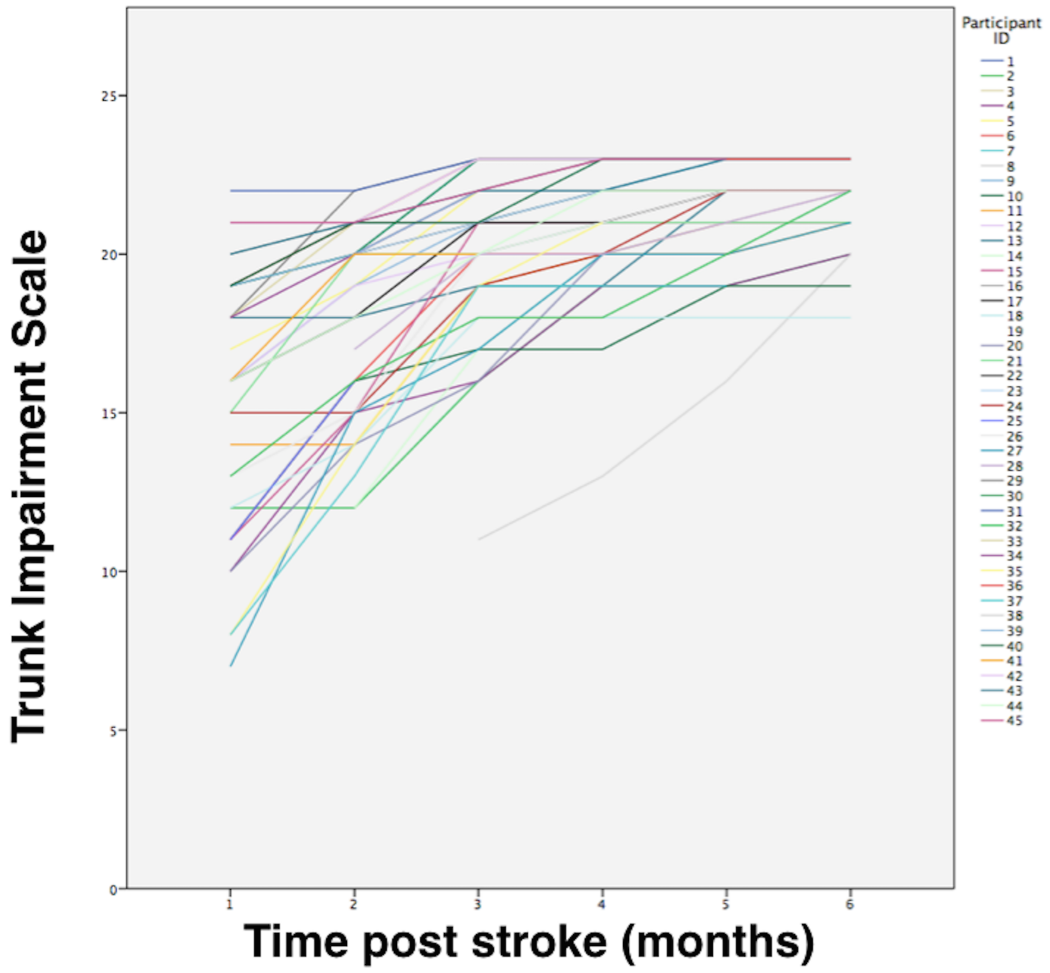


Figure 6-4 Individual TIS recovery curves of 45 subacute stroke participants

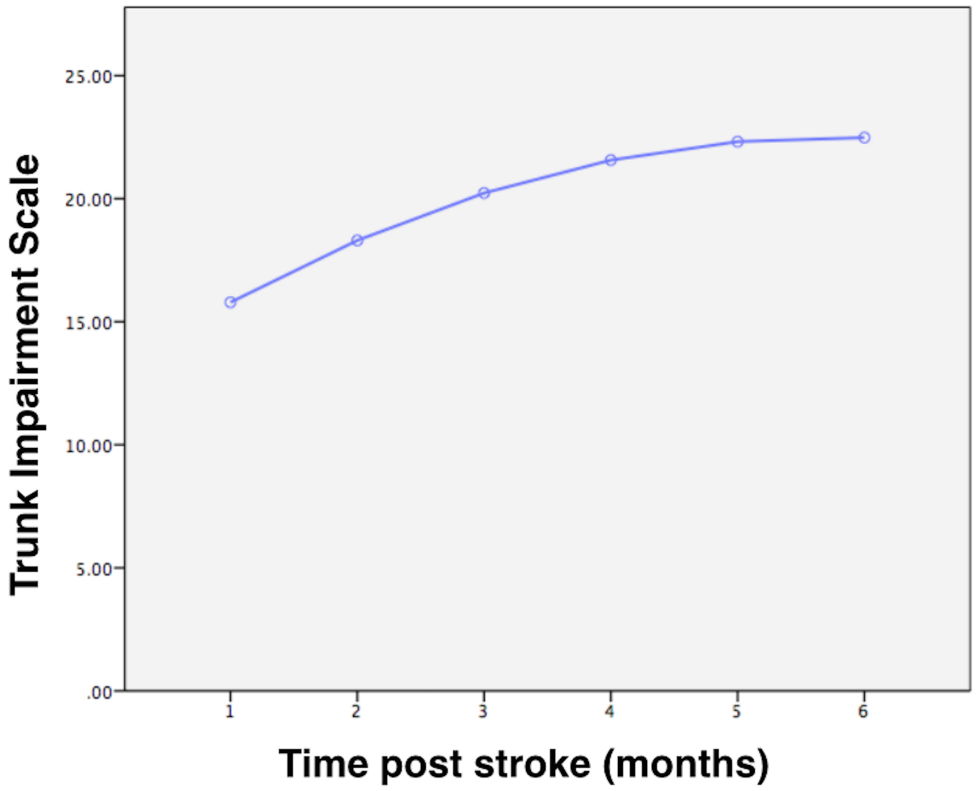


Figure 6-5 Prototypical plot of the recovery curve of TIS

Table 6-8 Instantaneous rate of change of TIS recovery curve in the first 6 months post stroke

Time post stroke	Rate of change (TIS points/month)
1st month	2.81
2nd month	2.20
3rd month	1.59
4th month	0.99
5th month	0.38
6th month	-0.23

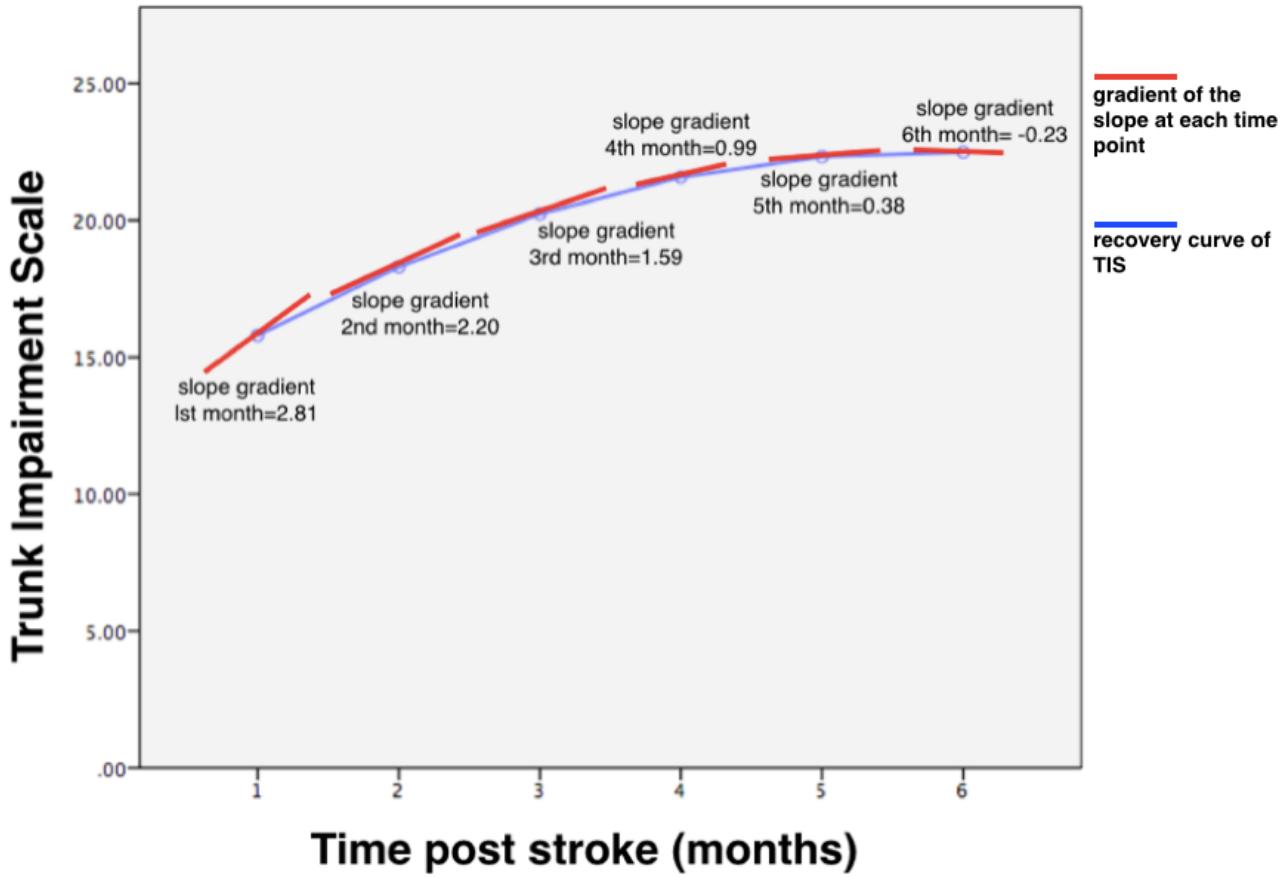


Figure 6-6 Instantaneous rate of change of TIS recovery curve in the first 6 months post stroke

6.4.4.1.2 Impact of initial TIS score on the trajectory of recovery curve

Results demonstrated a negative and significant intercept-slope covariance (covariance = -0.97, p<0.001). This suggests that as the intercept increased, the slope decreased (Figure 6-7). In other words, those participants with lower initial TIS score demonstrated a faster rate of change, on average, than those with higher initial TIS score. Similarly, those participants with higher initial TIS score demonstrated a slower rate of change, on average, than those with lower initial TIS score.

The negative and significant intercept-slope covariance also suggest that those participants with lower TIS score at initial status might catch up to those with higher TIS score, as the initial differences in TIS would tend to become less pronounced over time (Figure 6-7).

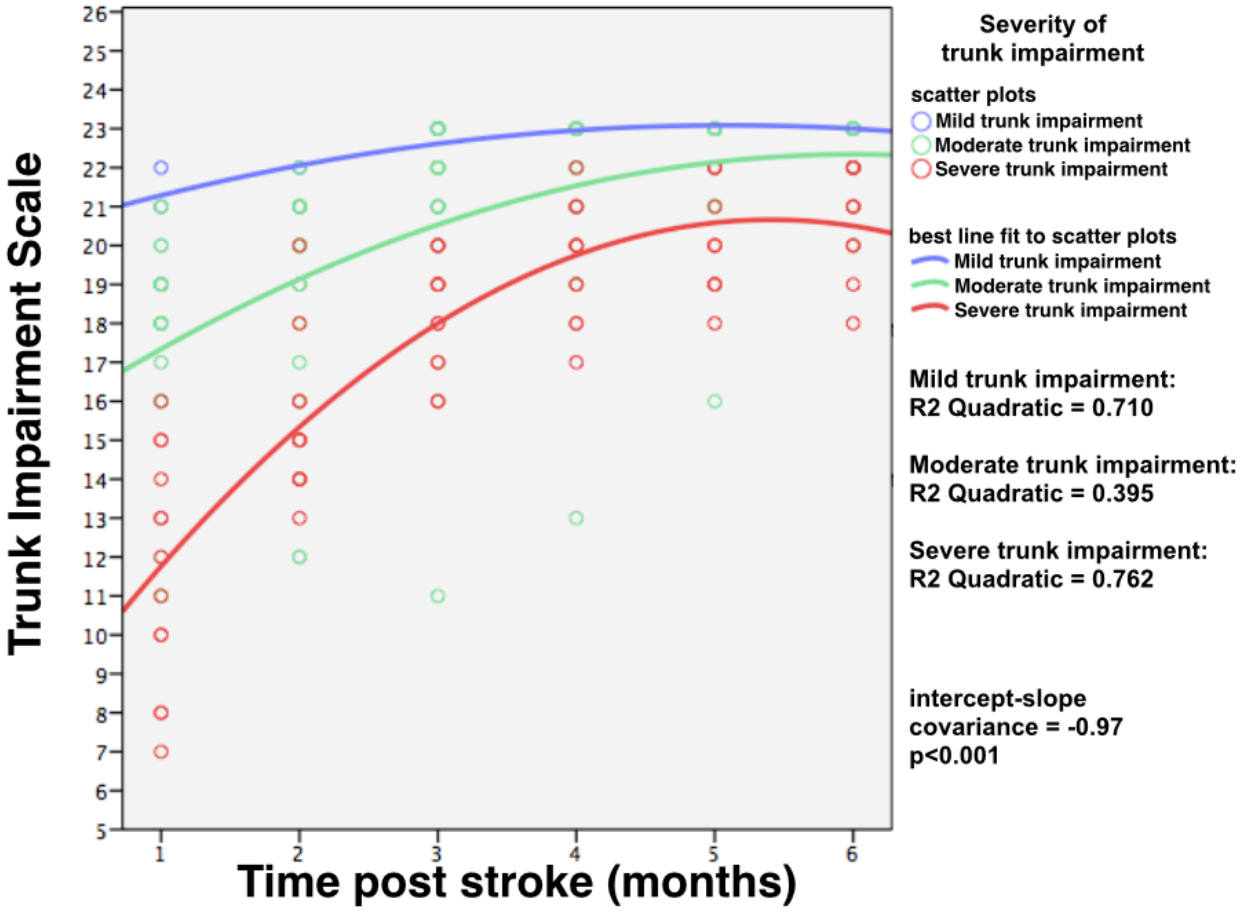


Figure 6-7 TIS recovery curves based on severity of trunk impairment

6.4.4.1.3 Intra-individual and inter-individual variability in TIS

Results from the final TIS model demonstrated significant intra-individual variability across each wave of measurement (residual variance = 0.75, p<0.001). There was inter-individual variability in the intercept (variance = 0.94, p<0.001) and slope (variance = 0.18, p<0.001) over time.

6.4.4.2 Fugl-Meyer Upper Extremity (FMA)

The IGC modelling results for FMA demonstrated that the quadratic model (Model 3 – shaded in grey) improved model fit over the linear model (Model 2) based on the -2 log likelihood test ($\chi^2(1) = 1590.07 - 1563.52 = 26.55$, $p<0.001$) (Table 6-9). However, the cubic model (Model 4) did not further improve model fit ($\chi^2(1) = 1563.52 - 1563.45 = 0.07$, $p>0.05$). Therefore, the quadratic change of FMA (Model 3 – shaded in grey) was modelled in all subsequent analyses. In addition, the AR(1) heterogeneous covariance structure was used for all analyses as it has the lowest -2LL value compared to the compound symmetry and AR(1) structures (Table 6-10).

6.4.4.2.1 Shape of FMA recovery curve

Table 6-11 illustrates the impact of each predictor when it was added to the quadratic model of FMA. The significant predictors of FMA were age, side of affected UE, time post stroke, severity of UE impairment, severity of trunk impairment, TIS score and therapy time. This implies that these predictors have an influence on the overall shape of FMA recovery curve. The combination of significant predictors in a conditional multivariable model is presented in Table 6-12. Results showed that the combined predictors, i.e., (TIS score x TIME^2) (shaded in grey), demonstrated the largest pseudo R^2 of 9%. Hence, the full equation for the estimated model for FMA is:

$$\text{FMA} = 24.95 + (-5.18 \times \text{TIME}) + (1.86 \times \text{TIME}^2) + (0.35 \times \text{TIS}) + (0.43 \times \text{TIS} \times \text{TIME}) + (-0.1 \times \text{TIS} \times \text{TIME}^2)$$

This equation was used to plot the predicted FMA against the observed FMA (Figure 6-8). The R^2 value was 15.3%.

Table 6-9 Comparison of growth curve model parameter estimates for FMA

	Model 1 Unconditional means model	**Model 2** Unconditional Linear Model	**Model 3** Unconditional quadratic model	**Model 4** Unconditional cubic model
FIXED EFFECTS				
Initial status				
Intercept	38.76***	30.99***	29.83***	29.79***
Rate of change				
Linear slope		3.21***	4.87***	5.03***
Quadratic slope			-0.34***	-0.43
Cubic slope				0.01
RANDOM EFFECTS				
Level 1 intra-individual:				
Residual variance	54.58***	6.83***	5.80***	5.80***
Level 2 inter-individual:				
Variance of intercept	452.62***	531.39***	537.58***	537.67***
Variance of slope		4.22***	4.29***	4.30***
GOODNESS-OF-FIT				
-2LL	1917.00	1590.07	1563.52	1563.45
No. of parameters	3	5	6	7
x^2		326.93***	26.55***	0.07
Degrees of freedom		2	1	1

***p<0.001; **p<0.01; *p<0.05
-2LL: -2 Log Likelihood
x^2: chi-square
critical value $x^2(1) = 10.83$ $p < 0.001$
$x^2(1) = 6.64$ $p < 0.01$
$x^2(1) = 3.84$ $p < 0.05$

The column shaded in grey represents the best model fit.

Table 6-10 Covariance structure models for FMA

Covariance structure	-2 Log Likelihood -2LL
Compound symmetry	1715.00
AR(1)	1715.00
AR(1) heterogeneous	1553.22

Table 6-11 Effect of predictors on the FMA model

Predictors	Conditional quadratic model	
	F statistic	p value
Age	0.92	0.343
Age x TIME (linear slope)	8.47**	0.004
Age x TIME x TIME (quadratic slope)	8.06**	0.005
Gender	0.26	0.614
Gender x TIME	0.14	0.712
Gender x TIME x TIME	0.40	0.527
Hand dominance	0.14	0.708
Hand dominance x TIME	0.62	0.433
Hand dominance x TIME x TIME	1.63	0.204
Affected UE	0.03	0.862
Affected UE x TIME	9.34**	0.003
Affected UE x TIME x TIME	7.38**	0.007
Time post stroke	7.63**	0.008
Time post stroke x TIME	0.001	0.992
Time post stroke x TIME x TIME	1.12	0.291
Stroke type	2.65	0.111
Stroke type x TIME	0.48	0.490
Stroke type x TIME x TIME	0.22	0.639
Severity of UE impairment	149.34***	0.001
Severity of UE impairment x TIME	4.97**	0.027
Severity of UE impairment x TIME x TIME	0.30	0.584
Severity of trunk impairment	14.02***	0.001
Severity of trunk impairment x TIME	0.23	0.631
Severity of trunk impairment x TIME x TIME	4.67*	0.032
TIS score	3.72	0.055
TIS score x TIME	16.23***	0.001
TIS score x TIME x TIME	9.30**	0.003
Therapy Time	1.24	0.268
Therapy Time x TIME	3.10	0.080
Therapy Time x TIME x TIME	4.37*	0.038

***p<0.001; **p<0.01; *p<0.05

Table 6-12 FMA: Combination of predictors and pseudo R^2

Predictors	-2LL	df	Deviance statistics	*p* value	Residual variance	Proportional variance reduction Pseudo R^2
Age x Affected UE x Time since stroke x UE impairment x Trunk impairment x TIS score x TIME^2	1540.49	10	12.73	0.01	5.37	6.8%
Age x Affected UE x UE impairment x Trunk impairment x TIME^2	1532.08	10	21.14	0.001	5.53	4.0%
Age x UE impairment x TIS score x TIME^2	1547.87	10	5.35	0.20	5.57	3.3%
Age x Affected UE x UE impairment x TIS score x TIME^2	1549.98	10	3.24	0.98	5.64	2.1%
Affected UE x UE impairment x TIS score x TIME^2	1550.66	10	2.56	0.98	5.64	2.1%
UE impairment x Trunk impairment x TIME^2	1502.86	10	50.36	0.001	5.70	1.0%
UE impairment x TIS score x TIME^2	1537.50	10	15.72	0.01	5.38	6.6%
Affected UE x UE impairment x Trunk Impairment x TIME^2	1524.82	10	28.40	0.001	5.54	3.8%
Time since stroke x UE impairment x TIME^2	1530.00	10	23.22	0.001	5.66	1.7%
Time since stroke x Trunk impairment x TIME^2	1533.13	10	20.09	0.001	5.56	3.5%
Affected UE x Trunk impairment x TIME^2	1538.80	10	14.42	0.01	5.41	6.1%
Affected UE x UL impairment x TIME^2	1525.31	10	27.91	0.001	5.56	3.5%
Age x Trunk impairment x TIS score x TIME^2	1542.39	10	10.83	0.05	5.56	3.5%
TIS x TIME^2	1532.84	10	20.38	0.001	5.24	9.0%

Note the baseline quadratic curve : -2 Log Likelihood (-2LL) = 1553.22
Degrees of freedom (df) = 7
Residual = 5.76

critical value $x^2(3) = 16.27$ $p < 0.001$
$x^2(3) = 11.35$ $p < 0.01$
$x^2(3) = 7.82$ $p < 0.05$

The row shaded in grey represents the model with the largest pseudo R^2.

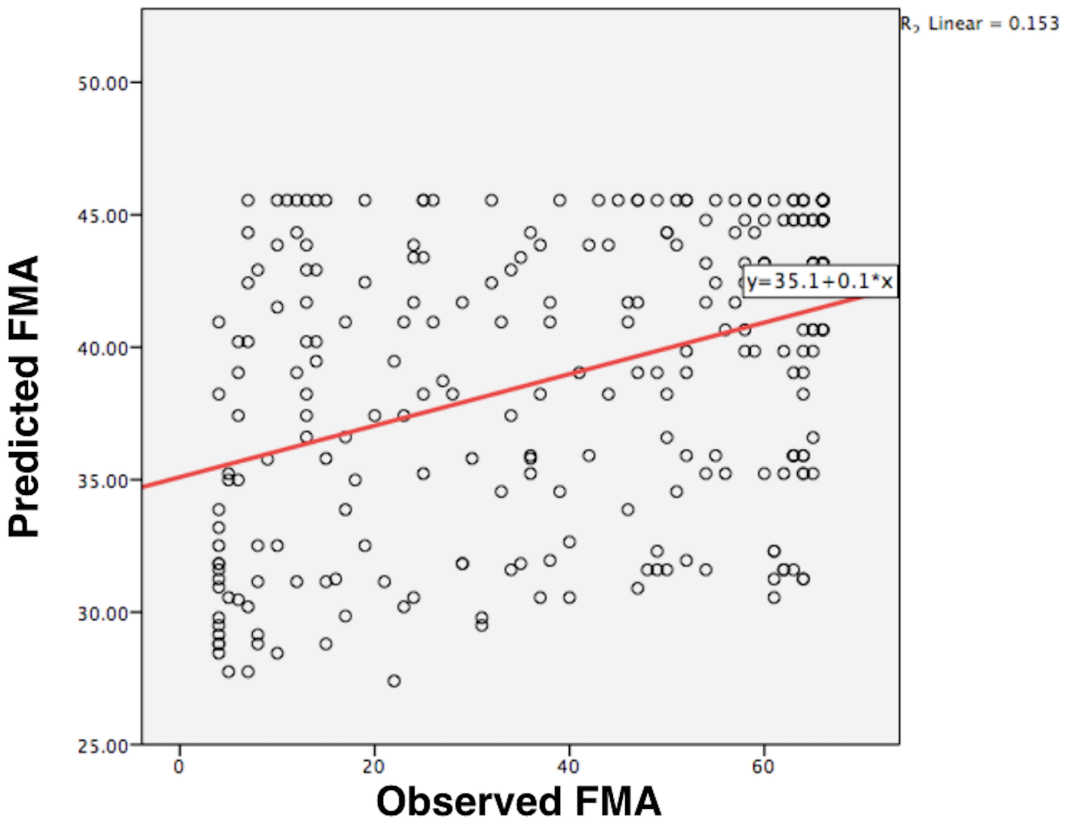


Figure 6-8 Plot of the predicted FMA against the observed FMA

Figure 6-9 illustrates the individual FMA recovery curves for the group of 45 subacute stroke participants. Figure 6-10 illustrates the prototypical plot of the FMA recovery curve derived from the equation of the estimated model. The curve showed that the most rapid recovery of FMA occurred in the first 4 months post stroke and then the rate of recovery decreased from 4th to 6th month period. This finding is supported by the SPSS analysis of the instantaneous rate of change (slope) for the FMA recovery curve at each time point (Table 6-13 and Figure 6-11).

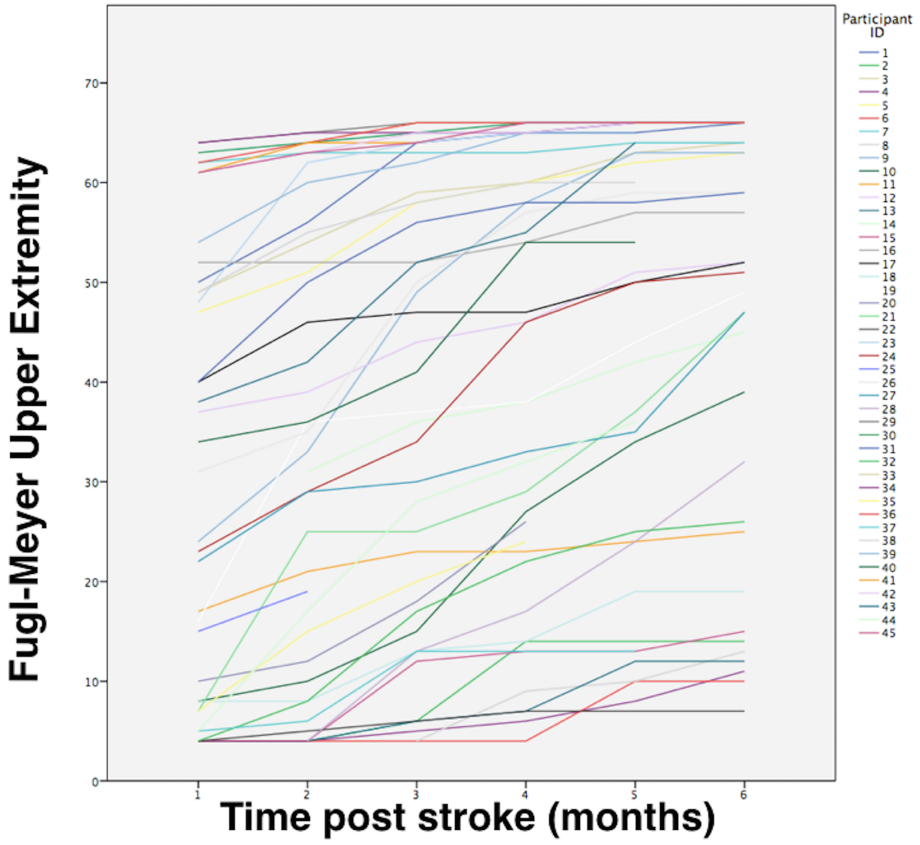


Figure 6-9 Individual FMA recovery curves of 45 subacute stroke participants

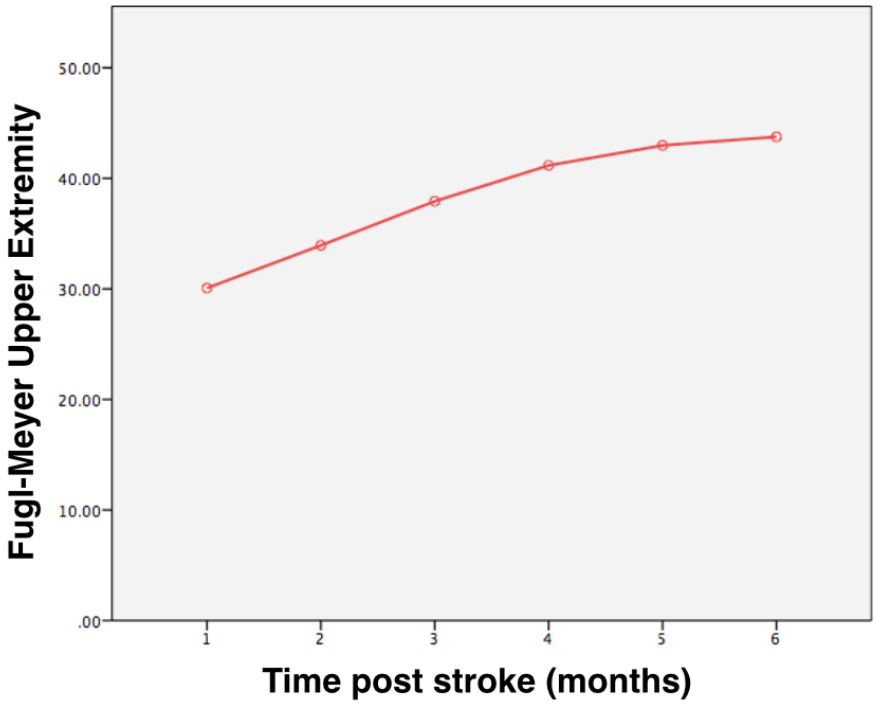


Figure 6-10 Prototypical plot of the recovery curve of FMA

Table 6-13 Instantaneous rate of change of FMA recovery curve in the first 6 months post stroke

Time post stroke	Rate of change (FMA points/month)
1st month	4.89
2nd month	4.22
3rd month	3.54
4th month	2.87
5th month	2.19
6th month	1.52

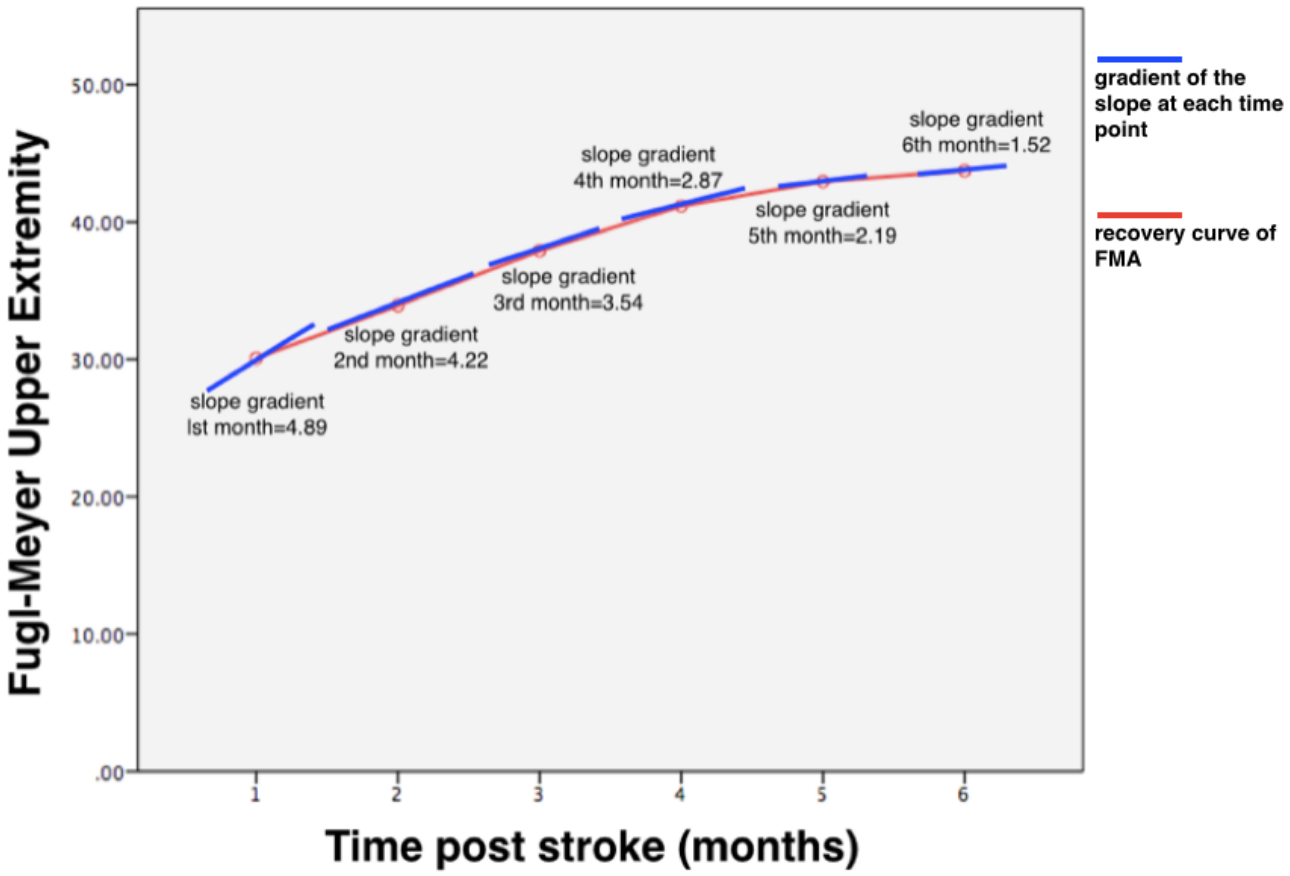


Figure 6-11 Instantaneous rate of change of FMA recovery curve in the first 6 months post stroke

6.4.4.2.2 Impact of initial FMA score on the trajectory of recovery curve

Results demonstrated a negative and significant intercept-slope covariance (covariance = -0.36, p<0.05). This suggests that as the intercept increased, the slope decreased (Figure 6-12). In other words, those participants with lower initial FMA score demonstrated a faster rate of change, on average, than those with higher initial FMA score. Similarly, those participants with higher initial FMA score demonstrated a slower rate of change, on average, than those with lower initial FMA score.

The negative and significant intercept-slope covariance also suggest that those participants with lower FMA score at initial status might catch up to those with higher FMA score, as the initial differences in FMA would tend to become less pronounced over time (Figure 6-12).

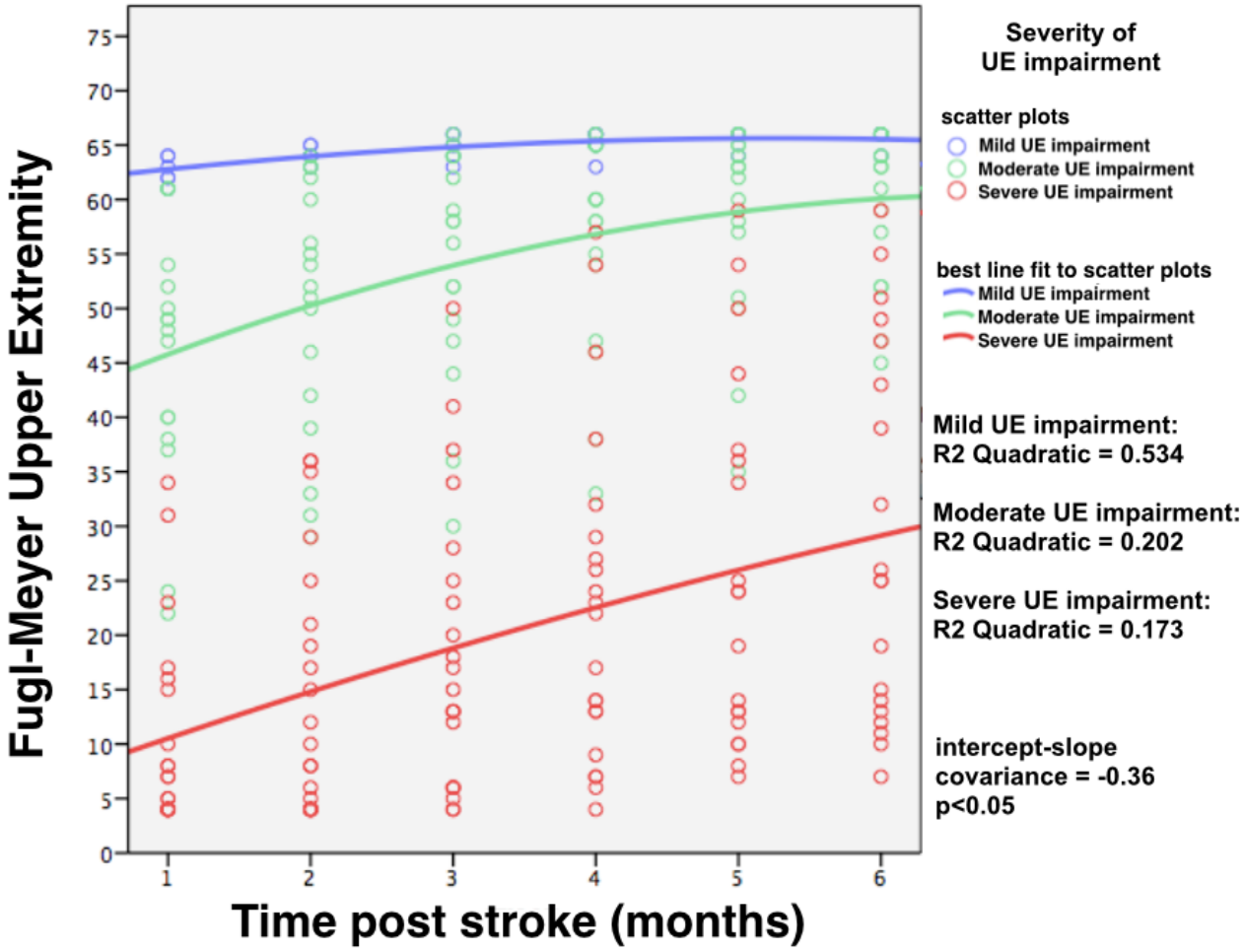


Figure 6-12 FMA recovery curves based on severity of upper extremity impairment

6.4.4.2.3 Impact of severity of trunk impairment on the trajectory of FMA recovery curve

Figure 6-13 illustrates the recovery curves of FMA based on the severity of trunk impairment. Subacute stroke participants with poor trunk control scored lower on the FMA score. By the 6th month, the FMA for the participants with severe trunk impairment remained lower than those participants with mild and moderate trunk impairment.

The R^2 quadratic value is a measure of how close the data are to the fitted quadratic curve. The R^2 quadratic value of 0.023 for the participants with moderate trunk impairment was very low, thus implying a wide spread of data around the quadratic curve (in green). The fit of FMA data was very good for the group with mild trunk impairment (R^2 quadratic value = 0.837). The results suggest that those participants with better trunk control exhibited better FMA score.

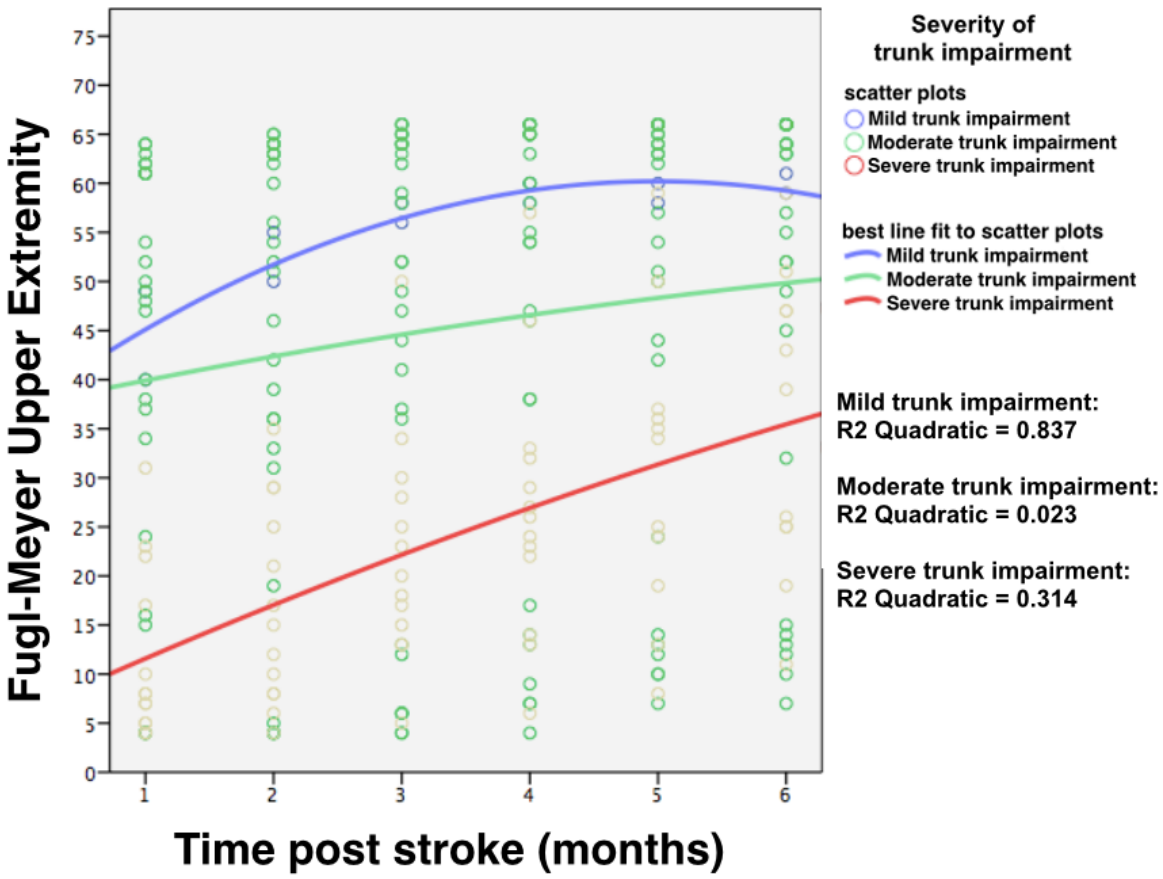


Figure 6-13 FMA recovery curves based on the severity of trunk impairment

6.4.4.2.4 Intra-individual and inter-individual variability in FMA

Results from the final FMA model demonstrated significant intra-individual variability across each wave of measurement (residual variance = 5.24, p<0.001). There was inter-individual variability in the intercept (variance = 470.62, p<0.001) and slope (variance = 4.17, p<0.001) over time.

6.4.4.3 Fugl-Meyer Shoulder-Elbow subscore (FMA-SE)

The IGC modelling results for FMA-SE demonstrated that the quadratic model (Model 3 – shaded in grey) improved model fit over the linear model (Model 2) based on the -2 log likelihood test ($x^2(1)$ = 1357.03 – 1337.29 = 19.74, p<0.001) (Table 6-14). However, the cubic model (Model 4) did not further improve model fit ($x^2(1)$ = 1337.29 – 1337.29 = 0, p>0.05). Therefore, the quadratic change of FMA-SE (Model 3) was modelled in all subsequent analyses. In addition, the AR(1) heterogeneous covariance structure was used for all analyses as it has the lowest -2LL value compared to the compound symmetry and AR(1) structures (Table 6-15).

6.4.4.3.1 Shape of FMA-SE recovery curve

Table 6-16 illustrates the impact of each predictor when it was added to the quadratic model of FMA-SE. The significant predictors of FMA-SE were age, side of affected UE, severity of trunk impairment and TIS score. This implies that these predictors have an influence on the overall shape of FMA-SE recovery curve. The combination of significant predictors in a conditional multivariable model is presented in Table 6-17. Results showed that the combined predictors, i.e., (TIS score x TIME^2) (shaded in grey), demonstrated the largest pseudo R^2 of 5.7%. Hence, the full equation for the estimated model for FMA-SE is:

FMA-SE = 21.36 + (-2.66 x TIME) + (0.94 x TIME^2) + (0.09 x TIS) +

(0.25 x TIS x TIME) + (-0.05 x TIS x TIME^2)

This equation was used to plot the predicted FMA-SE against the observed FMA-SE (Figure 6-14). The R^2 value was 11.2%.

Table 6-14 Comparison of growth curve model parameter estimates for FMA-SE

	Model 1 Unconditional means model	**Model 2** Unconditional Linear Model	**Model 3** Unconditional quadratic model	**Model 4** Unconditional cubic model
FIXED EFFECTS				
Initial status				
Intercept	25.39***	20.79***	20.14***	20.14***
Rate of change				
Linear slope		1.89***	2.81***	2.83***
Quadratic slope			-0.19***	-0.20
Cubic slope				0.001
RANDOM EFFECTS				
Level 1 intra-individual:				
Residual variance	19.65***	2.83***	2.50***	2.50***
Level 2 inter-individual:				
Variance of intercept	165.03***	200.56***	202.85***	202.85***
Variance of slope		1.57***	1.62***	1.62***
GOODNESS-OF-FIT				
-2LL	1657.04	1357.03	1337.29	1337.29
No. of parameters	3	5	6	7
x^2		300.01***	19.74***	0
Degrees of freedom		2	1	1

***p<0.001; **p<0.01; *p<0.05
-2LL: -2 Log Likelihood
x^2: chi-square
critical value $x^2(1) = 10.83$ $p < 0.001$
$x^2(1) = 6.64$ $p < 0.01$
$x^2(1) = 3.84$ $p < 0.05$

The column shaded in grey represents the best model fit.

Table 6-15 Covariance structure models for FMA-SE

Covariance structure	-2 Log Likelihood -2LL
Compound symmetry	1487.89
AR(1)	1487.89
AR(1) heterogeneous	1322.86

Table 6-16 Effect of predictors on the FMA-SE model

Predictors	Conditional quadratic model	
	F statistic	p value
Age	0.83	0.369
Age x TIME (linear slope)	8.68**	0.004
Age x TIME x TIME (quadratic slope)	7.11**	0.008
Gender	0.08	0.778
Gender x TIME	0.15	0.697
Gender x TIME x TIME	0.15	0.699
Hand dominance	0.22	0.638
Hand dominance x TIME	0.06	0.803
Hand dominance x TIME x TIME	0.07	0.405
Affected UE	0.02	0.880
Affected UE x TIME	7.29**	0.008
Affected UE x TIME x TIME	4.71*	0.031
Time post stroke	8.25**	0.006
Time post stroke x TIME	0.01	0.928
Time post stroke x TIME x TIME	0.96	0.330
Stroke type	2.90	0.095
Stroke type x TIME	0.95	0.332
Stroke type x TIME x TIME	0.17	0.685
Severity of UE impairment	126.28***	0.001
Severity of UE impairment x TIME	7.59**	0.007
Severity of UE impairment x TIME x TIME	0.001	0.996
Severity of trunk impairment	13.80***	0.001
Severity of trunk impairment x TIME	0.41	0.521
Severity of trunk impairment x TIME x TIME	4.47*	0.036
TIS score	0.60	0.440
TIS score x TIME	12.37***	0.001
TIS score x TIME x TIME	6.18*	0.014
Therapy Time	0.05	0.825
Therapy Time x TIME	0.58	0.447
Therapy Time x TIME x TIME	0.93	0.336

Table 6-17 FMA-SE: Combination of predictors and pseudo R^2

Predictors	-2LL	df	Deviance statistics	*p* value	Residual variance	Proportional variance reduction Pseudo R^2
Age x Affected UE x Trunk impairment x TIS score x TIME²	1319.29	10	3.57	0.98	2.41	2.4%
Age x Affected UE x TIME²	1313.13	10	9.73	0.05	2.37	4.0%
Age x TIS score x TIME²	1322.18	10	0.68	0.98	2.43	1.6%
Affected UE x TIS score x TIME²	1321.94	10	0.92	0.98	2.47	0%
Affected UE x Trunk impairment x TIME²	1311.41	10	11.45	0.01	2.36	4.5%
Trunk impairment x TIS score x TIME²	1312.59	10	10.27	0.05	2.40	2.8%
Age x Trunk impairment x TIME²	1312.17	10	10.69	0.05	2.37	4.0%
Affected UE x Trunk impairment x TIS score x TIME²	1319.74	10	3.12	0.98	2.41	2.4%
Trunk impairment x TIME²	1303.48	10	19.38	0.001	2.40	2.8%
Affected UE x TIME²	1314.45	10	8.41	0.05	2.40	2.8%
TIS score x TIME²	1309.63	10	13.23	0.01	2.33	5.7%
Age x TIME²	1313.80	10	9.06	0.05	2.36	4.5%

Note: the baseline quadratic curve: -2 log likelihood (-2LL) = 1322.86
Degrees of freedom (df) = 7
Residual = 2.47

critical value $x^2(3) = 16.27$ $p < 0.001$
$x^2(3) = 11.35$ $p < 0.01$
$x^2(3) = 7.82$ $p < 0.05$

The row shaded in grey represents the model with the largest pseudo R^2.

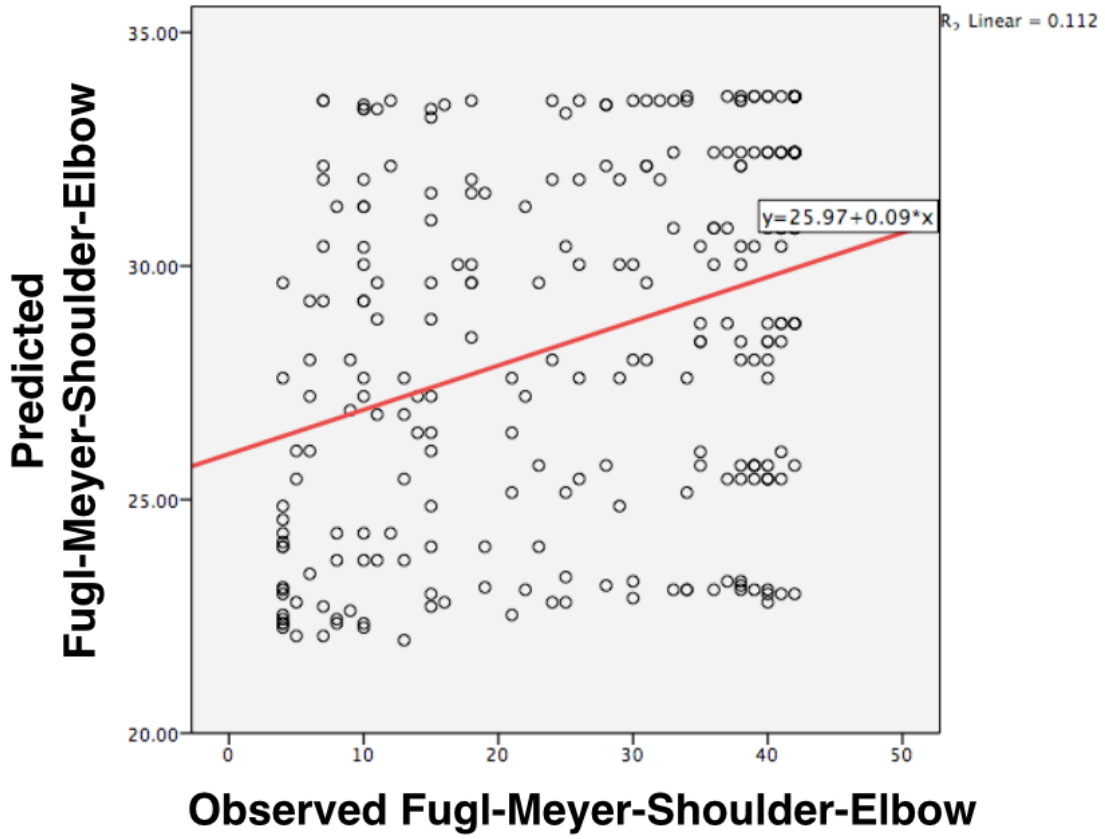


Figure 6-14 Plot of the predicted FMA-SE against the observed FMA-SE

Figure 6-15 illustrates the individual FMA-SE recovery curves for the group of 45 subacute stroke participants. Figure 6-16 illustrates the prototypical plot of the FMA-SE recovery curve derived from the equation of the estimated model. The curve showed that the most rapid recovery of FMA-SE occurred in the first 3 months post stroke and then the rate of recovery decreased from 4th to 6th month period. This finding is supported by the SPSS analysis of the instantaneous rate of change (slope) for the FMA-SE recovery curve at each time point (Table 6-18 and Figure 6-17).

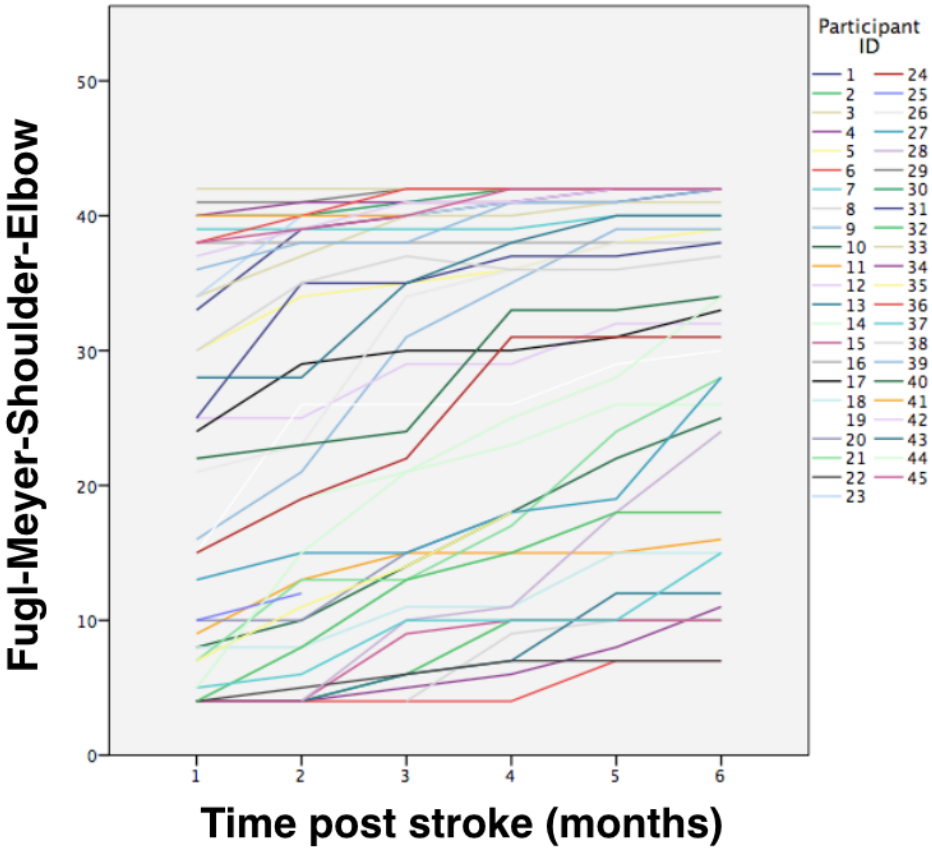


Figure 6-15 Individual FMA-SE recovery curves of 45 subacute stroke participants

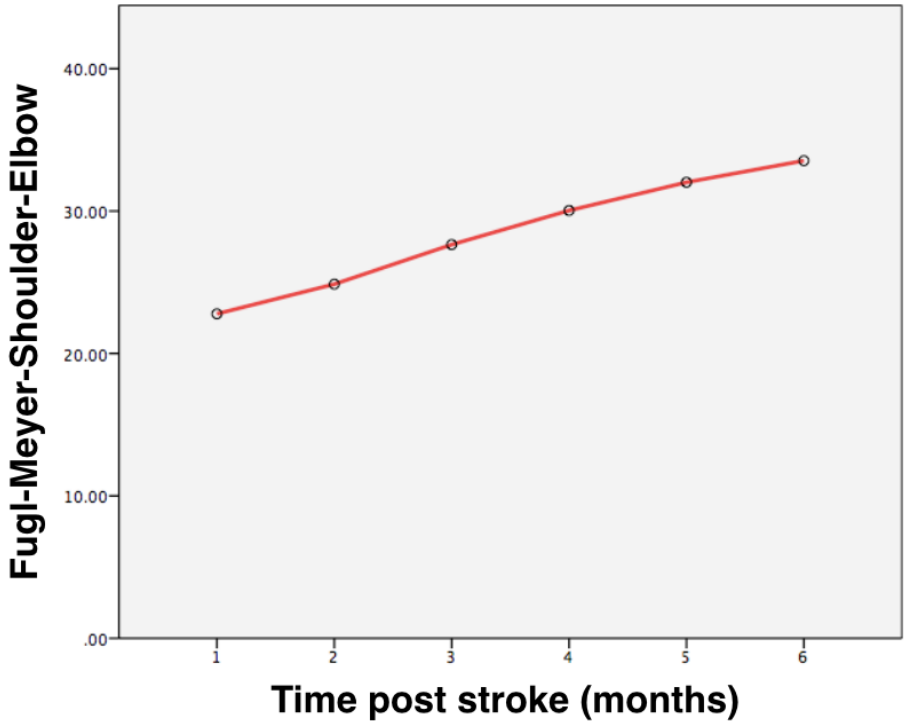


Figure 6-16 Prototypical plot of the recovery curve of FMA-SE

Table 6-18 Instantaneous rate of change of FMA-SE recovery curve in the first 6 months post stroke

Time post stroke	Rate of change (FMA points/month)
1st month	2.84
2nd month	2.46
3rd month	2.08
4th month	1.70
5th month	1.32
6th month	0.94

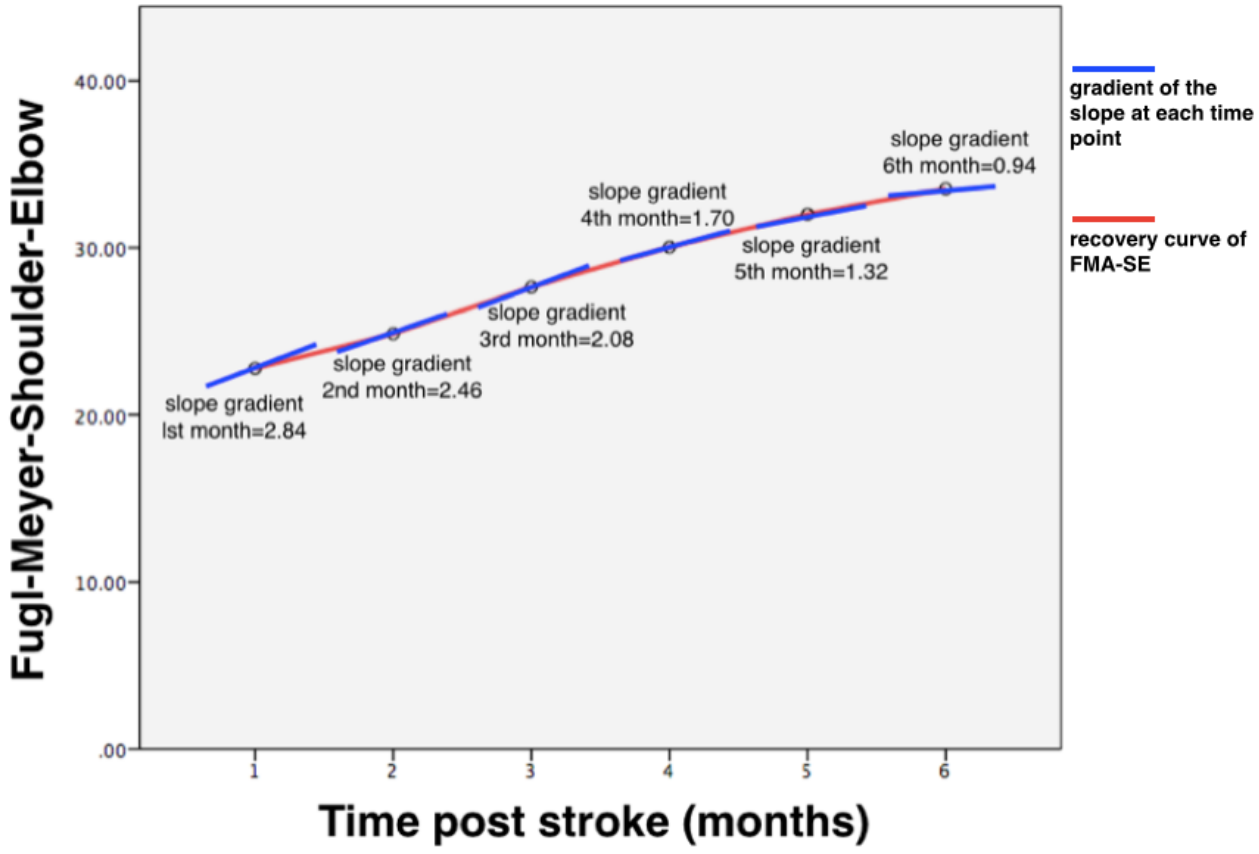


Figure 6-17 Instantaneous rate of change of FMA-SE recovery curve in the first 6 months post stroke

6.4.4.3.2 Impact of initial FMA-SE score on the trajectory of recovery curve

Results demonstrated a negative and significant intercept-slope covariance (covariance = -0.55, p<0.001). This suggests that as the intercept increased, the slope decreased (Figure 6-18). In other words, those participants with lower initial FMA-SE score demonstrated a faster rate of change, on average, than those with higher initial FMA-SE score. Similarly, those participants with higher initial FMA-SE score demonstrated a slower rate of change, on average, than those with lower initial FMA-SE score.

The negative and significant intercept-slope covariance also suggest that those participants with lower FMA-SE score at initial status might catch up to those with higher FMA-SE score, as the initial differences in FMA-SE would tend to become less pronounced over time (Figure 6-18).

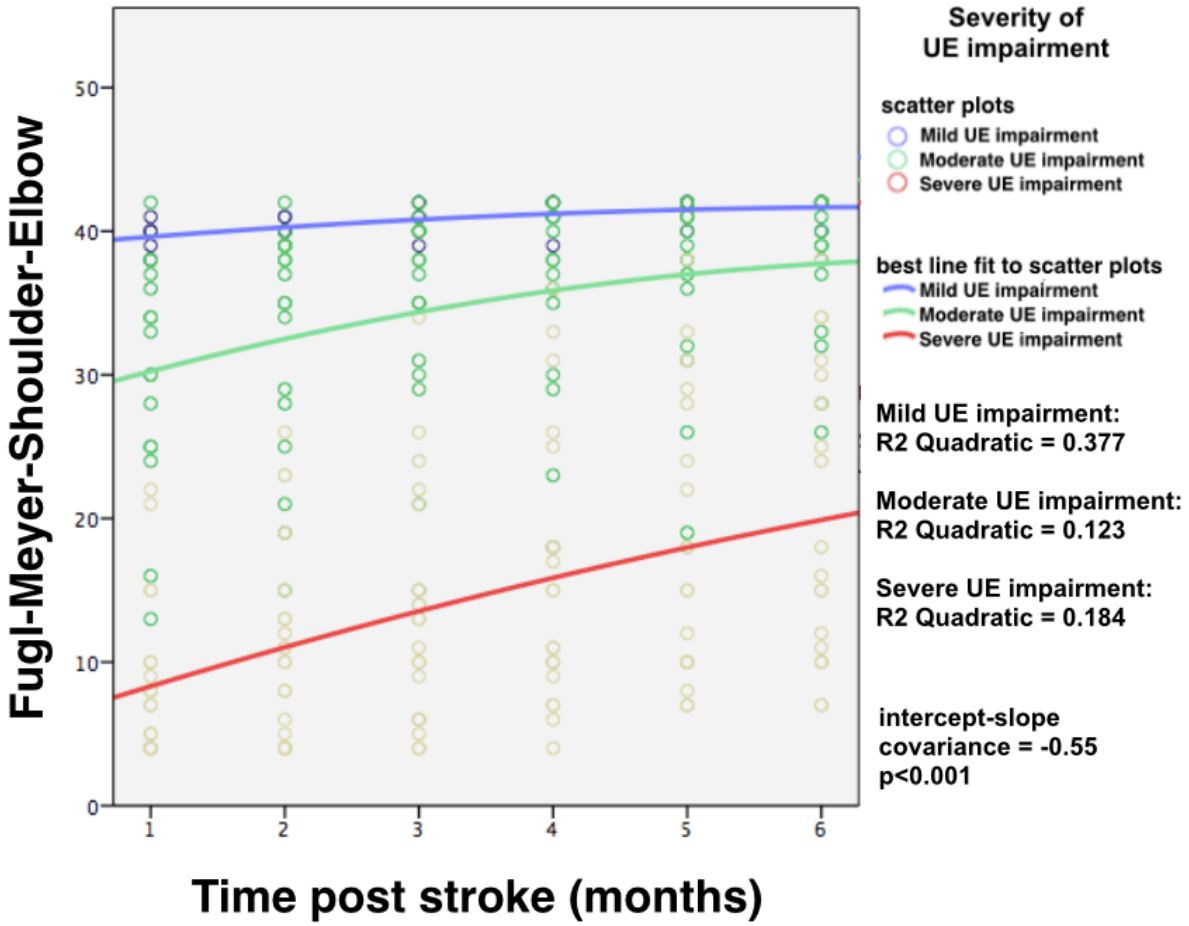


Figure 6-18 FMA-SE recovery curves based on severity of upper extremity impairment

6.4.4.3.3 Impact of severity of trunk impairment on the trajectory of FMA-SE recovery curve

Figure 6-19 illustrates the recovery curves of FMA-SE based on the severity of trunk impairment. Those subacute stroke participants with poorer trunk control scored lower on the FMA-SE score.

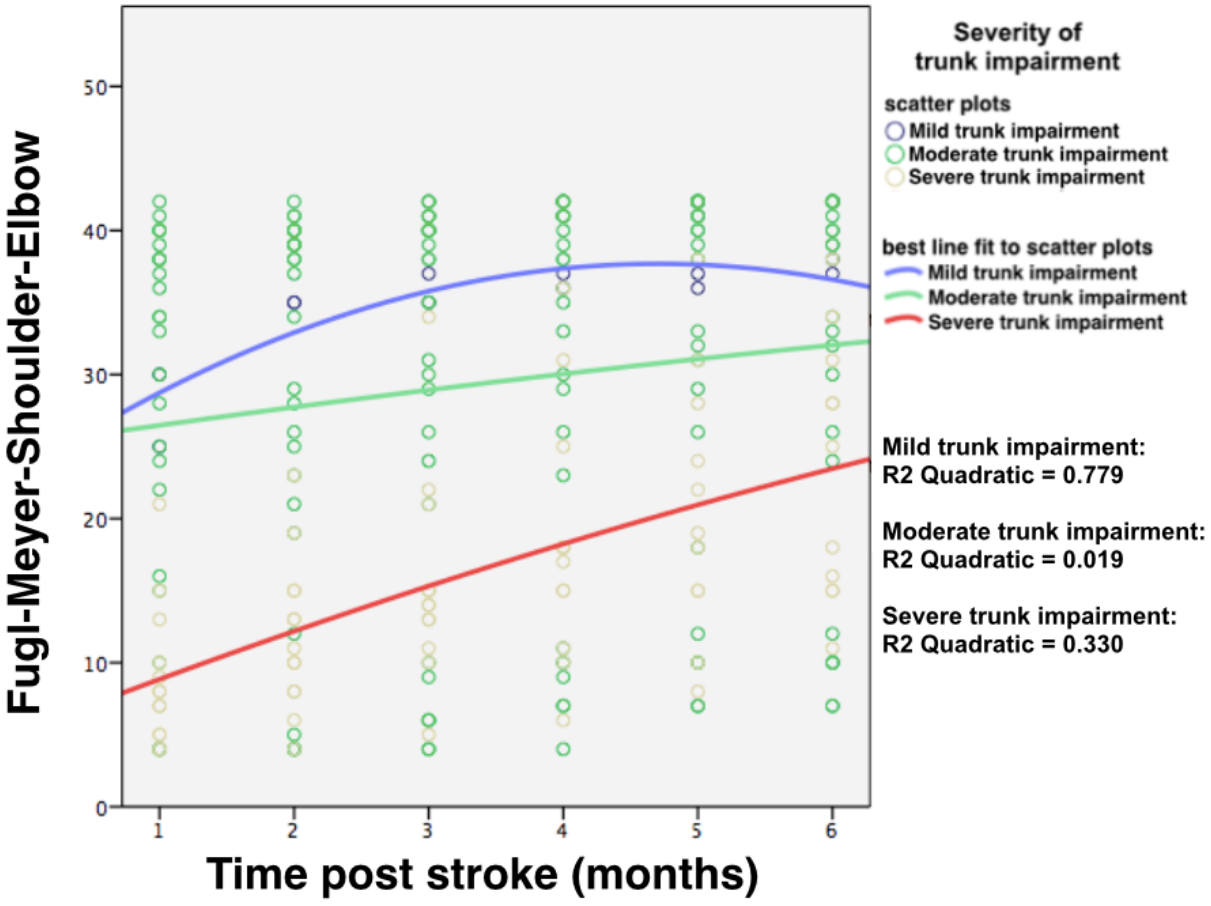


Figure 6-19 FMA-SE recovery curves based on the severity of trunk impairment

6.4.4.3.4 Intra-individual and inter-individual variability in FMA-SE

Results from the final FMA-SE model demonstrated significant intra-individual variability across each wave of measurement (residual variance = 2.33, p<0.001). There was inter-individual variability in the intercept (variance = 188.68, p<0.001) and slope (variance = 1.60, p<0.001) over time.

6.4.4.4 Fugl-Meyer Wrist-Hand subscore (FMA-WH)

The IGC modelling results for FMA-WH demonstrated that the quadratic model (Model 3 – shaded in grey) improved model fit over the linear model (Model 2) based on the -2 log likelihood test ($x^2(1)$ = 1238.47 – 1221.68 = 16.79, p<0.001) (Table 6-19). However, the cubic model (Model 4) did not further improve model fit ($x^2(1)$ = 1221.68 – 1221.55 = 0.13, p>0.05). Therefore, the quadratic change of FMA-WH (Model 3) was modelled in all subsequent analyses. In addition, the AR(1) heterogeneous covariance structure was used for all analyses as it has the lowest -2LL value compared to the compound symmetry and AR(1) structures (Table 6-20).

6.4.4.5 Shape of FMA-WH recovery curve

Table 6-21 illustrates the impact of each predictor when it was added to the quadratic model of FMA-WH. The significant predictors of FMA-WH were side of affected UE, TIS score and therapy time. This implies that these predictors have an influence on the overall shape of FMA-WH recovery curve. The combination of significant predictors in a conditional multivariable model is presented in Table 6-22. Results showed that the combined predictors, i.e., (TIS score x TIME^2) (shaded in grey), demonstrated the largest pseudo R^2 of 7%. Hence, the full equation for the estimated model for FMA-WH is:

FMA-WH = 7.2 + (-2.69 x TIME) + (0.75 x TIME^2) + (0.29 x TIS) +

(0.19 x TIS x TIME) + (-0.04 x TIS x TIME^2)

This equation was used to plot the predicted FMA-WH against the observed FMA-WH (Figure 6-20). The R^2 value was 24.3%.

Table 6-19 Comparison of growth curve model parameter estimates for FMA-WH

	Model 1 Unconditional means model	**Model 2** Unconditional Linear Model	**Model 3** Unconditional quadratic model	**Model 4** Unconditional cubic model
FIXED EFFECTS				
Initial status				
Intercept	13.37***	10.22***	9.70***	9.67***
Rate of change				
Linear slope		1.31***	2.05***	2.11***
Quadratic slope			-0.15***	-0.22
Cubic slope				0.01
RANDOM EFFECTS				
Level 1 intra-individual:				
Residual variance	10.50***	2.08***	1.89***	1.88***
Level 2 inter-individual:				
Variance of intercept	73.34***	81.23***	82.03***	82.05***
Variance of slope		0.80***	0.80***	0.80***
GOODNESS-OF-FIT				
-2LL	1489.17	1238.47	1221.68	1221.55
No. of parameters	3	5	6	7
x^2		250.70***	16.79***	0.13
Degrees of freedom		2	1	1

***p<0.001; **p<0.01; *p<0.05
-2LL: -2 Log Likelihood
x^2: chi-square
critical value $x^2(1) = 10.83$ $p < 0.001$
$x^2(1) = 6.64$ $p < 0.01$
$x^2(1) = 3.84$ $p < 0.05$

The column shaded in grey represents the best model fit.

Table 6-20 Covariance structure models for FMA-WH

Covariance structure	-2 Log Likelihood -2LL
Compound symmetry	1361.82
AR(1)	1361.82
AR(1) heterogeneous	1216.75

Table 6-21 Effect of predictors on the FMA-WH model

Predictors	Conditional quadratic model	
	F statistic	p value
Age	1.00	0.323
Age x TIME (linear slope)	3.78	0.054
Age x TIME x TIME (quadratic slope)	3.34	0.069
Gender	0.71	0.406
Gender x TIME	0.03	0.863
Gender x TIME x TIME	0.34	0.564
Hand dominance	0.04	0.840
Hand dominance x TIME	1.70	0.194
Hand dominance x TIME x TIME	1.85	0.196
Affected UE	0.04	0.841
Affected UE x TIME	6.44*	0.012
Affected UE x TIME x TIME	4.51*	0.035
Time post stroke	6.36*	0.015
Time post stroke x TIME	0.001	0.979
Time post stroke x TIME x TIME	0.36	0.551
Stroke type	2.13	0.151
Stroke type x TIME	0.01	0.911
Stroke type x TIME x TIME	0.17	0.680
Severity of UE impairment	156.55***	0.001
Severity of UE impairment x TIME	0.88	0.351
Severity of UE impairment x TIME x TIME	0.82	0.368
Severity of trunk impairment	13.50***	0.001
Severity of trunk impairment x TIME	0.05	0.822
Severity of trunk impairment x TIME x TIME	1.44	0.231
TIS score	8.92**	0.003
TIS score x TIME	9.51**	0.002
TIS score x TIME x TIME	4.75*	0.030
Therapy Time	3.36	0.068
Therapy Time x TIME	5.73	0.018
Therapy Time x TIME x TIME	7.27	0.008

***p<0.001; **p<0.01; *p<0.05

Table 6-22 FMA-WH: Combination of predictors and pseudo R^2

Predictors	-2LL	df	Deviance statistics	*p* value	Residual variance	Proportional variance reduction Pseudo R^2
Affected UE x TIS score x Therapy Time x TIME²	1212.97	10	3.77	0.98	1.87	0%
Affected UE x TIS score x TIME²	1211.04	10	5.70	0.05	1.87	0%
Affected UE x Therapy Time x TIME²	1214.65	10	2.09	0.98	1.86	0.5%
TIS score x Therapy Time x TIME²	1209.43	10	7.31	0.10	1.80	3.7%
Affected UE x TIME²	1210.07	10	6.67	0.10	1.82	2.7%
Therapy Time x TIME²	1208.48	10	8.26	0.05	1.80	3.7%
TIS score x TIME²	1197.19	10	19.55	0.001	1.74	7.0%

Note: the baseline quadratic curve: -2 log likelihood (-2LL) = 1216.74
Degrees of freedom (df) = 7
Residual = 1.87

critical value $x^2(3) = 16.27$ $p < 0.001$
$x^2(3) = 11.35$ $p < 0.01$
$x^2(3) = 7.82$ $p < 0.05$

The row shaded in grey represents the model with the largest pseudo R^2.

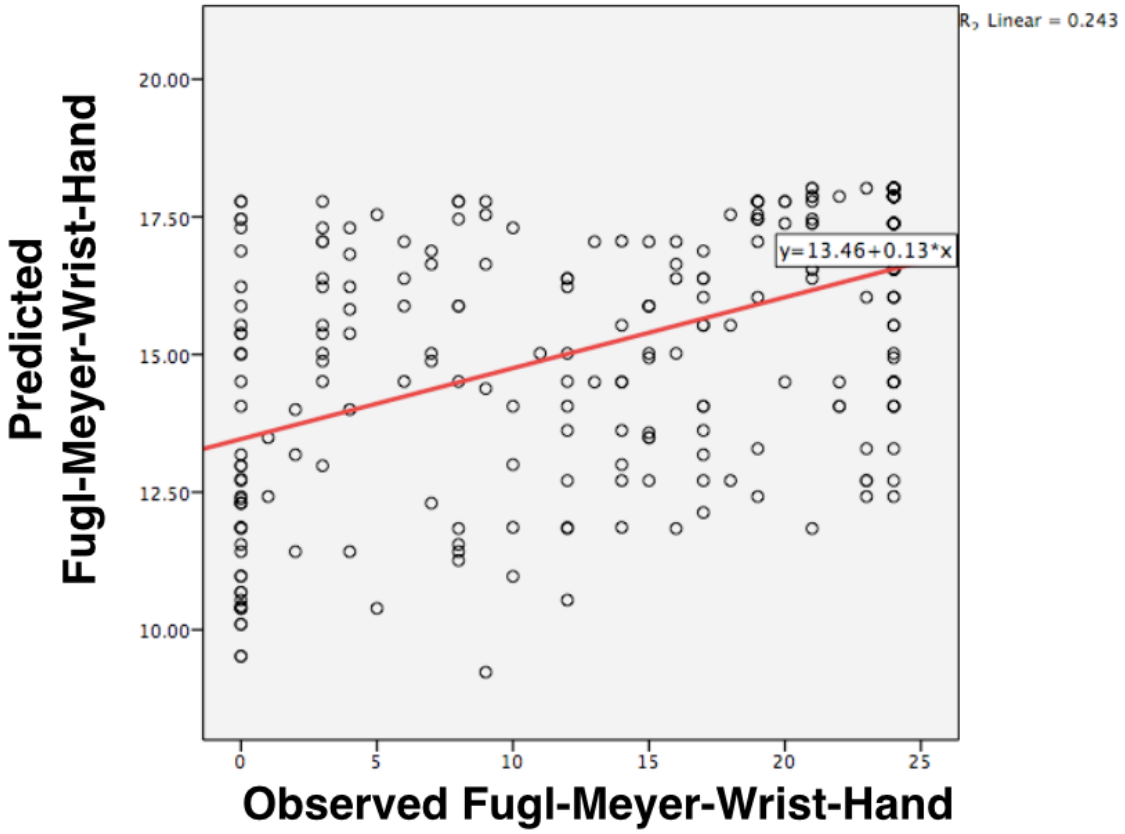


Figure 6-20 Plot of the predicted FMA-WH against the observed FMA-WH

Figure 6-21 illustrates the individual FMA-WH recovery curves for the group of 45 subacute stroke participants. Figure 6-22 illustrates the prototypical plot of the FMA-WH recovery curve derived from the equation of the estimated model. The curve showed that the most rapid recovery of FMA-WH occurred in the first 4 months post stroke and then the rate of recovery decreased from 4th to 6th month period. This finding is supported by the SPSS analysis of the instantaneous rate of change (slope) for the FMA-WH recovery curve at each time point (Table 6-23 and Figure 6-23).

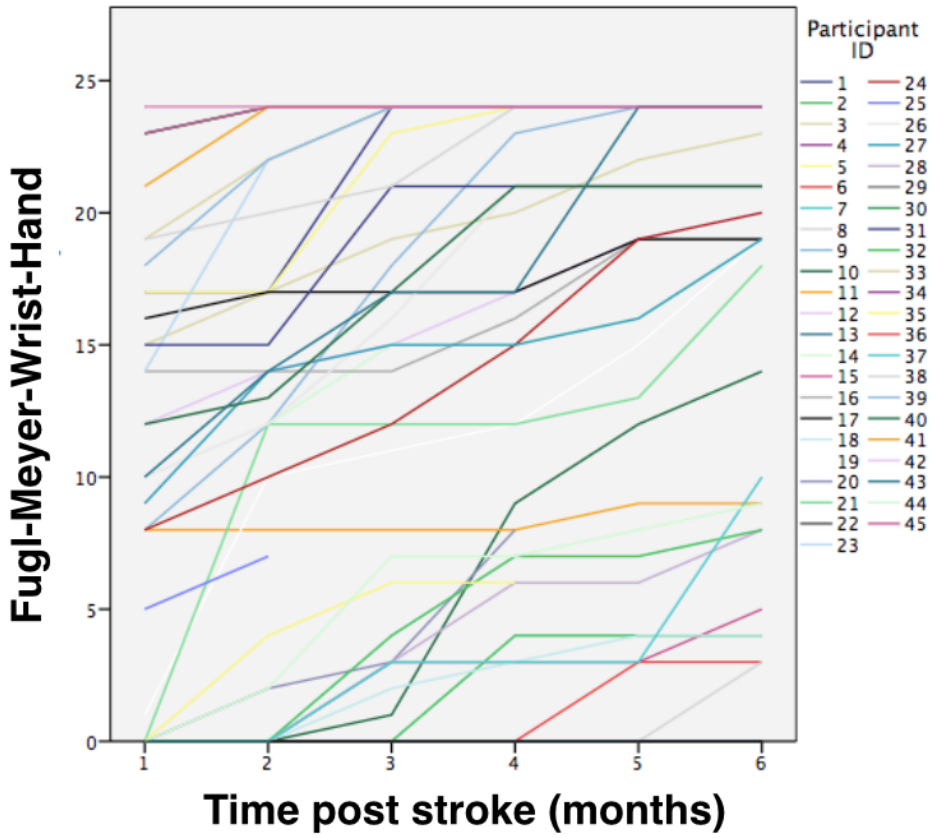


Figure 6-21 Individual FMA-WH recovery curves of 45 subacute stroke participants

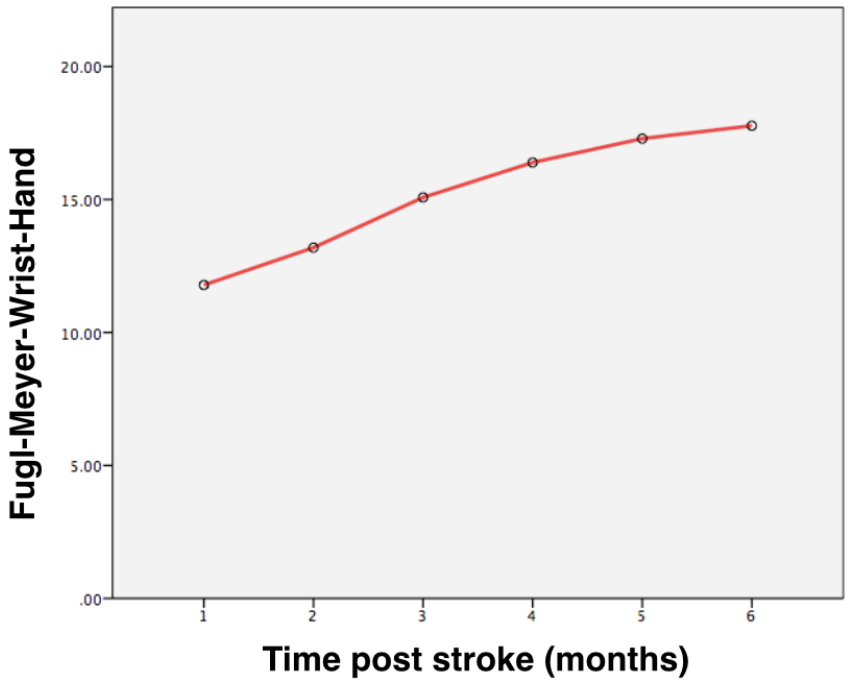


Figure 6-22 Prototypical plot of the recovery curve of FMA-WH

Table 6-23 Instantaneous rate of change of FMA-WH recovery curve in the first 6 months post stroke

Time post stroke	Rate of change (FMA points/month)
1st month	2.06
2nd month	1.76
3rd month	1.46
4th month	1.16
5th month	0.86
6th month	0.56

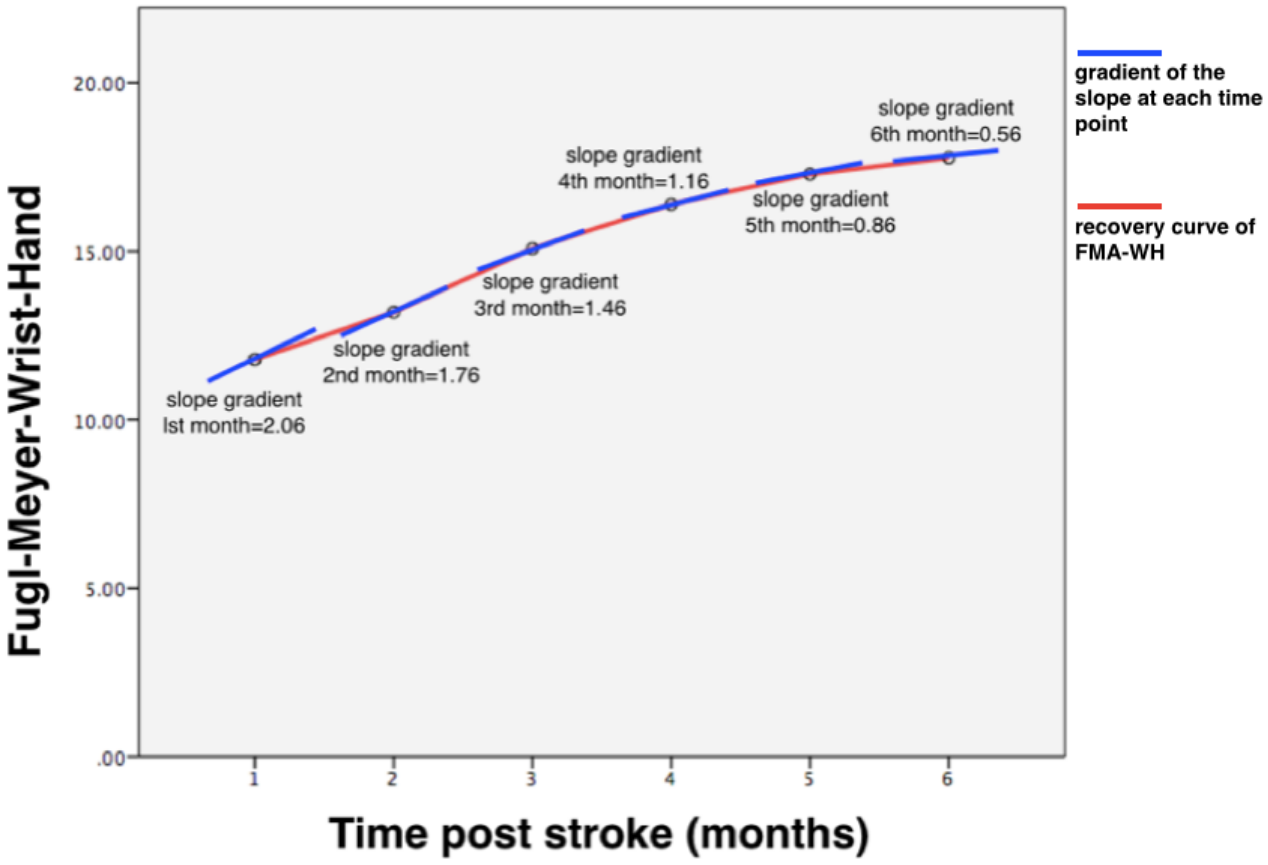


Figure 6-23 Instantaneous rate of change of FMA-WH recovery curve in the first 6 months post stroke

6.4.4.5.1 Impact of initial FMA-WH score on the trajectory of recovery curve

Results demonstrated a negative and significant intercept-slope covariance (covariance = -0.55, p<0.001). This suggests that as the intercept increased, the slope decreased (Figure 6-24). In other words, those participants with lower initial FMA-WH score demonstrated a faster rate of change, on average, than those with higher initial FMA-WH score. Similarly, those participants with higher initial FMA-WH score demonstrated a slower rate of change, on average, than those with lower initial FMA-WH score.

The negative and significant intercept-slope covariance also suggest that those participants with lower FMA-WH score at initial status might catch up to those with higher FMA-WH score, as the initial differences in FMA-WH would tend to become less pronounced over time (Figure 6-24).

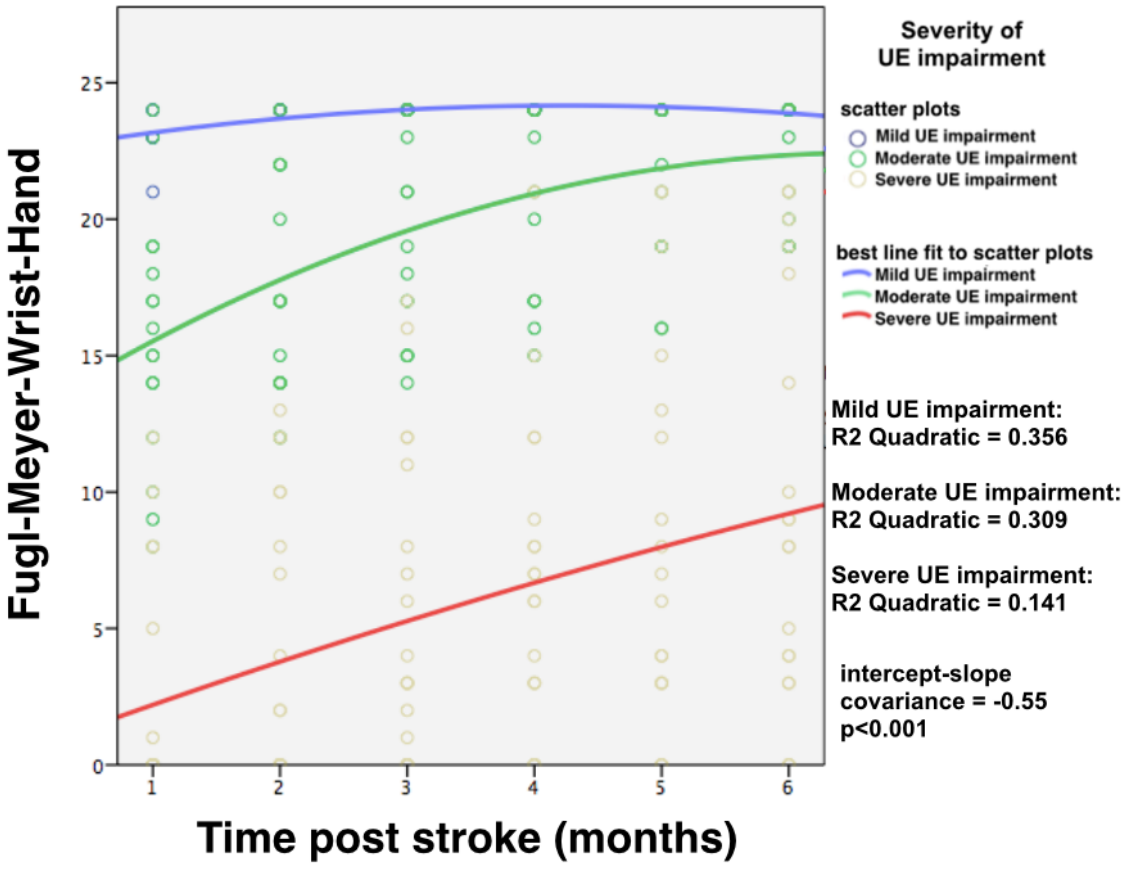


Figure 6-24 FMA-WH recovery curves based on severity of upper extremity impairment

6.4.4.5.2 Impact of severity of trunk impairment on the trajectory of FMA-WH recovery curve

Figure 6-25 illustrates the recovery curves of FMA-WH based on the severity of trunk impairment. Those subacute stroke participants with poorer trunk control scored lower on the FMA-WH score. By the 6th month, the FMA-WH for the participants with severe trunk impairment remained lower than those participants with mild and moderate trunk impairment.

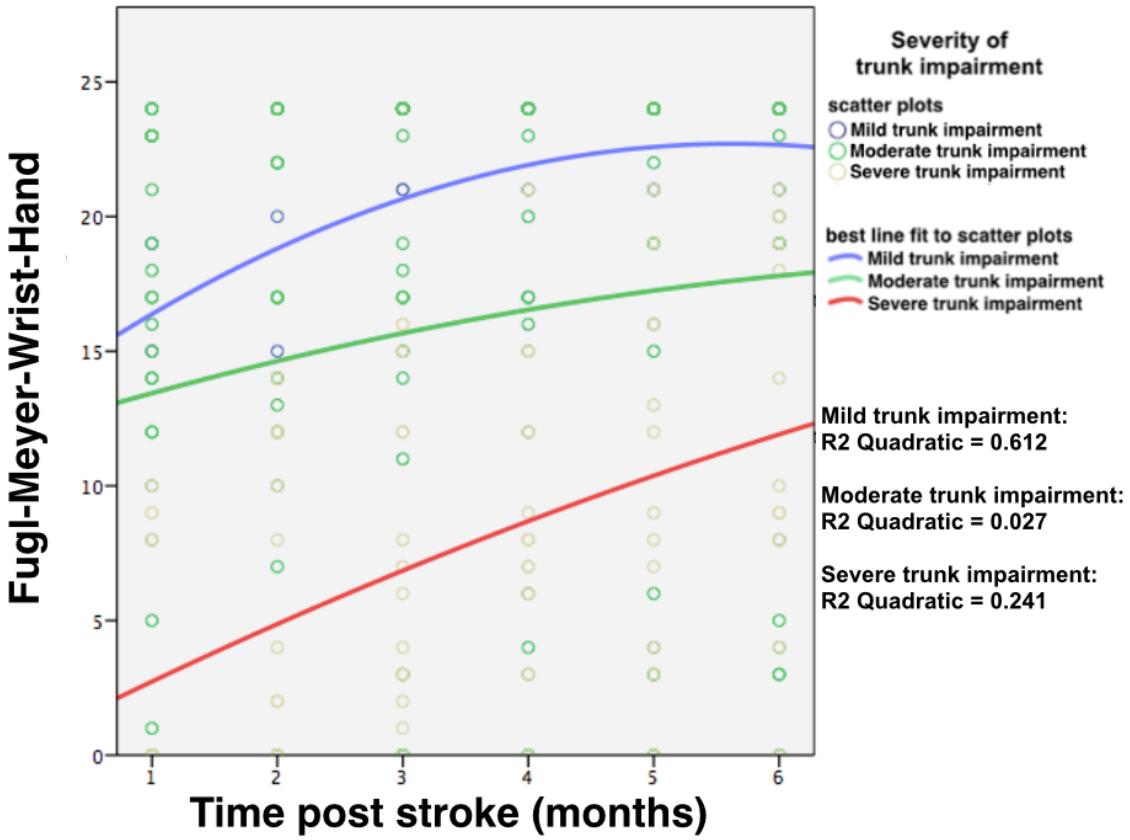


Figure 6-25 FMA-WH recovery curves based on the severity of trunk impairment

6.4.4.5.3 Intra-individual and inter-individual variability in FMA-WH

Results from the final FMA-WH model demonstrated significant intra-individual variability across each wave of measurement (residual variance = 1.75, p<0.001). There was inter-individual variability in the intercept (variance = 65.92, p<0.001) and slope (variance = 0.83, p<0.001) over time.

6.4.4.5.4 Comparison between recovery curve of FMA-SE and FMA-WH

Figure 6-26 illustrates the recovery curves of FMA-SE and FMA-WH. Visual inspection of the graphs suggests that the rate of change of FMA-SE was faster than that of FMA-WH in the first 6 months post stroke. The FMA-SE appeared to continue to improve from the 3rd to 6th month while the FMA-WH started to slow down in progress from the 3rd month to 6th month. This finding was confirmed with the plot of the rate of change of FMA-SE and FMA-WH over the first six months post stroke by using the data from Table 6-18 (FMA-SE) and Table 6-23 (FMA-WH). The gradient (-0.38) of FMA-SE was steeper than that of FMA-WH (gradient -0.30) (Figure 6-27).

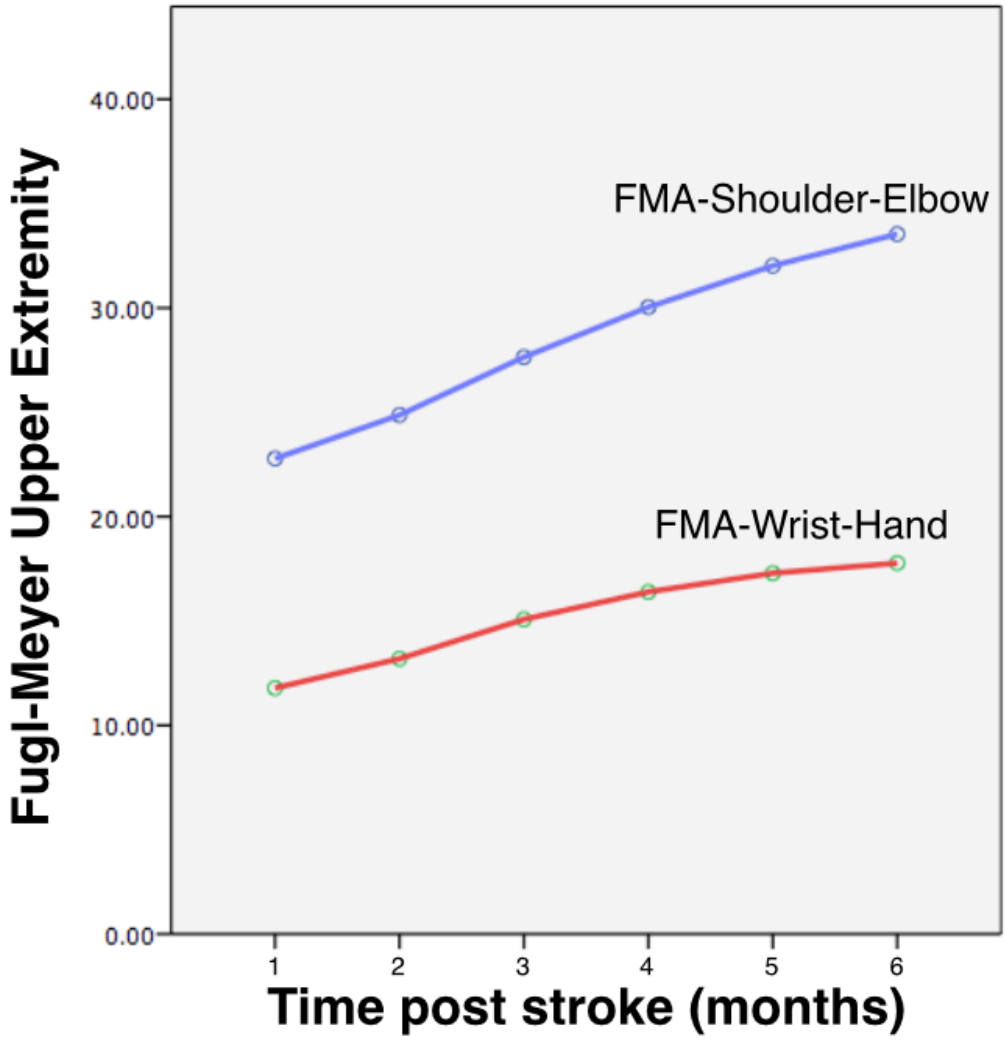


Figure 6-26 Recovery curves of FMA-SE and FMA-WH

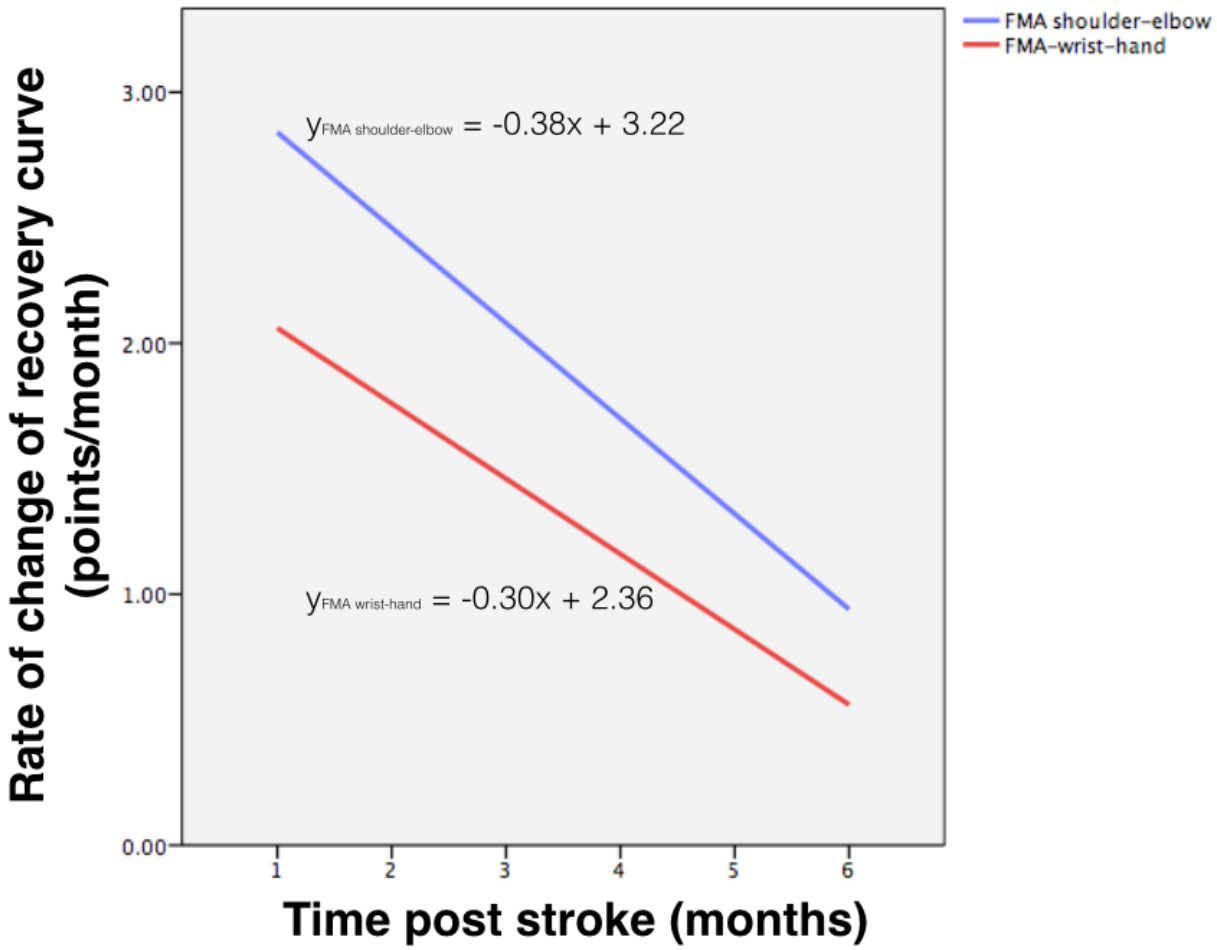


Figure 6-27 Rate of change of FMA-SE and FMA-WH in the first 6 months post stroke

6.4.4.6 Streamlined Wolf Motor Function Test-Time (SWMFT-Time)

The IGC modelling results of SWMFT-Time demonstrated that the quadratic model (Model 3 – shaded in grey) improved model fit over the linear model (Model 2) based on the -2 log likelihood test ($\chi^2(1) = 2105.42 - 2081.96 = 23.46$, $p<0.001$) (Table 6-24). However, the cubic model (Model 4) did not further improve model fit ($\chi^2(1) = 2081.96 - 2080.83 = 1.13$, $p>0.05$). Therefore, the quadratic change of SWMFT-Time (Model 3) was modelled in all subsequent analyses. The AR(1) heterogeneous covariance structure was used for all analyses as it has the lowest -2LL value compared to the compound symmetry and AR(1) structures (Table 6-25).

6.4.4.6.1 Shape of SWMFT-Time recovery curve

Table 6-26 illustrates the impact of each predictor when it was added to the quadratic model. The significant predictors of SWMFT-Time were age, stroke type, time post stroke, side of affected UE, severity of UE impairment, severity of trunk impairment, TIS score and FMA score. This implies that these predictors have an influence on the overall shape of SWMFT-Time recovery curve. The combination of significant predictors in a conditional multivariable model was presented in Table 6-27. Results showed that the combined predictors, i.e., (FMA x TIME^2) (shaded in grey), demonstrated the largest pseudo R^2 of 19.8%. Hence, the full equation for the estimated model for SWMFT-Time is:

$$\text{SWMFT-Time} = 169.68 + (-5.26 \times \text{TIME}) + (1.01 \times \text{TIME}^2) + (-2.05 \times \text{FMA}) + (0.14 \times \text{FMA} \times \text{TIME}) + (-0.02 \times \text{FMA} \times \text{TIME}^2)$$

This equation was used to plot the predicted SWMFT-Time against the observed SWMFT-Time (Figure 6-28). The R^2 value was 91.6%.

Table 6-24 Comparison of growth curve model parameter estimates for SWMFT-Time

	Model 1 Unconditional means model	**Model 2** Unconditional Linear Model	**Model 3** Unconditional quadratic model	**Model 4** Unconditional cubic model
FIXED EFFECTS				
Initial status				
Intercept	43.76***	55.55***	58.90***	59.37***
Rate of change				
Linear slope		-4.79***	-9.56***	-11.62***
Quadratic slope			0.96***	2.10
Cubic slope				-0.15
RANDOM EFFECTS				
Level 1 intra-individual:				
Residual variance	224.70***	63.60***	54.64***	54.19***
Level 2 inter-individual:				
Variance of intercept	1889.79***	2213.04***	2249.14***	2251.31***
Variance of slope		24.68***	26.06***	26.23***
GOODNESS-OF-FIT				
-2LL	2278.45	2105.42	2081.96	2080.83
No. of parameters	3	5	6	7
x^2		173.03***	23.46***	1.13
Degrees of freedom		2	1	1

***p<0.001; **p<0.01; *p<0.05
-2LL: -2 Log Likelihood
x^2: chi-square
critical value $x^2(1) = 10.83$ $p < 0.001$
$x^2(1) = 6.64$ $p < 0.01$
$x^2(1) = 3.84$ $p < 0.05$

The column shaded in grey represents the best model fit.

Table 6-25 Covariance structure models for SWMFT-Time

Covariance structure	-2 Log Likelihood -2LL
Compound symmetry	2214.63
AR(1)	2214.63
AR(1) heterogeneous	2072.69

Table 6-26 Effect of predictors on the SWMFT-Time model

Predictors	Conditional quadratic model	
	F statistic	p value
Age	0.43	0.515
Age x TIME (linear slope)	3.18	0.077
Age x TIME x TIME (quadratic slope)	4.06*	0.045
Gender	0.23	0.635
Gender x TIME	0.07	0.793
Gender x TIME x TIME	0.15	0.698
Hand dominance	0.25	0.621
Hand dominance x TIME	0.42	0.519
Hand dominance x TIME x TIME	0.37	0.541
Affected UE	0.004	0.952
Affected UE x TIME	17.86***	0.001
Affected UE x TIME x TIME	16.11***	0.001
Time post stroke	10.35**	0.002
Time post stroke x TIME	16.74***	0.001
Time post stroke x TIME x TIME	12.21***	0.001
Stroke type	3.49	0.068
Stroke type x TIME	7.11**	0.008
Stroke type x TIME x TIME	4.11*	0.047
Severity of UE impairment	114.72***	0.001
Severity of UE impairment x TIME	7.80**	0.006
Severity of UE impairment x TIME x TIME	1.29	0.258
Severity of trunk impairment	17.73***	0.001
Severity of trunk impairment x TIME	1.24	0.268
Severity of trunk impairment x TIME x TIME	0.44	0.509
TIS score	13.55***	0.001
TIS score x TIME	0.24	0.628
TIS score x TIME x TIME	15.77***	0.001
FMA score	647.10***	0.001
FMA score x TIME	9.19**	0.003
FMA score x TIME x TIME	5.88*	0.016
Therapy Time	0.06	0.809
Therapy Time x TIME	0.004	0.948
Therapy Time x TIME x TIME	0.01	0.916

***p<0.001; **p<0.01; *p<0.05

Table 6-27 SWMFT-Time: Combination of predictors and pseudo R^2

Predictors	-2LL	df	Deviance statistics	*p* value	Residual variance	Proportional variance reduction Pseudo R^2
Affected UE x Time post stroke x Stroke type x UE impairment x TIS score x FMA x TIME²	2026.36	10	46.33	0.01	43.84	19.0%
FMA x TIME²	1998.93	10	73.76	0.001	43.40	19.8%
Time post stroke x FMA x TIS score x TIME²	1985.01	10	87.68	0.001	43.87	18.9%
FMA x TIS score x TIME²	1916.29	10	156.40	0.001	53.59	1.5%
FMA x affected UE x TIME²	1986.15	10	86.54	0.001	46.67	13.7%
FMA x Trunk impairment x TIME²	1965.98	10	106.71	0.01	47.62	12.0%
Affected UE x Time post stroke x FMA x TIME²	2012.05	10	60.64	0.001	45.30	16.3%
Affected UE x TIS score x TIME²	2053.55	10	19.14	0.001	50.12	7.4%
Time post stroke x FMA x Trunk impairment xTIME²	2008.55	10	64.14	0.001	44.24	18.2%

Note: the baseline quadratic curve: -2 log likelihood (-2LL) = 2072.69
Degrees of freedom (df) = 7
Residual = 54.11

critical value $x^2(3) = 16.27$ $p < 0.001$
$x^2(3) = 11.35$ $p < 0.01$
$x^2(3) = 7.82$ $p < 0.05$

The row shaded in grey represents the model with the largest pseudo R^2.

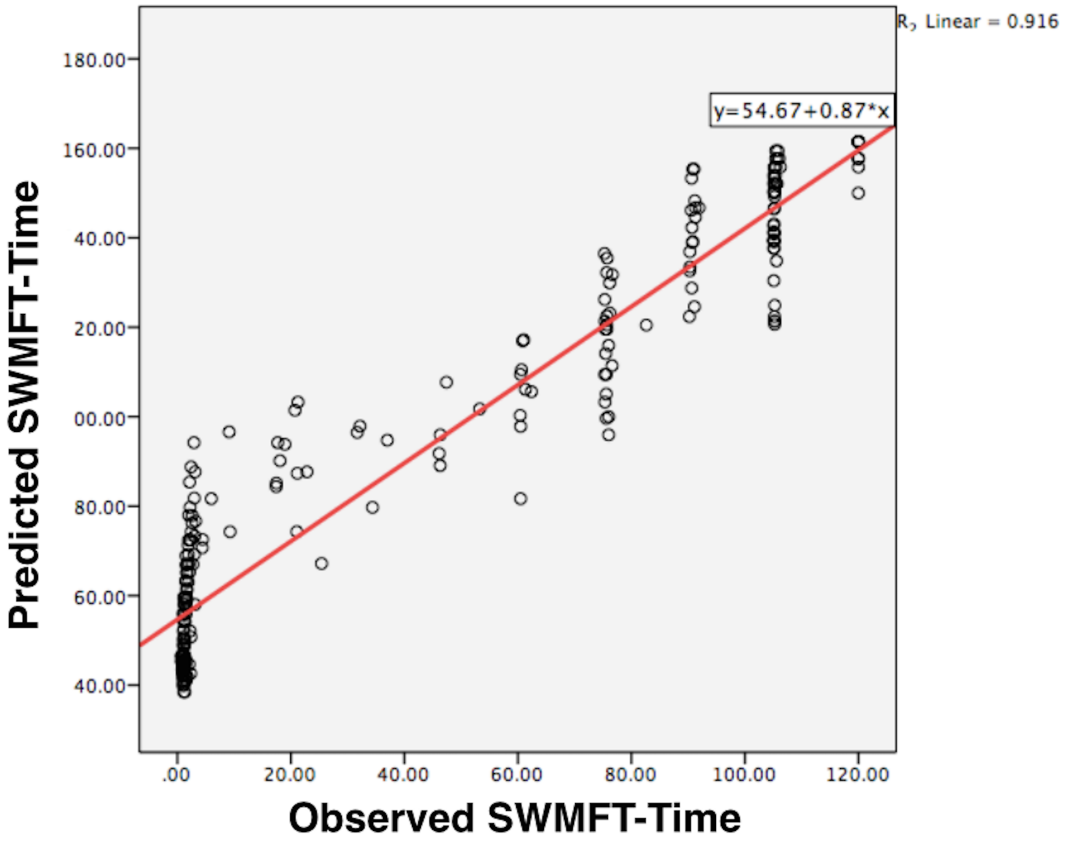


Figure 6-28 Plot of the predicted SWMFT-Time against the observed SWMFT-Time

Figure 6-29 illustrates the individual SWMFT-Time recovery curves for the group of 45 subacute stroke participants. Figure 6-30 illustrates the prototypical plot of the SWMFT-Time recovery curve derived from the equation of the estimated model. The curve showed that the most rapid recovery of SWMFT-Time occurred in the first 3 months post stroke and then the rate of recovery decreased from 3rd to 6th month period. This finding is supported by the SPSS analysis of the instantaneous rate of change (slope) for the SWMFT-Time recovery curve at each time point (Table 6-28 and Figure 6-31).

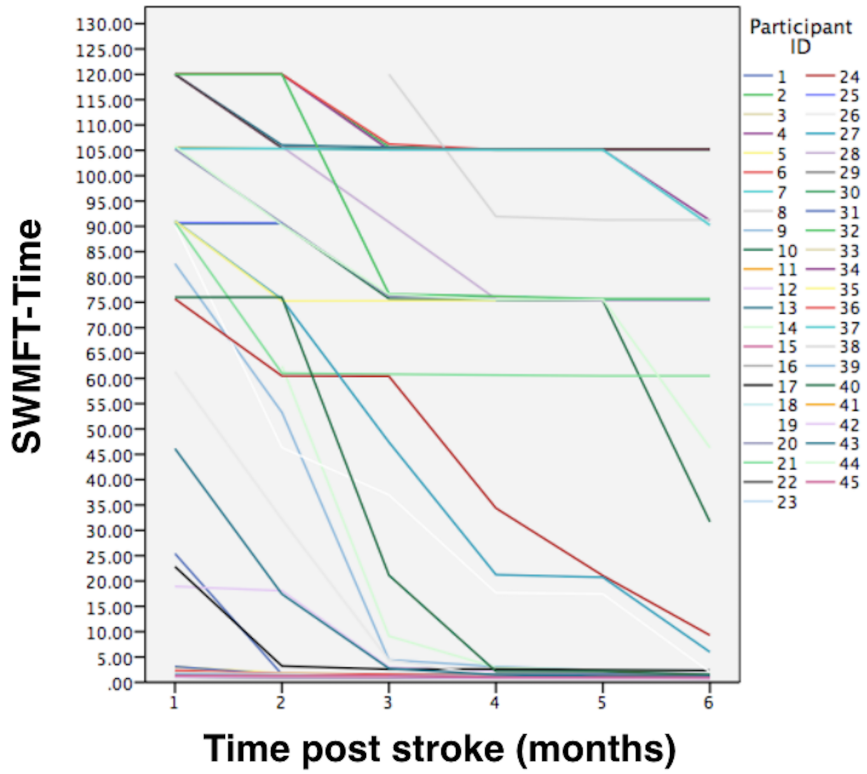


Figure 6-29 Individual SWMFT-Time recovery curves of 45 subacute stroke participants

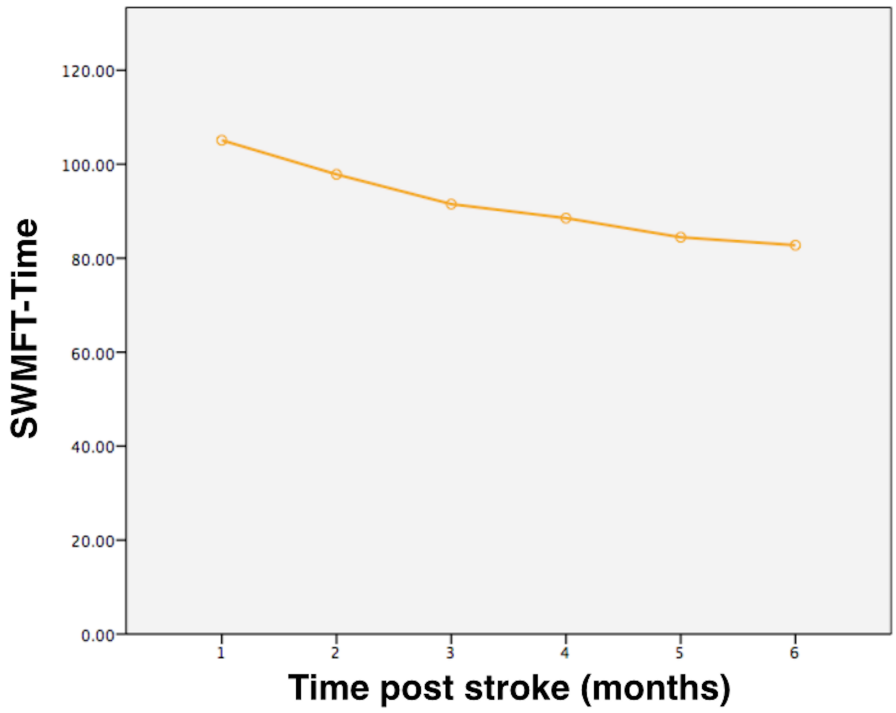


Figure 6-30 Prototypical plot of the recovery curve of SWMFT-Time

Table 6-28 Instantaneous rate of change of SWMFT-Time recovery curve in the first 6 months post stroke

Time post stroke	Rate of change (seconds/month)
1st month	-9.64
2nd month	-7.70
3rd month	-5.76
4th month	-3.82
5th month	-1.89
6th month	0.05

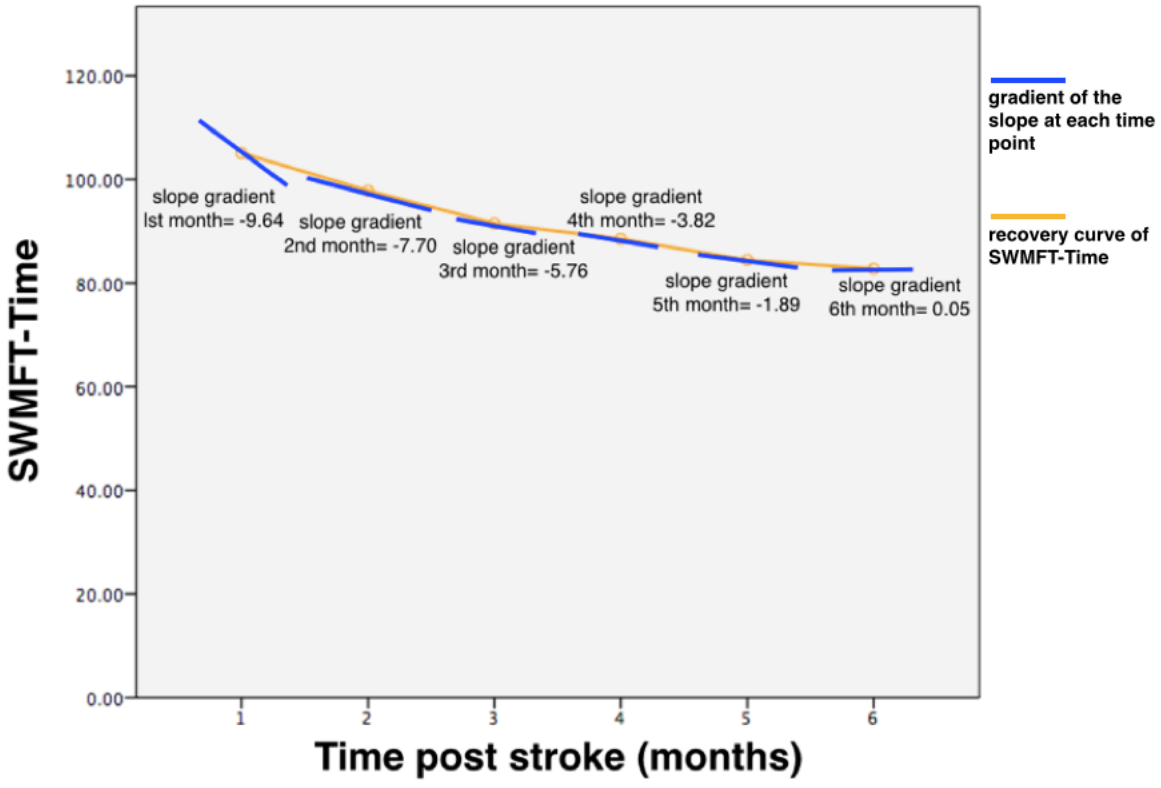


Figure 6-31 Instantaneous rate of change of SWMFT-Time recovery curve in the first 6 months post stroke

6.4.4.6.2 Impact of initial SWMFT-Time on the trajectory of recovery curve

Results demonstrated a negative and significant intercept-slope covariance (covariance = -0.46, p<0.001). Note that the rate of change (-9.64) for SWMFT-Time was negative. Hence, this suggests that as the intercept increased, the slope increased (in negative direction) (Figure 6-32). In other words, those participants with higher initial SWMFT-Time demonstrated a faster rate of change, on average, than those with lower initial SWMFT-Time. Similarly, those participants with lower initial SWMFT-Time demonstrated a slower rate of change, on average, than those with higher initial SWMFT-Time.

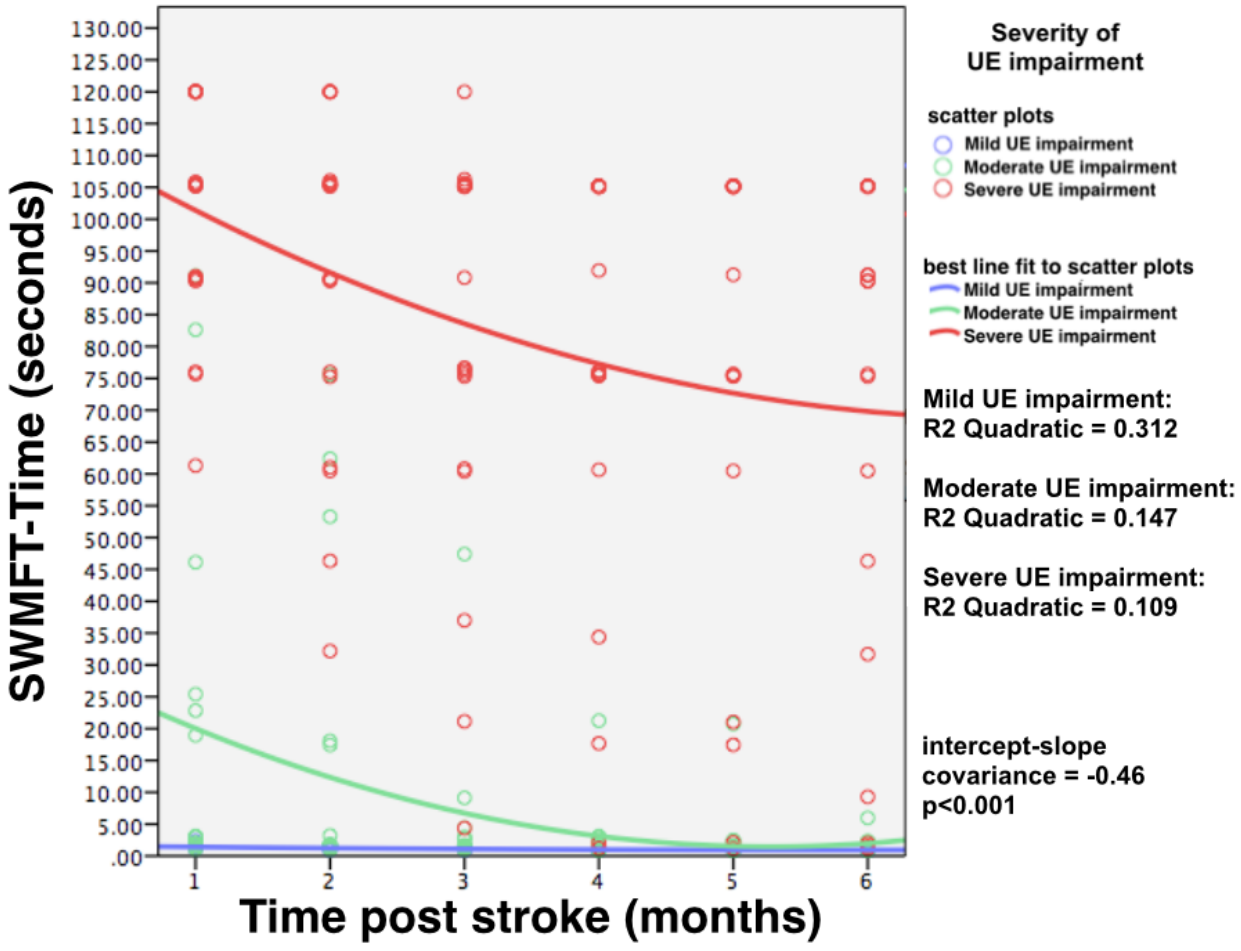


Figure 6-32 SWMFT-Time recovery curves based on severity of upper extremity impairment

6.4.4.6.3 Impact of upper extremity impairment level on the trajectory of SWMFT-Time recovery curve

Figure 6-32 demonstrated the different trajectories of SWMFT-Time recovery curve based on the initial UE impairment level (mild, moderate and severe).

From visual inspection of Figure 6-32, it appears that those participants with moderate upper extremity impairment at initial status might catch up to those with mild upper extremity impairment, as the differences in SWMFT-Time between the two groups tend to become less pronounced over time approximately from the 5th month onwards.

6.4.4.6.4 Impact of severity of trunk impairment on the trajectory of SWMFT-Time recovery curve

Figure 6-33 demonstrated the different trajectories of SWMFT-Time recovery curve based on the initial severity of trunk impairment.

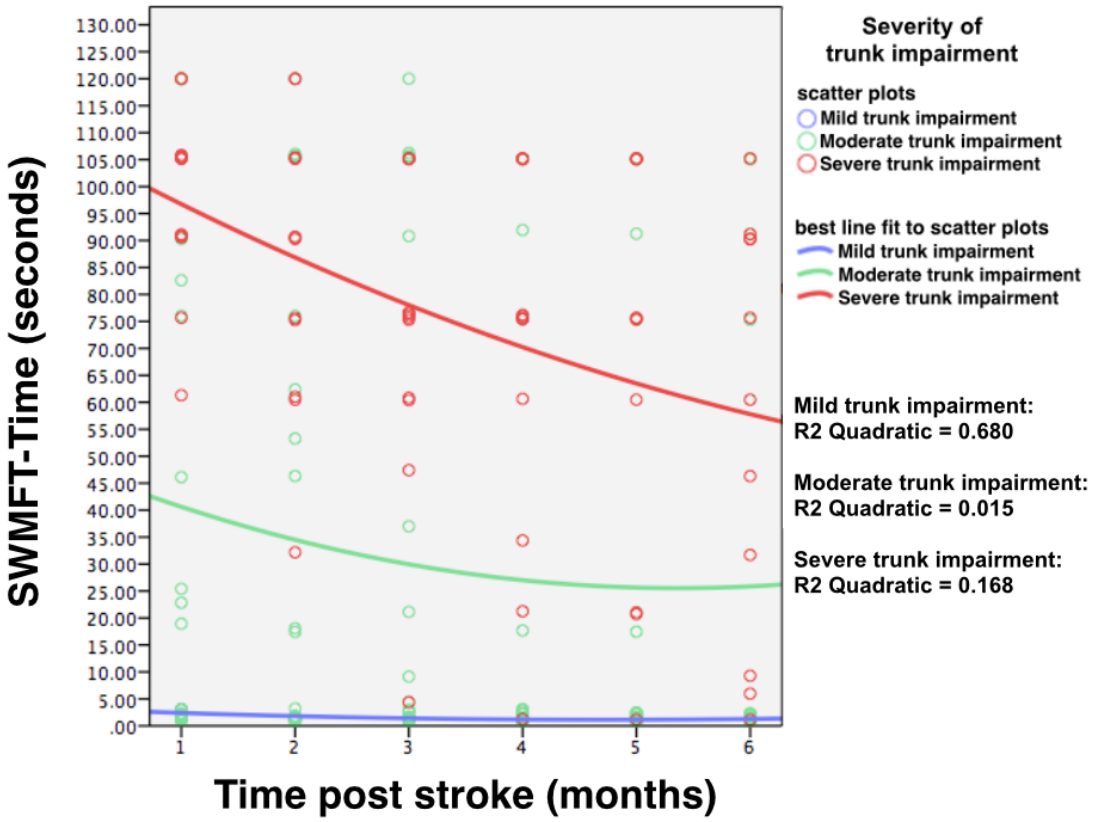


Figure 6-33 SWMFT-Time recovery curves based on severity of trunk impairment

6.4.4.6.5 Intra-individual and inter-individual variability in SWMFT-Time

Results from the final SWMFT-Time model demonstrated significant intra-individual variability across each wave of measurement (residual variance = 48.91, p<0.001). There was inter-individual variability in the intercept (variance = 118.21, p<0.001) and slope (variance = 10.66, p<0.001) over time.

6.4.4.7 Streamlined Wolf Motor Function Test-Functional Ability Scale (SWMFT-FAS)

The IGC modelling results of SWMFT-FAS demonstrated that the quadratic model (Model 3 – shaded in grey) improved model fit over the linear model (Model 2) based on the -2 log likelihood test (x^2(1) = 348.66 – 293.09 = 54.38, p<0.001) (Table 6-29). However, the cubic model (Model 4) did not further improve model fit (x^2(1) = 293.09 – 290.07 = 3.02, p>0.05). Therefore, the quadratic change of SWMFT-FAS (Model 3) was modelled in all subsequent analyses. The AR(1) heterogeneous covariance structure was used for all analyses as it has the lowest -2LL value compared to the compound symmetry and AR(1) structures (Table 6-30).

6.4.4.7.1 Shape of SWMFT-FAS recovery curve

Table 6-31 illustrates the impact of each predictor when it was added to the quadratic model. The significant predictors of SWMFT-FAS were age, side of affected UE, time post stroke, severity of UE impairment and severity of trunk impairment, TIS score, FMA and SWMFT-Time. This implies that the predictors have an influence on the overall shape of SWMFT-FAS recovery curve. The combination of significant predictors in a conditional multivariable model was presented in Table 6-32. Results showed that the combined predictors, i.e., (Trunk Impairment x SWMFT-Time x TIME^2) (shaded in grey), demonstrated the largest pseudo R^2 of 28.2%.

Table 6-29 Comparison of growth curve model parameter estimates for SWMFT-FAS

	Model 1 Unconditional means model	**Model 2** Unconditional Linear Model	**Model 3** Unconditional quadratic model	**Model 4** Unconditional cubic model
FIXED EFFECTS				
Initial status				
Intercept	2.67***	2.09***	1.94***	1.91***
Rate of change				
Linear slope		0.24***	0.46***	0.57***
Quadratic slope			-0.05***	0.11***
Cubic slope				0.01
RANDOM EFFECTS				
Level 1 intra-individual:				
Residual variance	0.31***	0.07***	0.05***	0.05***
Level 2 inter-individual:				
Variance of intercept	2.84***	2.90***	2.99***	2.96***
Variance of slope		0.02***	0.02***	0.02***
GOODNESS-OF-FIT				
-2LL	602.98	348.66	293.09	290.07
No. of parameters	3	5	6	7
x^2		254.32***	54.38***	3.02
Degrees of freedom		2	1	1

***p<0.001; **p<0.01; *p<0.05
-2LL: -2 Log Likelihood
x^2: chi-square
critical value $x^2(1) = 10.83$ $p < 0.001$
$x^2(1) = 6.64$ $p < 0.01$
$x^2(1) = 3.84$ $p < 0.05$

The column shaded in grey represents the best model fit.

Table 6-30 Covariance structure models for SWMFT-FAS

Covariance structure	-2 Log Likelihood -2LL
Compound symmetry	443.61
AR(1)	443.61
AR(1) heterogeneous	288.83

Table 6-31 Effect of predictors on the SWMFT-FAS model

Predictors	Conditional quadratic model	
	F statistic	p value
Age	0.50	0.483
Age x TIME (linear slope)	5.32	0.022
Age x TIME x TIME (quadratic slope)	4.22*	0.041
Gender	0.01	0.906
Gender x TIME	0.88	0.349
Gender x TIME x TIME	0.66	0.420
Hand dominance	0.01	0.755
Hand dominance x TIME	0.22	0.638
Hand dominance x TIME x TIME	0.39	0.532
Affected UE	0.09	0.765
Affected UE x TIME	11.77***	0.001
Affected UE x TIME x TIME	5.40*	0.021
Time post stroke	8.82**	0.005
Time post stroke x TIME	0.97	0.326
Time post stroke x TIME x TIME	0.01	0.915
Stroke type	2.37	0.131
Stroke type x TIME	0.89	0.348
Stroke type x TIME x TIME	0.31	0.582
Severity of UE impairment	149.57***	0.001
Severity of UE impairment x TIME	1.52	0.219
Severity of UE impairment x TIME x TIME	0.10	0.754
Severity of trunk impairment	16.35**	0.001
Severity of trunk impairment x TIME	0.37	0.546
Severity of trunk impairment x TIME x TIME	0.04	0.852
TIS score	8.15**	0.005
TIS score x TIME	2.04	0.155
TIS score x TIME x TIME	6.75**	0.010
FMA score	1083.77***	0.001
FMA score x TIME	0.02	0.890
FMA score x TIME x TIME	1.49	0.225
SWMFT-Time	254.56***	0.001
SWMFT-Time x TIME	14.60	0.001
SWMFT-Time x TIME x TIME	1.99	0.160
Therapy Time	0.01	0.943
Therapy Time x TIME	0.38	0.537
Therapy Time x TIME x TIME	0.95	0.331

***p<0.001; **p<0.01; *p<0.05

Table 6-32 SWMFT-FAS: Combination of predictors and pseudo R^2

Predictors	-2LL	df	Deviance statistics	*p* value	Residual variance	Proportional variance reduction Pseudo R^2
Affected UE x TIS score x SWMFT-Time x TIME²	192.00	10	101.09	0.001	0.039	15.2%
Affected UE x Trunk Impairment x FMA x TIME²	212.65	10	80.44	0.001	0.038	17.4%
TIS score x SWMFT-Time x TIME²	179.03	10	114.06	0.001	0.040	20.0%
TIS score x FMA x TIME²	95.92	10	197.17	0.001	0.046	0%
Trunk Impairment x FMA x TIME²	169.69	10	123.40	0.001	0.036	21.7%
Trunk Impairment x SWMFT-Time x TIME²	114.88	10	178.21	0.001	0.033	28.2%
Affected UE x UE Impairment x FMA x TIME²	266.70	10	26.39	0.01	0.045	2.2%
Affected UE x SWMFT-Time x TIME²	137.70	10	155.39	0.001	0.035	23.9%
Affected UE x TIS score x TIME²	285.70	10	7.39	0.10	0.046	0%
FMA x SWMFT-Time x TIME²	254.48	10	38.61	0.001	0.043	6.5%

Note: the baseline quadratic curve: -2 log likelihood (-2LL) = 293.09
Degrees of freedom (df) = 7
Residual = 0.046

critical value $x^2(3) = 16.27$ $p < 0.001$
$x^2(3) = 11.35$ $p < 0.01$
$x^2(3) = 7.82$ $p < 0.05$

The row shaded in grey represents the model with the largest pseudo R^2.

Hence, the full equation for the estimated model for SWMFT-FAS is:

SWMFT-FAS = 3.18 + (0.35 x TIME) + (-0.03 x TIME^2) +

(-0.01x Trunk impairment x SWMFT-Time) +

(-0.0007 x Trunk impairment x SWMFT-Time x TIME) +

(0.00003 x Trunk impairment x SWMFT-Time x TIME^2)

This equation was used to plot the predicted SWMFT-FAS against the observed SWMFT-FAS (Figure 6-34). The R^2 value was 86.8%.

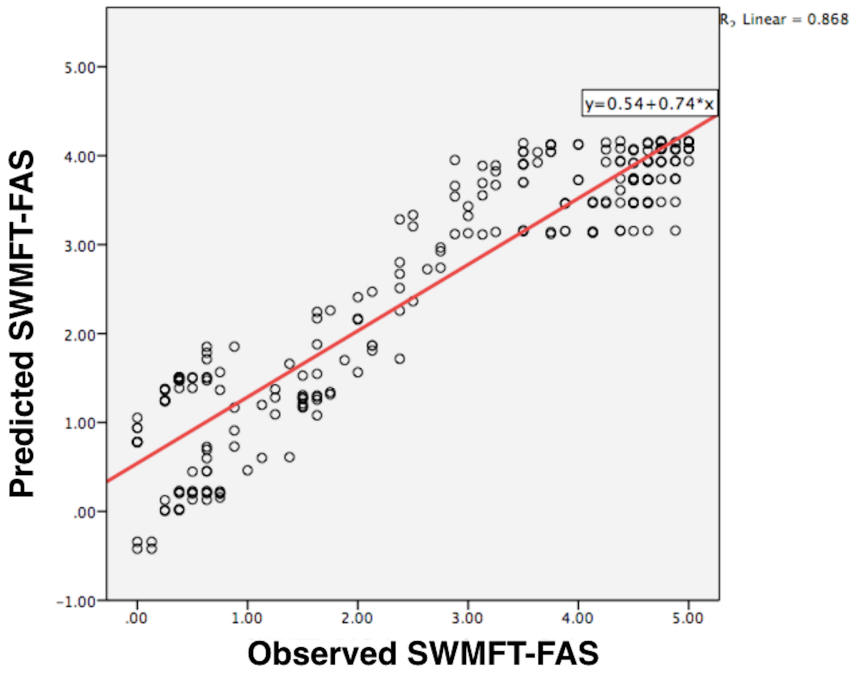


Figure 6-34 Plot of the predicted SWMFT-FAS against the observed SWMFT-FAS

Figure 6-35 illustrates the individual SWMFT-FAS recovery curves for the group of 45 subacute stroke participants. Figure 6-36 illustrates the prototypical plot of the SWMFT-FAS recovery curve derived from the equation of the estimated model. The curve showed that the most rapid recovery of SWMFT-FAS occurred in the first 3 months post stroke and then the rate of recovery decreased from 3rd to 6th month period. This finding is supported by the SPSS analysis of the

instantaneous rate of change (slope) for the SWMFT-FAS recovery curve at each time point (Table 6-33 and Figure 6-37).

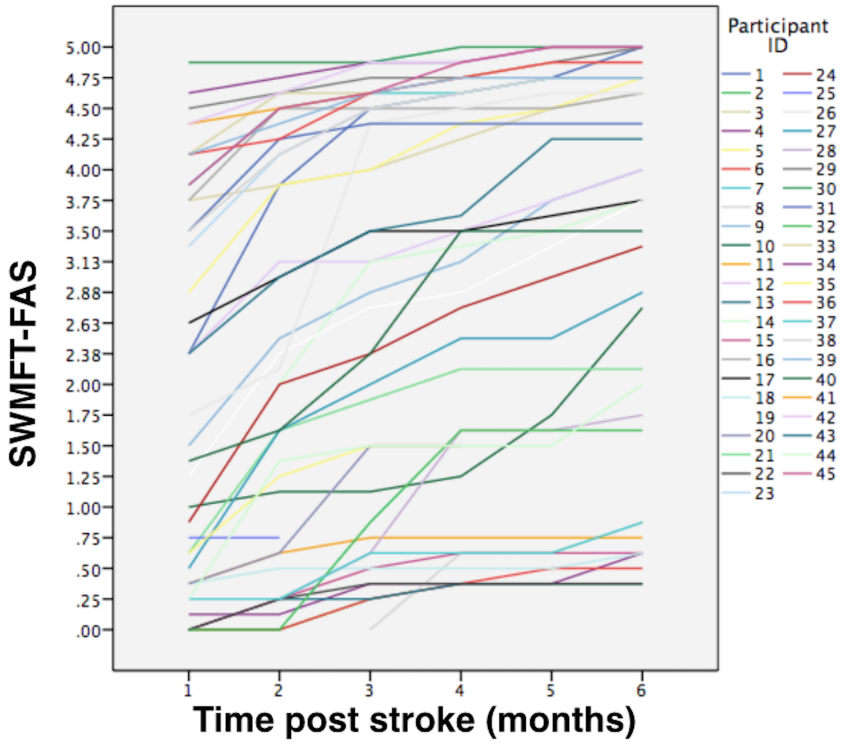


Figure 6-35 Individual SWMFT-FAS recovery curves of 45 subacute stroke participants

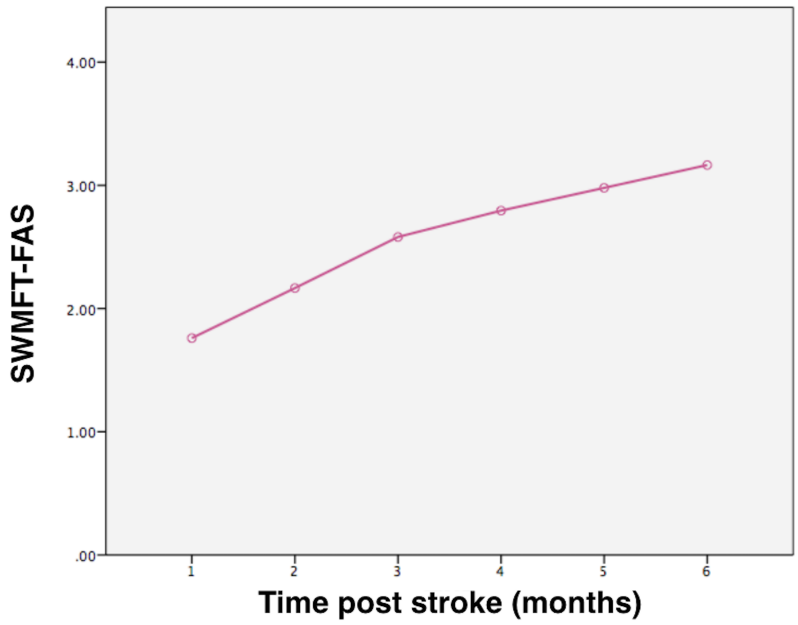


Figure 6-36 Prototypical plot of the recovery curve of SWMFT-FAS

Table 6-33 Instantaneous rate of change of SWMFT-FAS recovery curve in the first 6 months post stroke

Time post stroke (months)	Rate of change (FAS points/month)
1st	0.45
2nd	0.37
3rd	0.28
4th	0.19
5th	0.10
6th	0.01

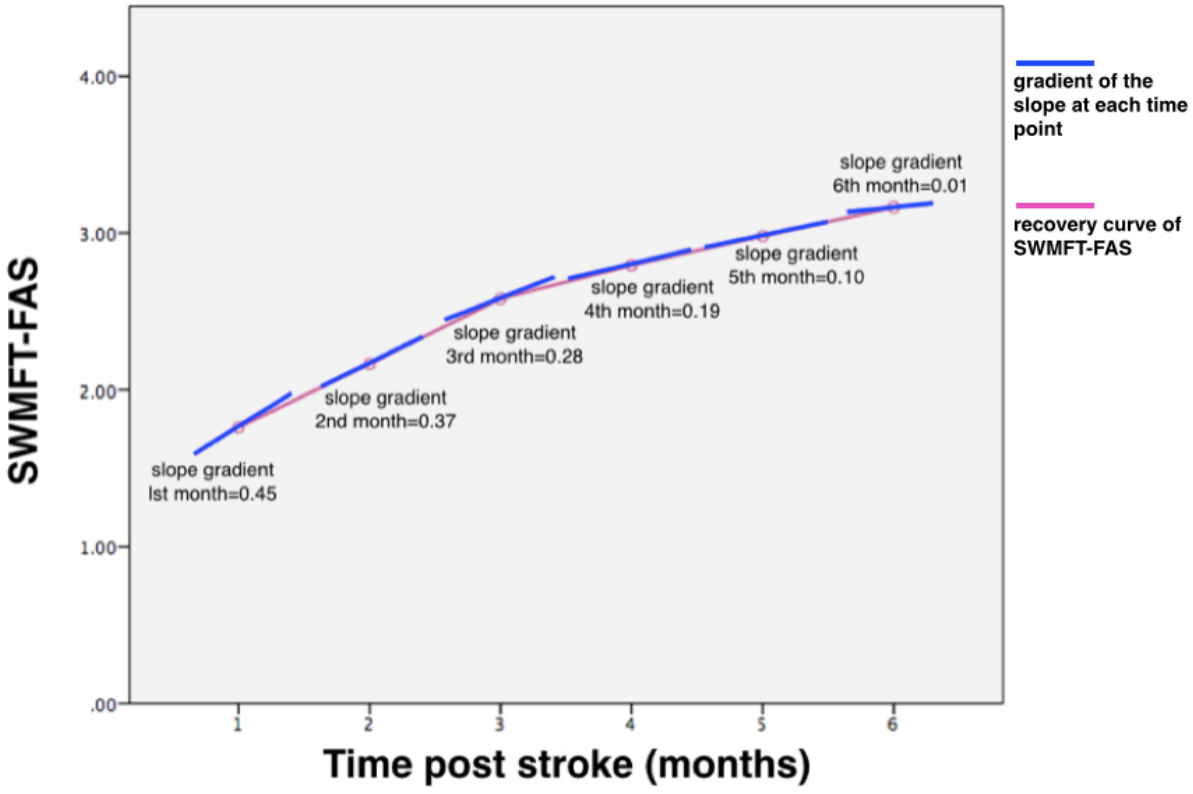


Figure 6-37 Instantaneous rate of change of SWMFT-FAS recovery curve in the first 6 months post stroke

6.4.4.7.2 Impact of initial SWMFT-FAS on the trajectory of recovery curve

Results demonstrated a negative and non-significant intercept-slope covariance (covariance= -0.37, p>0.05). Hence, this suggests that there was lack of systematic relationship between initial SWMFT-FAS score and trajectory of the recovery curve of SWMFT-FAS. In other words, the trajectory was unrelated to the initial SWMFT-FAS score.

6.4.4.7.3 Impact of upper extremity impairment level on the trajectory of SWMFT-FAS recovery curve

Figure 6-38 demonstrated the different trajectories of SWMFT-FAS recovery curve based on the initial upper extremity impairment level (mild, moderate and severe).

From visual inspection of Figure 6-38, it appears that those participants with moderate UE impairment at initial status might catch up to those with mild UE impairment, as the differences in SWMFT-FAS between the two groups tend to become less pronounced over time approximately from the 5th month onwards.

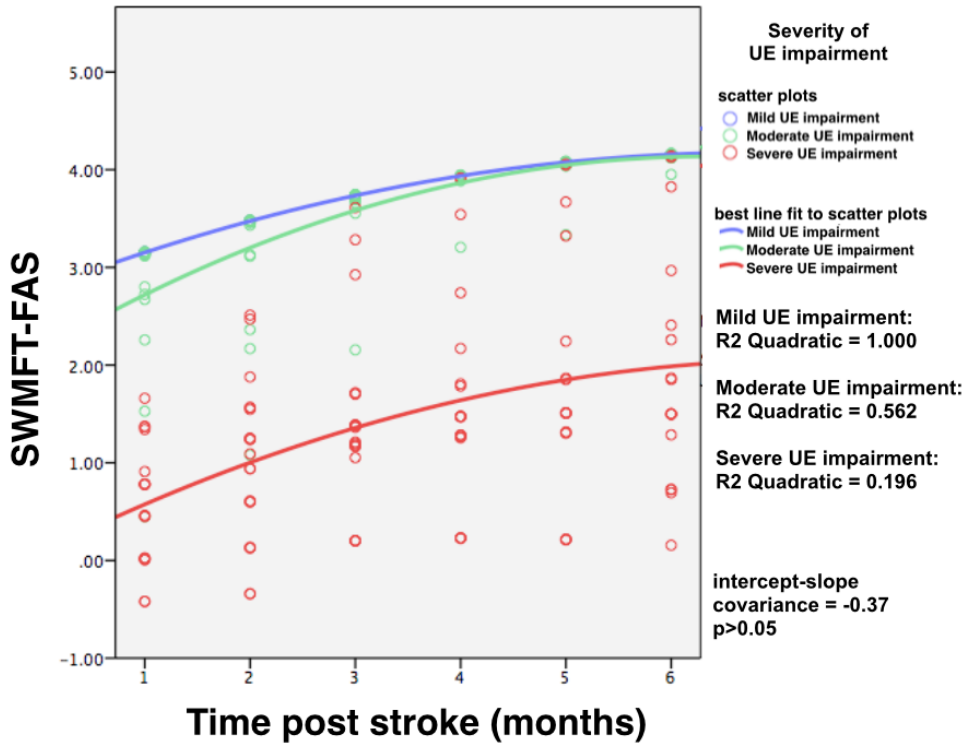


Figure 6-38 SWMFT-FAS recovery curves based on severity of upper extremity impairment

6.4.4.7.4 Impact of severity of trunk impairment on the trajectory of SWMFT-FAS recovery curve

Figure 6-39 demonstrated the different trajectories of SWMFT-FAS recovery curve based on the severity of initial trunk impairment level.

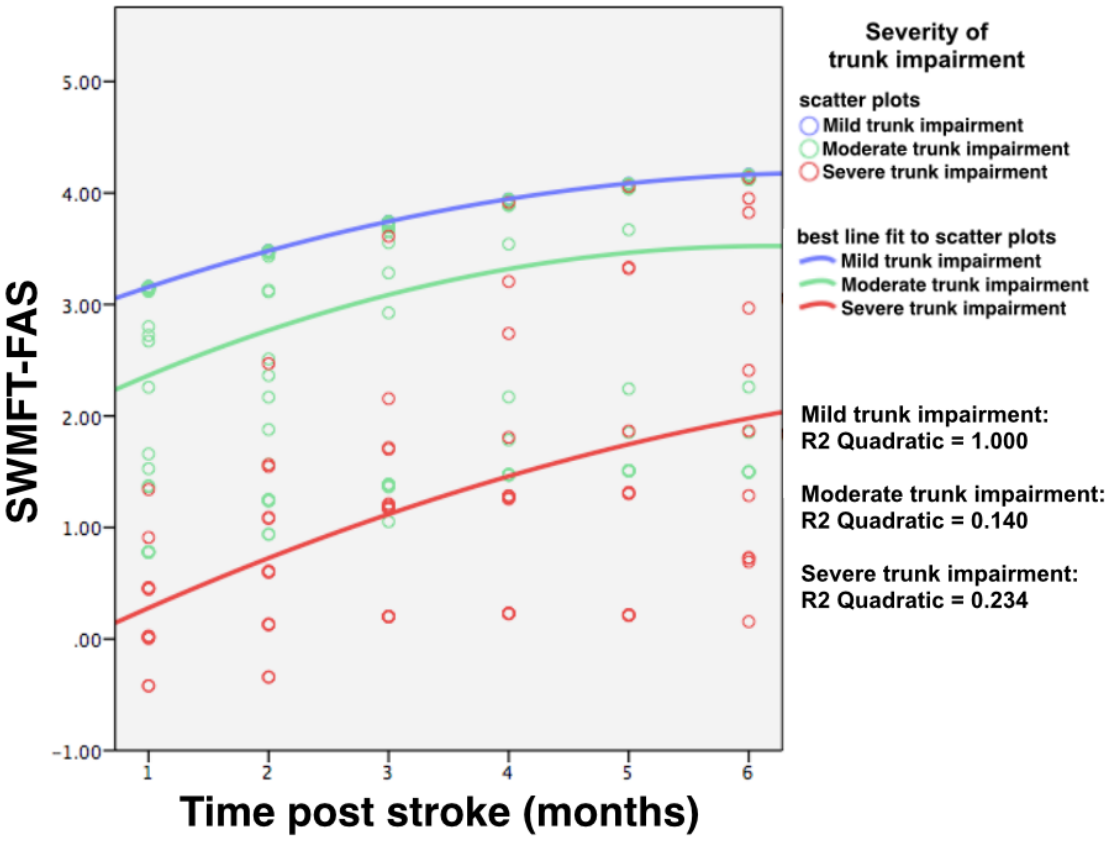


Figure 6-39 SWMFT-FAS recovery curves based on severity of trunk impairment

6.4.4.7.5 Intra-individual and inter-individual variability in SWMFT-FAS

Results from the final SWMFT-FAS model demonstrated significant intra-individual variability across each wave of measurement (residual variance = 0.03, p<0.001). There was inter-individual variability in the intercept (variance = 0.67, p<0.001) and slope (variance = 0.004, p<0.01) over time.

6.4.4.8 Rate of change of TIS, FMA, SWMFT-Time and SWMFT-FAS in the first six months post stroke

Graphs were plotted using the data from the instantaneous rate of change for TIS, FMA, SWMFT-Time and SWMFT-FAS (Tables 6-8, 6-13, 6-28 and 6-33) across the 6 time points (Figure 6-40). For all the variables, the rate of change decreased from the 1st month to the 6th month. The rate of change (gradient -0.61) of TIS was similar to the rate of change (gradient -0.68) of FMA.

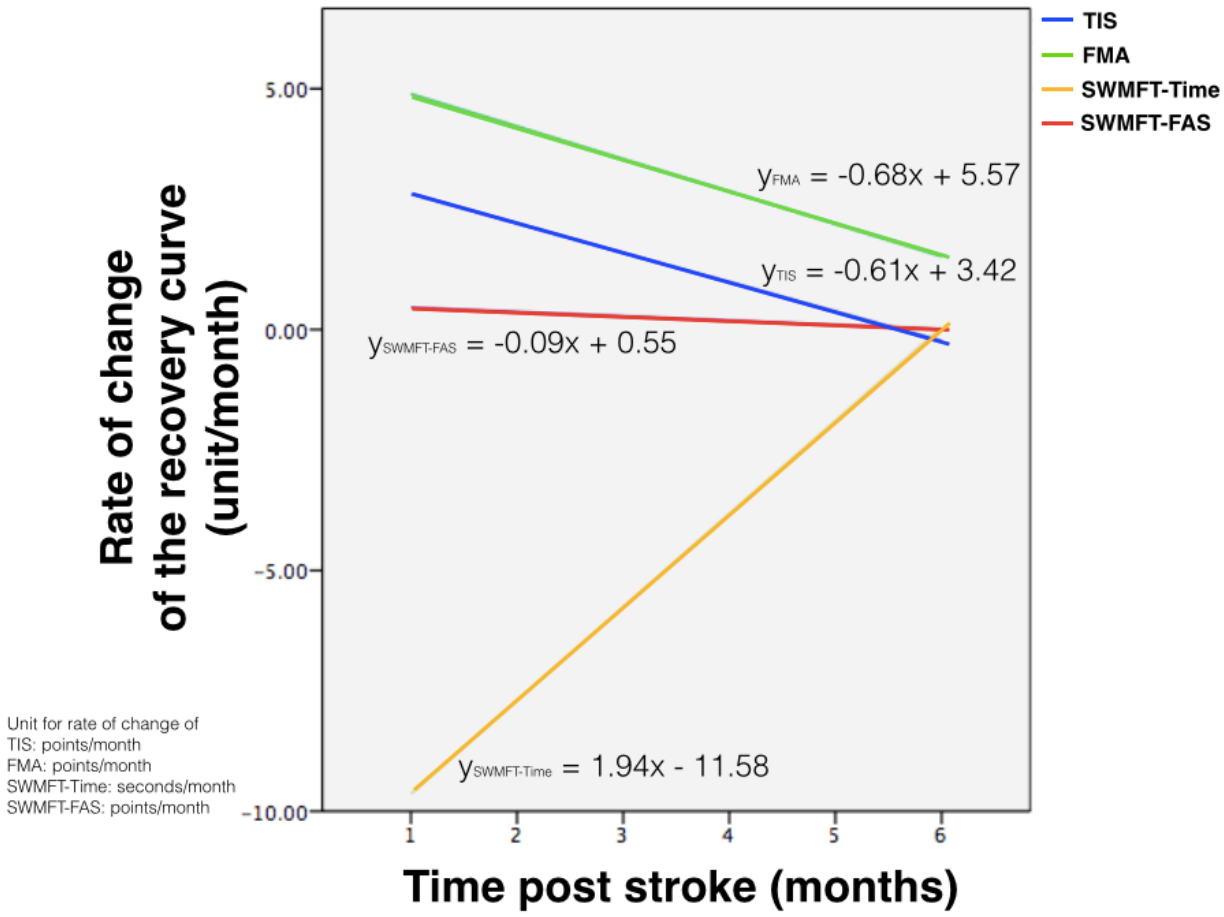


Figure 6-40 Rate of change of TIS, FMA, SWMFT-Time and SWMFT-FAS in the first six months post stroke

To summarise the results of the recovery pattern, the individual recovery curves are superimposed as shown in Figure 6-41. It demonstrates that as TIS scores improved over time, both the upper extremity impairment (FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS) improved almost in parallel with the TIS increase.

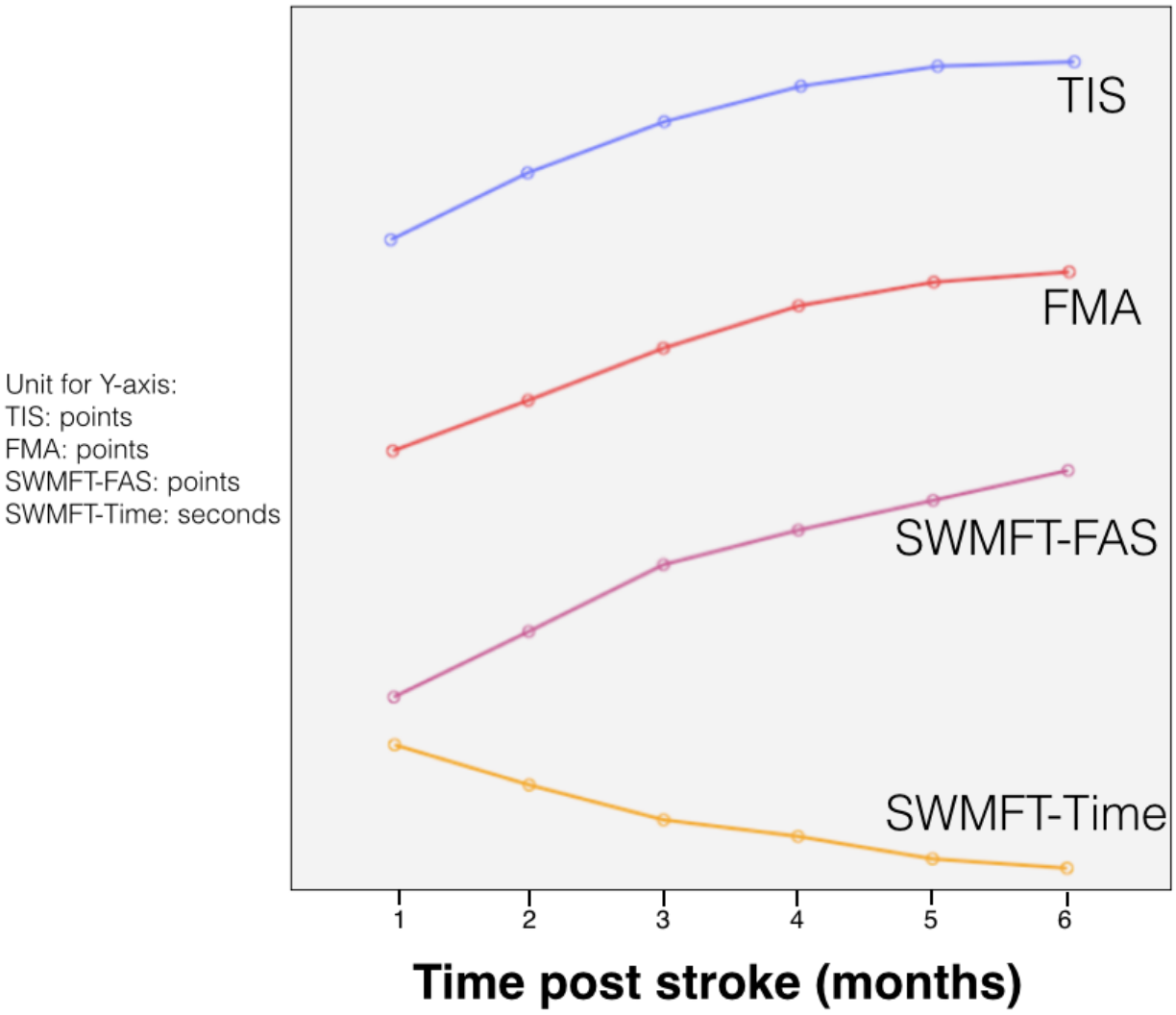


Figure 6-41 Recovery curves of TIS, FMA, SWMFT-Time and SWMFT-FAS in the first six months post stroke

6.5 Summary of Chapter 6

This Chapter has presented the results of the Phase 2 study (longitudinal study) with 45 subacute stroke participants over the period of first 6 months post stroke. The key findings are summarised below. Discussion of these findings in relation to previous research and clinical practice will be presented in Chapter 7.

6.5.1 Trunk Impairment Scale (TIS)

1) The recovery curve of TIS followed a quadratic trend, with most rapid recovery occurring in the first 3 months post stroke and then the rate of recovery decreased from 3rd to 6th month period.

2) The significant predictors of TIS outcome were stroke type, time post stroke, initial severity of UE impairment and initial severity of trunk impairment.

3) Participants with lower initial TIS score demonstrated a faster rate of change, on average, than those with higher initial TIS score.

4) The rate of change of TIS recovery is similar to the rate of change of FMA recovery in the first 6 months post stroke.

5) As TIS scores improved over time, both the upper extremity impairment (FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS) improved almost in parallel with the TIS increase.

6.5.2 Fugl-Meyer Assessment (FMA)

1) The recovery curve of FMA followed a quadratic trend, with most rapid recovery occurring in the first 4 months post stroke and then the rate of recovery decreased from 4th to 6th month period.

2) The significant predictors of FMA outcome were age, side of affected upper extremity, time post stroke, initial severity of upper extremity impairment, initial severity of trunk impairment, TIS score and therapy time.

3) Participants with lower initial FMA score demonstrated a faster rate of change, on average, than those with higher initial FMA score.

4) The rate of change of FMA recovery was similar to the rate of change of TIS recovery.

5) The rate of change of FMA-SE recovery was faster than the rate of change of FMA-WH recovery.

6.5.3 Streamlined Wolf Motor Function Test-Time (SWMFT-Time)

1) The recovery curve of SWMFT-Time followed a quadratic trend, with most rapid recovery occurring in the first 3 months post stroke and then the rate of recovery decreased from 3rd to 6th month period.

2) The significant predictors of SWMFT-Time were age, stroke type, time post stroke, side of affected upper extremity, initial severity of upper extremity impairment, initial severity of trunk impairment, TIS score and FMA score.

3) Participants with higher initial SWMFT-Time demonstrated a faster rate of change (in negative direction), on average, than those with lower initial SWMFT-Time.

6.5.4 Streamlined Wolf Motor Function Test-Functional Ability Scale (SWMFT-FAS)

1) The recovery curve of SWMFT-FAS followed a quadratic trend, with most rapid recovery occurring in the first 3 months post stroke and then the rate of recovery decreased from 3rd to 6th month period.

2) The significant predictors of SWMFT-FAS outcome were age, side of affected upper extremity, time post stroke, initial severity of upper extremity impairment and initial severity of trunk impairment, TIS score, FMA score and SWMFT-Time.

3) The trajectory of the recovery curve of SWMFT-FAS was unrelated to the initial SWMFT-FAS score.

The next Chapter will discuss the results of Phase 1A, Phase 1B and Phase 2 studies in greater depth in relation to the existing literature.

Chapter 7: Discussion

7. Discussion

The trunk is considered an important postural stabilizer which enables the dissociation of the upper and lower extremities from the trunk for function (Carr & Shepherd 1987; Davies 1990a; Mohr 1990; Gillen 1998; Davies 2000; Rosenblum & Josman 2003; Heyrman et al. 2013). However, this common assumption in neurorehabilitation has not been validated in clinical trials. The association of trunk control with upper extremity function in people with stroke was unknown to date. This knowledge is critical to the design of targeted rehabilitation programmes for the trunk and upper extremity so that optimal functional outcomes for stroke patients can be achieved. Hence, this is a gap in knowledge that warrants research to illuminate this relationship.

This PhD work investigated the relationship between trunk control and recovery of upper extremity function in stroke patients. In order to achieve the overarching aim, the author (SKW) conducted two cross-sectional studies (Phase 1A and Phase 1B studies) and a longitudinal study (Phase 2 study).

The aims of the Phase 1A and Phase 1B study were to investigate the effect of an external trunk support on trunk control and upper extremity function, and examine the relationship between trunk control and upper extremity function in people with subacute stroke and chronic stroke and healthy controls. The aims of the Phase 2 study were to examine the recovery curves of trunk control and upper extremity, and investigate the impact of trunk control on the recovery of upper extremity in subacute stroke participants.

This Chapter is subdivided into 8 sections, discussing the results of the Phase 1 and Phase 2 studies in relation to previous research findings. The limitations of this study and implications for clinical practice will be discussed. In addition, recommendations for future research to extend this PhD work will be provided. The final section highlights the original contributions to the body of knowledge in stroke rehabilitation drawn from this PhD work.

7.1 Clinical outcomes (with and without trunk support) in healthy and stroke participants

7.1.1 Trunk Impairment Scale (TIS)

The TIS is an outcome measure developed by Verheyden et al. (2004) to assess trunk control in stroke patients. Verheyden et al. (2005) found that a cut-off TIS score of 20 had the ability to discriminate between stroke patients and healthy individuals.

The TIS score for the 34 healthy participants in this study ranged from 19 to 23. Twenty-nine participants (85.3%) demonstrated a maximum TIS score of 23. One female participant, aged 82, had a TIS score 19. She had limited trunk flexibility and mobility for some of the test items, such as pelvic lift using lower trunk muscle groups and lower trunk rotation. Despite the lower TIS score, she was ADL independent and community ambulant without any walking aids. All the participants were community independent. These results illustrate that a person can remain functionally independent without having achieved a maximum score on the TIS. This is consistent with the findings of Verheyden et al. (2005) that maximal score on the TIS is not a prerequisite for normal, functional daily activities. In that study (Verheyden et al. 2005), 45% of the 40 healthy participants scored less than the maximum TIS score. Hence, therapists should not expect stroke patients to obtain a full score on the TIS before classifying them as having normal trunk function.

A cut-off TIS score of 20 was found to be able to discriminate between people with stroke and healthy individuals (Verheyden et al. 2005). A TIS score of 20 was the 90th percentile for the stroke patients and the 10th percentile for the healthy individuals (Verheyden et al. 2005). This implies that the normative range of TIS is between 20 to 23. In this doctoral study, 56% of the chronic stroke participants and 95.6% of the subacute stroke participants attained TIS score of less than 20. Hence, these results support the usefulness of the cut-off TIS score of 20 to discriminate between trunk control of individuals with subacute stroke and healthy individuals. In the present study, participants with a TIS score of less than 20 exhibited difficulty in activating the appropriate upper and lower trunk muscle groups for trunk movements in all planes. In the clinics, deficits observed in the respective test items in the TIS assessment will

provide therapists with the appropriate task-orientated goals to improve trunk control.

Results from this doctoral study demonstrated a statistically significant large interaction effect between group and support condition. The TIS score increased significantly more with the trunk support in the subacute stroke group as compared to the chronic stroke and healthy group. There were statistically significant improvements in the TIS score from 18 to 20 in the chronic stroke participants, and from 13.11 to 18.33 in the subacute stroke participants. This change in score needs to be considered in the context of minimal clinically important difference (MCID). MCID is defined as the smallest change or difference that patients perceived as clinically beneficial (Wright et al. 2012). To date, the MCID for TIS score has not been established. Verheyden et al. (2004) reported that an increase of 4 points on the TIS can be seen as an improvement without reproducibility bias. Therefore, a change of 5.22 points on the TIS score with trunk support in the subacute stroke participants in this doctoral study can be considered a clinically important change while a 2-point change for the chronic stroke participants is not. This suggests that trunk control in subacute stroke participants is more amenable to change than chronic stroke participants. In other words, the potential for change is larger for the subacute stroke participants and suggest that therapy targeted at trunk rehabilitation early in the stroke recovery may be beneficial. Although the potential for change in trunk control in the chronic stroke participants may be smaller, the results support the notion that chronic stroke participants can continue to improve further when therapy, with the appropriate stimuli and feedback are provided. Ongoing recovery at the neurological level has been demonstrated to occur, even in the chronic stage of stroke (Page et al. 2004; Teasell et al. 2012; Dobkin & Dorsch 2013; Korner-Bitensky 2013; Simpson & Eng 2013; Frykberg & Vasa 2015; Hubbard et al. 2015).

An increase in the TIS score illustrates that an external support can assist stroke participants to improve their trunk control. It was observed that in some stroke participants, tactile feedback at the side of the trunk support provided cues to the individuals and assisted them to elicit the activation of the appropriate muscle groups for shortening and lengthening of the trunk, and hence, increasing the TIS scores. Studies have shown that tactile feedback improves movement accuracy and control (Rao & Gordon 2001; Rabin et al.

2010; Polechonski & Olex-Zarychta 2012; Kim et al. 2013). A recent study demonstrated that tactile feedback at the back (T10 level) of healthy subjects was effective in reducing trunk sway (Maaswinkel et al. 2014). This is in agreement with the findings of Rabin et al. (2008) which suggest that the pressure receptors in contact with an external object provide the subject with additional information of his/her sway and increase the awareness of postural alignment. These findings support this doctoral research that the external trunk support, which provides tactile feedback at the posterior and lateral aspects of the lower trunk, can help to stabilize the trunk by reducing trunk sway.

Therapists utilising the Bobath approach in neurorehabilitation would use their hands to facilitate patients to perform selective muscle activation for optimal movement control (Bobath 1990; Davies 2000; Platz et al. 2005b). To some extent, the trunk support is similar to having the therapist's hands to support around the lateral and posterior aspects of the lumbar and thoracic regions of the individual. This may account for the author's (SKW) observation of appropriate shortening and lengthening of the trunk muscles with the use of the external trunk support. Intensive practice of the correct movement pattern of the trunk over time may lead to better control and outcome.

7.1.2 Streamlined Wolf Motor Function Test

For the group of healthy participants, there was a statistically significant reduction in the SWMFT-Time for both dominant and non-dominant upper extremity. Similarly for the chronic and subacute stroke groups, there was a statistically significant reduction in the SWMFT-Time for both the affected and less affected upper extremity with trunk support, with large effect sizes. There was no significant difference in the SWMFT-Time between the order of testing with or without trunk support, gender, hand dominance and side of affected upper extremity. The order of testing with and without trunk support was randomized to avoid any possible order bias due to practice or fatigue. Hence, the reduction in SWMFT-Time could be attributed to provision of trunk support.

With trunk support, the mean SWMFT-Time for the affected upper extremity was reduced by 2.01 seconds and 1.40 seconds in the subacute stroke and chronic stroke participants respectively (Table 5-5). The MCID for WMFT-Time

was reported to be between 1.5 seconds to 2 seconds for stroke patients (Lin et al. 2009b). Therefore, the improvement in SWMFT-Time for the subacute stroke participants in this doctoral study is considered a clinically important difference. This suggests that the trunk support has a significant impact on the upper extremity function in the early phase of stroke recovery. Stabilizing the trunk enables an improvement in the ability to use the upper extremity for functional activities.

The Wilcoxon signed rank test for the SWMFT-FAS demonstrated a statistically significant improvement in the median SWMFT-FAS from 3.3 points to 3.6 points with the trunk support, regardless of the groups. There was an increase of median 0.1 point in the chronic stroke group and 0.4 points in the subacute stroke group. The MCID for WMFT-FAS was reported to be between 0.2 to 0.4 points for stroke patients (Lin et al. 2009b). Hence, with trunk support, a gain of 0.3 points on the SWMFT-FAS for the 3 groups (healthy, subacute and chronic stroke groups) and a gain of 0.4 points in the subacute stroke group in this doctoral study are considered clinically important difference.

Taken together, these results demonstrated that stabilization of the trunk has an impact on improving the upper extremity function. Hence, the findings support the hypothesis that a stable trunk enables a better dissociation of the upper extremity from the trunk for function.

7.1.3 Possible mechanisms to account for the improvements in SWMFT-Time and SWMFT-FAS

There are a number of possible explanations for the statistically significant reduction in the SWMFT-Time and improvement in SWMFT-FAS. Firstly, a possible key reason to account for a better upper extremity function with the trunk support is the stabilization of the trunk. The trunk support was customised to fit around each participant snugly and fastened securely to the plinth by straps. In contrast to the chest harness used in the research on trunk restraint (Michaelsen et al. 2001; Michaelsen & Levin 2004; Michaelsen et al. 2006; de Oliveira et al. 2007; Thielman et al. 2008; Thielman 2010; Lima et al. 2012; Wu et al. 2012a; Wu et al. 2012b), the trunk support used in this doctoral study was not restrictive, but supportive in nature, allowing free forward movement but minimal movement posteriorly and laterally. The

participants were also not instructed to make a conscious effort maintain an upright posture during the performance of SWMFT tasks. With these factors controlled during the task performance, the positive outcomes (SWMFT-Time and SWMFT-FAS) observed may be attributed to the stabilization of the trunk provided by the support.

With the trunk stabilized, it enables improved movement of the proximal and distal segments of the upper extremity to occur against a background of stabilized core muscles of the body (Wee et al. 2015a; Wee et al. 2015b). This is supported by a study that demonstrated statistically significant improvement in functional reach ability of the upper extremity in people with stroke after an intervention consisting of trunk stability exercise (Kim et al. 2011). This suggests that trunk stability has an effect on the stability of the shoulders, and that in turn improves the movement of the elbow, wrist and fingers (Miyake et al. 2013). A stable trunk provides a solid foundation for the torque generated by the extremities (Behm et al. 2010). Performing reaching movement on a stable surface is different from the challenges faced when attempting to reach out for objects while balancing on an unstable surface. Studies have demonstrated that unstable conditions can lead to decreased force output and muscle activation of the extremities (Behm et al. 2002; Anderson & Behm 2004).

Research in developmental sciences demonstrated that when appropriate support of the entire trunk was provided to newborn infants, emergence of reaching movements was observed (Grenier & Amiel-Tison 1981; von Hofsten 1982; Rochat & Goubet 1995). Without such support, the reaching movements could not be performed. The findings suggest that stability of the trunk is key to enabling the dissociation of the upper extremities from the trunk of the infant for reaching activity. In a recent study, Rachwani et al. (2013) explored the influence of an external support at the thoracic and pelvic level of the trunk on the success of reaching, postural stability and reaching kinematics while 17 healthy infants (aged between 4 to 6 months) reached for a toy. Results showed that with the pelvic support, only infants who had acquired control of their thoracic and lumbar regions performed significantly better in quality of reaching as compared to those with only thoracic control. There was statistically significant reduction in movement time and movement units, improved reaching straightness score and increased path length per

movement unit. These findings are consistent with previous studies which demonstrated that the infants' ability to control the trunk influences the quality of reaching (Spencer et al. 2000; Hopkins & Rönnqvist 2002). Another resent study found a relationship between segmental level of trunk control and gross motor function in children with cerebral palsy; trunk control predicts 38% to 40% of the variation in gross motor function (Curtis et al. 2015). Extrapolating these findings to the adult population, stabilizing the trunk may promote a better reaching ability as the reaching task requires dynamic stability of the shoulder girdle on a stable trunk (Rosenblum & Josman 2003).

Another possible explanation for the reduction in SWMFT-Time and improvement in SWMFT-FAS with the trunk support could be due to the nature of the design ("C-shaped") of the support and its height (up to approximately T10-T12 vertebra level). The external support may have assisted the pelvis to tilt more anteriorly, thus facilitating the lower lumbar spine into a more extended position. This alteration will lead to improvement in the posture of the participants for upper extremity task performance. Taking into account all the positive postural changes with the external trunk support, it may improve the performance time and quality of movement. This postulation is supported by the findings of other research (Gandavadi & Ramsay 2005; Gillen et al. 2007). In a study on 15 healthy volunteers performing a simple upper extremity task (passing a metal ring into a sinuous wire, tracing its path to the end), Gandavadi and Ramsay (2005) found that the task error rate (a light illuminated each time the metal ring contacted the wire) was significantly reduced when the volunteers were seated in an anterior pelvic tilt position compared to posterior tilt position. The results indicated an improved upper extremity performance with a better postural alignment.

Gillen et al. (2007) examined the effects of various seated trunk postures on upper extremity function. Fifty-nine healthy adults were tested using the Jebsen Taylor Hand Function Test (JTHFT) while in the neutral, flexed and laterally flexed trunk postures. Results showed that the neutral trunk posture was the most efficient postural alignment to perform the JTHFT tasks as the performance time was the shortest. Hence, the findings support that a neutral trunk posture improves upper extremity performance. Further analysis demonstrated that the JTHFT tasks most affected by trunk postural alignment

were related to accuracy, such as lifting small objects, or those which loaded the upper extremity, such as lifting heavy cans. This is similar to two of the SWMFT tasks used in this doctoral study, which are, lifting pencil using 3-jaw chuck grasp (thumb and first two fingers) that requires accuracy and lifting a canned drink. Thus, an improvement in the trunk postural alignment provided by the trunk support can help to improve the SWMFT-Time and SWMFT-FAS.

Taken together, the findings of this study and previous research support the hypothesis that a stable trunk enables the dissociation of the upper extremity from the trunk for function.

7.2 Kinematic outcomes (with and without trunk support) in healthy and chronic stroke participants

As mentioned in Chapter 4, the kinematic data of the 'lift can' task was analysed in detail and presented for the purpose of this PhD thesis. This is because the 'lift can' task was reported to be the best task of the WMFT that provides a good overview of the upper extremity function in stroke patients (Bogard et al. 2009).

In the chronic stroke participants, during the phase of reaching for the can and lifting it to the mouth, the movement was 3.40 times more segmented (i.e., less smooth), the trajectory was 0.80 times less straight, and the average ulnar styloid velocity was 1.43 times slower compared to healthy participants. In addition, there was an increase in trunk flexion by 2.82 times in the chronic stroke participants compared to healthy participants. This amount of compensatory trunk movement is similar to the findings of previous studies (Michaelsen et al. 2001; Levin et al. 2002b; Levin et al. 2004). The occurrence of compensatory trunk movement assisted the stroke participants to extend the arm reach as shoulder flexion and elbow extension was significantly less compared to the healthy participants. Similar observations were reported in several studies (Roby-Brami et al. 2003a; Roby-Brami et al. 2003b; Michaelsen et al. 2004; Robertson & Roby-Brami 2011). Excessive use of compensatory movements can result in secondary complications such as muscle contractures, joint misalignment, pain, limb disuse, and increased energy expenditure (Ada et al. 1994; Levin et al. 2005; Cirstea & Levin 2007). These

complications can impede the longer-term functional recovery of the upper extremity.

In this doctoral study, analysis of the movement patterns of the trunk (flexion, lateral flexion and rotation), scapula (internal rotation, upward rotation and posterior tilt), shoulder (flexion), and elbow (flexion and extension) during the 'lift can' task revealed no significant difference, with and without trunk support, for both healthy and chronic stroke participants. In other words, the waveform of the movement patterns during execution of the 'lift can' task, from start to endpoint, were similar with and without trunk support. The maximum angle of each kinematic variable was not significantly different, with and without trunk support, for both healthy participants and chronic stroke participants. The point of occurrence of the maximum angles, based on the percentage of task, was also similar, with and without trunk support. Taken together, the external trunk support did not have any significant effect on the movement patterns of the trunk, scapula, shoulder and elbow in both healthy participants and chronic stroke participants.

Further, comparison of the movement patterns of the trunk, scapula, shoulder and elbow revealed similar patterns between the healthy participants and chronic stroke participants although the standard deviations for trunk lateral flexion, trunk rotation, scapular upward rotation, scapular posterior tilt, shoulder flexion and elbow flexion/extension were larger in the chronic stroke participants compared to the healthy participants; thus, implying larger variability in these kinematic variables during execution of 'lift can' task in the chronic stroke participants. This is not surprising as the pool of chronic stroke participants exhibit different severity of upper extremity impairment, thus leading to larger variability in movement patterns.

Although the general movement patterns of the trunk, scapula, shoulder and elbow were similar between the healthy participants and chronic stroke participants, the maximum angle of each kinematic variable differ slightly at certain phase of the 'lift can' task. A plausible explanation for these results is the partial preservation of movement pattern or joint coordination when chronic stroke participants execute the 'lift can' task. This is supported by a study that demonstrated that people with mild to moderate hemiparesis retained some ability to coordinate their joints during reaching (within arm's

length) to minimise changes in the hand's path (Reisman & Scholz 2003). While the joint coordination was different and less flexible in terms of the pattern of joint couplings, the error compensation feature of a movement synergy found in age-matched control persons was preserved in the subgroup of stroke participants with mild to moderate hemiparesis (Reisman & Scholz 2003). In addition, another study showed that the directional control of reaching was relatively preserved in those with mild to moderate stroke (Reinkensmeyer et al. 2002). One explanation is that the motor control system sensed an initial movement misdirection and attempted a feedback correction (Reinkensmeyer et al. 2002). The extent of successful correction will depend on the severity of stroke.

In this doctoral study, the maximum angle of the trunk forward flexion occurred at 69% phase of the ‘lift can’ task in the chronic stroke participants compared to 57% in the healthy participants. The results implied that the stroke participants continued to flex their trunk forward in order to complete the task. Hence, this is a compensatory trunk movement to extend the reach of the arm towards the target; similar to findings of other studies (Levin et al. 2004; Roby-Brami et al. 2003a). The maximum angle of the trunk lateral flexion occurred earlier at 24% phase of the ‘lift can’ task in the chronic stroke participants compared to 52% in the healthy participants. This might be due to utilization of trunk lateral flexion as a compensatory strategy to assist in the elevation of the upper extremity during the reaching phase of the task.

Previous studies have demonstrated that during elevation of the upper extremity in healthy individuals, there was a consistent pattern of scapular upward rotation, posterior tilting, and external rotation/internal rotation (depending on the plane of elevation and portion of the range of motion) (McClure et al. 2001; Appelboom et al. 2014). In this doctoral study, the maximum angle of scapular posterior tilt was found to occur earlier in the phase of ‘lift can’ task in the chronic stroke participants (stroke 2% versus healthy 11% of task). This result suggests either a compensatory strategy to tilt the scapula posteriorly early on in the ‘lift can’ task to aid in elevation of the upper extremity or a strategy to aid in stabilizing the scapula before the elevation of the upper extremity. These hypotheses may be tested with detailed electromyography in the future.

In this doctoral study, the SPANOVA results demonstrated statistically significant main effect of trunk support for movement duration, movement smoothness, maximum ulnar styloid velocity, ROM of scapular upward rotation and elbow extension. The effect sizes ranged from 0.08 to 0.27, i.e. medium to large effect sizes. The reduction in the ROM of scapular upward rotation with the trunk support may arise partly from the improved elbow extension during reaching. These results suggest that stabilizing the trunk enables better-coordinated movement of the upper extremity, with increased activation of the elbow extensors during reaching as supported by an increased ROM of elbow extension.

There was no significant change in the trunk flexion with trunk support. This result differs from studies that used trunk restraint (Michaelsen & Levin 2004; Michaelsen et al. 2006; Thielman 2010), whereby compensatory trunk movements were reduced after upper extremity practice with the restraint. As the trunk support used in this doctoral study was not restrictive in nature, the participants had the freedom to move their trunk. In addition, they were not instructed to maintain an upright posture. Hence, the chronic stroke participants may still utilise compensatory trunk strategies to complete the tasks. The results may be different if the participants were instructed to make a conscious effort to minimise leaning forward with their trunk during performance of SWMFT tasks.

Surprisingly, the maximum and average ulnar styloid velocity were found to be significantly reduced with the trunk support. One possible reason for this finding is the reduction in reaching velocity as a trade-off for the execution of a smoother reaching movement, as supported by a statistically significant improvement in movement smoothness. The velocity of the ulnar styloid may also be reduced as the participants attempted actively to utilise their elbow extensor muscles for the reach, as evidenced by a significant increase in ROM of elbow extension.

Analysis with SPANOVA revealed a moderately large significant interaction effect between group and support condition for movement smoothness. The movement smoothness was significantly improved, i.e. the number of velocity peaks decreased, with the trunk support in the chronic stroke group as compared to the healthy group. This clearly illustrates that stabilization of the

trunk enables a better coordinated reaching movement of the upper extremity. The concept of “degrees of freedom” will be discussed in the subsequent paragraphs to explain the results of improvement in upper extremity movement and performance with stabilization of the trunk.

In a classic and widely cited work by Russian physiologist, Bernstein (1967) pointed out that the central nervous system (CNS) has redundant degrees of freedom. The human skeletal system has 244 DOF (Zatsiorsky 1998). This means that there are numerous ways to complete the same task. This has been referred to as the “degrees of freedom problem”. He questioned how the CNS could control the numerous degrees of freedom (DOF) of each movement without specifying the details of the muscle activation pattern (Bernstein 1967; Bernstein 2001). Based on Bernstein’s work and theory, the dynamical system theory emerged (Perry 1998; Thelen & Spencer 1998). Dynamical system theory suggest that critical subsystems are able to self-organise and there is compression of DOF into coordinated patterns of movement (Perry 1998). Based on several parameters, such as energy expenditure, speed, accuracy, and success, the motor system will gradually adapt its strategy to master the DOF until all relevant parameters are optimally adjusted and coordinated movement emerges (Latash & Anson 1996; Perry 1998; Latash et al. 2010). Latash and Anson (1996) argued that the ability to optimise motor control implies that motor compensations should not be considered pathological, but rather adaptive to existing motor impairments.

In the case of upper extremity movement, 3 DOF are available at the shoulder, 2 at the elbow and 2 at the wrist joint (Zatsiorsky 1998; Edwards 2010). Considering the muscles as the unit that control movement, there will be 10 muscles at the shoulder joint, 10 at the elbow joint, and 6 at the wrist joint (Edwards 2010). Hence, there will be a minimum of 26 DOF for the upper extremity movement. Three DOF are available in the upper trunk and 3 DOF in the lower trunk (Zatsiorsky 1998); and 3 DOF in the scapula (Roren et al. 2015). In other words, the motor system has to manage at least 35 DOF of an individual during reaching task in an unsupported seated condition. The greater the number of DOF that must be controlled, the greater the complexity of the problem that must be solved by the motor system (Li 2006; Edwards 2010).

In this doctoral study, the external support aids in the stabilization of the trunk, limiting trunk excursion and/or reducing the number of DOF especially in the lower trunk. That can lead to a decrease in demand on the motor system to reorganise the DOF of upper extremity into a coordinated pattern of reaching movement for the canned drink. These changes are mechanistic in nature and may provide an explanation for the improvement in SWMFT-Time and SWMFT-FAS with the trunk support. This is congruent with the findings of a recent systematic review that manipulation of the mechanical DOF of the trunk via trunk restraint during reaching enhance recovery of upper extremity function after stroke (Hayward et al. 2014).

7.3 Association between TIS and the clinical and kinematic variables

One of the aims of this study was to examine the relationship between trunk control and upper extremity function in subacute and chronic stroke participants.

Significant strong correlations were found between TIS and FMA; TIS and FMA-Shoulder-Elbow; TIS and FMA-Wrist-Hand; TIS and SWMFT-Time; and between TIS and SWMFT-FAS. FMA was found to correlate strongly with SWMFT-Time and SWMFT-FAS. These results implied a strong association between trunk control and upper extremity impairment and function and, therefore, supports the findings discussed in the earlier sections (sections 7.1.2, 7.1.3 and 7.2).

It is not surprising that FMA correlates very strongly with the SWMFT-Time (Spearman's rho = -0.80) and SWMFT-FAS (Spearman's rho = 0.96, $p < 0.01$) of the affected upper extremity. Motor impairment and function of the upper extremity post stroke have been found to be closely linked (Lang et al. 2013). Paresis is the most common motor impairment following a stroke (Sathian et al. 2011); and numerous studies have consistently shown that paresis is the largest contributor to loss of upper extremity function (Lang & Beebe 2007; Beebe & Lang 2008; Beebe & Lang 2009; Lang et al. 2009a; Prager & Lang 2012).

In this doctoral study, strong correlations were found between FMA and movement duration (Spearman's rho = -0.78); trunk flexion (Spearman's rho =

-0.79); and elbow extension (Spearman's rho = 0.76). The result of the association between FMA and trunk flexion are in congruence with other studies that found the correlation between FMA and compensatory anterior trunk displacement ranges from r = -0.50 to r = -0.87 (Cirstea & Levin 2000; Levin et al. 2002b; Cirstea et al. 2003b; Subramanian et al. 2010; Massie et al. 2014). In other words, the amount of compensatory trunk movement varies with the severity of upper extremity hemiparesis. People with more severe upper extremity paresis may exhibit impaired movement and control of the shoulder and elbow during reaching. Hence, they would utilise more compensatory trunk movements to assist arm and hand transport and to aid in hand positioning/orientation for grasping (Michaelsen et al. 2004; Ustinova et al. 2004) . Compensatory movement behaviour may improve upper extremity function in the short-term but may be detrimental to long-term recovery (Roby-Brami et al 2003a; Wee et al. 2014).

In comparison with healthy participants, the chronic stroke participants with moderate-to-severe upper extremity impairment (FMA score ≤50) exhibited significantly more ROM of trunk flexion, trunk lateral flexion and scapular upward rotation during reaching. The finding that more ROM of trunk flexion (3.75 times) occurred during the reaching task in chronic stroke participants with moderate-to-severe upper extremity impairment is similar to the findings by Levin et al. (2004) and Subramanian et al. (2010). The chronic stroke participants with mild upper extremity impairment (FMA score >50) demonstrated significantly more ROM of trunk lateral flexion (1.83 times more) when compared to the healthy participants. Hence, these findings are in agreement with other research findings (Cirstea & Levin 2000; Levin et al. 2002b; Cirstea et al. 2003b; Levin et al. 2004; Subramanian et al. 2010; Massie et al. 2014) that the the amount of compensatory trunk movement varies with the severity of upper extremity hemiparesis.

The ROM of scapular internal rotation during reaching was not significantly different between the healthy and chronic stroke participants in this doctoral study. The chronic stroke participants with moderate-to-severe upper extremity impairment (FMA score <50) exhibited significantly more ROM of scapular upward rotation (1.80 times more) compared to healthy participants during reaching. The greater ROM of scapular upward rotation may arise due to the recruitment of excessive ROM of trunk lateral flexion (3.16 times more than

healthy participants) during the elevation of the upper extremity for reaching. However, the ROM of scapular internal rotation was not significantly different. This suggests that there is none or negligible compensatory scapular movement during reaching. The significant compensatory movement that assists the stroke participants in reaching forward to grasp the canned drink comes primarily from the trunk flexion component instead of scapular internal rotation. This finding is in agreement with another study (Roby-Brami et al. 2003a). Roby-Brami et al. (2003a) found that the larger acromion displacement in patients with hemiparesis during reaching task was not linked to an increased trunk–scapular internal rotation but rather to a forward bending of the trunk.

The findings of this doctoral study highlight the presence of excessive compensatory trunk movements during reaching in the stroke participants. The increased recruitment of trunk movement is a compensatory motor strategy by which the central nervous system may extend the reach of the arm when there is impaired joint movements and control of the upper extremity. The redundancy in the number of degrees of freedom of the motor system enables completion of tasks by substitution of other degrees of freedom for movements of impaired joints or control of the extremities (Kamper et al. 2002; Roby-Brami et al. 2003b; Michaelsen et al. 2004). However, the recruitment of the trunk during forward reach may not result in improved occupational performance because from an optimal control framework, the energy demands of trunk flexion would be greater than using the upper extremity due to higher inertia (Dounskaia 2007).

Compensation rarely leads to efficient movement, and the use of compensatory movements can result in secondary complications such as muscle contractures, joint misalignment, pain and increased energy expenditure (Ada et al. 1994; Levin 1996b; Levin et al. 2005; Foroud & Whishaw 2006; Takeuchi & Izumi 2012). In addition, compensatory movement strategies used by people with stroke in performance of tasks may encourage maladaptive plasticity due to reinforcement of abnormal movement patterns, and therefore, it can affect motor recovery in the longer term (Jang 2013). Compensatory strategies may mask more normal movement from emerging.

Once compensation has been learned, it is very challenging to modify and unlearn (Ada et al. 1994; Thielman 2013); possibly due to maladaptive plasticity (Takeuchi & Izumi 2012; Jang 2013). Some stroke patients develop strong and efficient motor compensations that prevent them from attempting to generate more 'normal' motor patterns in daily activities (Roby-Brami et al. 2003a). In other words, these complications can affect the execution of more efficient movement patterns of the upper extremity and impede its longer-term functional recovery. This can add to the frustration for stroke patients who yearn for more improvement and recovery in their upper extremity (Barker & Brauer 2005). This is congruent with what was stated by Lum et al. (2009) that whilst compensatory movements may improve function, it may translate into less actual use in the real-world environment over time as the slow and awkward movements become frustrating for most stroke patients.

Prior to this doctoral study, it is unknown how the severity of trunk impairment post stroke affects or contributes to the amount of compensatory trunk movement in reaching tasks for stroke patients with different levels of upper extremity control. This doctoral study showed that TIS has a weak significant correlation with trunk flexion (Spearman's rho = -0.43, p <0.001). In contrast, the FMA has a strong statistically significant correlation with trunk flexion (Spearman's rho = -0.79, p <0.001). This implies that the amount of compensatory trunk movement is more associated with the severity of upper extremity hemiparesis than the severity of trunk impairment.

7.4 Longitudinal study on the recovery of trunk control and upper extremity in subacute stroke participants

Through the individual growth curve (IGC) modelling, it was demonstrated that the recovery curves of trunk control (TIS), upper extremity impairment (FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS) in the first 6 months post stroke followed a quadratic trend. The most rapid recovery of TIS, FMA, SWMFT-Time and SWMFT-FAS occurred in the first 3 to 4 months, followed by a gradual deceleration and levelling off from the 4th to 6th month period. These findings are congruent with those of previous studies (Skilbeck et al. 1983; Olsen 1989; Duncan et al. 1992; Duncan et al. 1994; Jorgensen et

al. 1995; Feys et al. 1998; Desrosiers et al. 2003a; Goodwin & Sunderland 2003; Kwakkel et al. 2004; Higgins et al. 2005; Kwakkel et al. 2006; Verheyden et al. 2008; Paci et al. 2012; Kwakkel & Kollen 2013; Lee et al. 2015a; Lee et al, 2015b). The TIS has no ceiling effect for the subacute and chronic stroke population (Verheyden et al. 2006); and the FMA does not exhibit any significant floor or ceiling effect (Lin et al. 2009a). Hence, the gradual leveling off of the TIS and FMA from the 4th to 6th month was unlikely to be due to ceiling effect of the scales but due to plateauing of stroke recovery.

Numerous studies have shown that spontaneous neurological recovery, which follows a natural logarithmic pattern, rather than type or amount of therapy, determines function (Skilbeck et al. 1983; Kwakkel et al. 2004; Dobkin 2005; Kwakkel et al. 2006; Langhorne et al., 2011). The recovery rate is highest in the first month after stroke, after which recovery levels off and reaches a plateau (Kwakkel et al., 2006; Langhorne et al, 2009; Ng et al., 2007). Motor recovery plateau is largely determined by the extent of damage to descending motor pathways, which is currently untreatable (Stinear & Byblow 2014).

Outcomes in terms of body functions and activities can be predicted with a very high degree of certainty in the first few weeks after stroke. After a time window of first 10 weeks, improvement of the outcome in terms of activities is thought to be mainly due to adaptation or compensatory motor strategies (Kwakkel et al. 2004; Kwakkel et al. 2006; Prabhakaran et al., 2008; Stinear et al., 2012). In a study on 101 patients with first-ever ischaemic strokes, approximately 19% to 26% of observed improvements in the upper extremity of stroke patients is a reflection of time-dependent changes due to intrinsic, spontaneous recovery which lasts for approximately 6 to 10 weeks (Kwakkel et al. 2006). Therefore, the mere progress of time in the first three months after stroke is a major confounder in understanding the effects of rehabilitation interventions (Buma et al. 2013). With this knowledge about the duration of spontaneous recovery, it enables clinicians to predict outcomes with improved accuracy, set realistic goals and provide appropriate therapy.

7.4.1 Recovery of upper extremity post stroke

For the TIS and FMA variables in this doctoral study, IGC modelling results illustrated that participants with lower initial score demonstrated a faster rate of change, on average, than those with higher initial score. As for the SWMFT-Time, participants with higher initial performance time demonstrated a faster rate of change (in negative direction), on average, than those with lower initial performance time. Further analysis of the recovery curves of FMA, SWMFT-Time and SWMFT-FAS demonstrated different rates of recovery (Figures 6-12, 6-32 and 6-38) based on the severity of initial upper extremity impairment level.

In this doctoral study, stroke participants with more severe upper extremity impairment started off with a lower initial FMA score and they recovered at a faster rate than those with moderate and mild impairment level. However, their FMA score at 6 months remained lower than participants with moderate and mild impairment level. Initial measures of upper extremity impairment and function were found to be the most significant predictors of upper extremity recovery (Counsell 2002; Kwakkel et al. 2003; Counsell 2004; Hatakenaka et al. 2007; Smania et al. 2007; Beebe & Lang 2008; Beebe & Lang 2009; Nijland et al. 2010b; Zarahn et al. 2011; Coupar et al. 2012; Kwakkel & Kollen 2013). A recent study on 129 acute stroke patients demonstrated that FMA is the best predictor for upper extremity recovery and general disability (modified Rankin Scale) at 3 months (Gebruers et al. 2014). Patients with lower initial FMA score had a poorer upper extremity outcome. This is supported by this doctoral study.

The SWMFT-Time, a measure of upper extremity function, was significantly longer for participants with severe upper extremity impairment compared to those with moderate and mild impairment. At 6 months post stroke, this group of participants with severe upper extremity impairment remained poor in terms of upper extremity function. In contrast, the SWMFT-Time of those participants with moderate and mild impairment converged towards the 5th month, right up to the 6th month. This suggests a higher potential for recovery for the moderate upper extremity impairment group compared to the severe group. Customised therapy should be delivered to people with stroke based on their level of impairment.

The effectiveness of therapy is not only determined by selecting the most effective therapy but also depends on selecting the most appropriate patients for that specific therapy (Kwakkel & Kollen 2013). Evidence-based therapies such as functional electrical stimulation (Howlett et al. 2015), constraint-induced movement therapy (Kwakkel et al. 2015), and upper extremity robotics (Kwakkel & Meskers 2014; Pollock et al. 2014) are dependent on an appropriate selection of stroke patients that may benefit most from a particular intervention (Langhorne et al. 2011). In people with severe stroke, where remediation is not possible, therapists would implement compensatory strategies to promote independence (Govender & Kalra 2007; Koh et al. 2015). Compensatory treatment goals should be pursued only if there is an expected outcome of poor motor recovery (Foley et al. 2013).

Inspection of the individual recovery curves of FMA, SWMFT-Time and SWMFT-FAS (Figures 6-9, 6-29 and 6-35) of the 45 subacute stroke participants revealed that there were some participants with severe initial upper extremity impairment who did not recover proportionally up to the 6th month in terms of impairment score (FMA) and function score (SWMFT-Time and SWMFT-FAS) whereas others did. This finding corroborated the results of previous studies about the existence of a subgroup of individuals with severe initial upper extremity impairment who exhibited minimal or no recovery while others made significant recovery (Binkofski et al. 2001; Prabhakaran et al. 2008; Lazar et al. 2014; Koh et al. 2015). One possible explanation for these findings could be related to the extent of corticospinal tract (CST) damage following stroke. Numerous studies have demonstrated that the recovery of the hemiparetic upper extremity is associated with the integrity of CST (Cho et al. 2007; DeVetten et al. 2010; Lindenberg et al. 2010; Sterr et al. 2010; Globas et al. 2011; Cho et al. 2012; Kou et al. 2013). A recent study using diffusion tensor imaging (DTI) demonstrated that CST integrity is a strong prognostic indicator of future motor functions of the upper extremity for stroke patients with substantial initial motor impairment (moderately-severe and severe impairment levels) (Groisser et al. 2014). Therefore, in this doctoral study, those individuals who did not make much recovery may have less residual CST post stroke compared with those individuals with similar initial severity but gained proportional recovery. This proposed mechanism can only be confirmed by

neurophysiology and neuroimaging techniques, such as transcranial magnetic stimulation and DTI, and not by any clinical measures.

Studies have shown that clinical measures of upper extremity impairment made within days of stroke are related to subsequent outcomes such as dexterity or activities of daily living (Smania et al., 2007; Nijland et al., 2010; Veerbeek et al., 2011), but have little individual prognostic value due to inter-individual variability (Stinear, 2010). Improved prognostic accuracy could be achieved by combining simple tests of motor impairment with neuroimaging and neurophysiological assessment of neural plasticity (Stinear, 2010). Hence, that led to the proposal of the *Predicting REcovery Potential* (PREP) algorithm to predict the potential for upper extremity recovery in acute and subacute stroke patients (Stinear et al. 2012; Stinear et al. 2014). The PREP algorithm combines clinical, neurophysiological and neuroimaging measures in a sequential way. The PREP algorithm has demonstrated a positive predictive power of 88%, negative predictive power of 83%, specificity of 88% and sensitivity of 73% (Stinear et al. 2012). This highlights the value of PREP algorithm in prognostication of upper extremity outcome. It will enable stratification of people with stroke and aid in the allocation of therapy resources, treatment planning and addressing of stroke survivors' expectation of recovery.

In the light of the complexity of recovery post stroke, there are other critical factors to consider when predicting recovery and outcomes. These factors include lesion size and lesion site. Although the impact of lesion size and lesion site on stroke recovery appears intuitive to clinicians, there are conflicting results. Some studies have demonstrated that the lesion size correlates with final stroke outcome (Beloosesky et al. 1995; Saunders et al. 1995; Lövblad et al. 1997; van Everdingen et al. 1998; Thijs et al. 2000; Fitzek et al. 2001; Crafton et al. 2003; Zhu et al. 2010; Vogt et al. 2012) while other studies did not find any significant association between both (Dromerick & Reding 1995; Pantano et al. 1996; Binkofski et al. 2001; Page et al. 2013). While some studies have found that the site of stroke lesion correlates with final outcome (Chaudhuri et al. 1988; Saeki et al. 1994; Beloosesky et al. 1995; Feys et al. 2000; Hand et al. 2006), other studies did not demonstrate such association (Dromerick & Reding 1995; Pantano et al. 1996). These conflicting results could be due to different outcome measures used in the studies. For

example, some studies used functional scales such as Functional Independence Measure (FIM), Barthel Index (Feys et al. 2000; Thijs et al. 2000); disability scale such as modified Rankin Scale (Hand et al. 2006; Vogt et al. 2012); impairment scales such as Fugl-Meyer Upper Extremity Assessment, National Institutes of Health Stroke Scale (NIHSS) (Fitzek et al. 2001; Crafton et al. 2003). Hence, the usage of different outcome measures makes it challenging to compare the studies.

Considering stroke lesion volume in isolation may overlook the influence of small lesions located in eloquent areas of the brain (sensory, motor, language, visual cortex, hypothalamus and thalamus, internal capsule, brainstem) (Stapleton et al. 2015), such as numerous lacunar strokes (Hand et al. 2006). Stroke affecting these eloquent areas may lead to poor outcomes (Hand et al. 2006). Researchers have found that a combination of lesion size and lesion site correlates better with motor and functional outcomes post stroke compared to lesion size or lesion site individually (Chen et al. 2000; Rangaraju et al. 2015). Hence, these findings are important consideration in prediction of stroke recovery.

Patients with purely cortical stroke have been found to exhibit better motor outcome than patients with purely subcortical stroke (Shelton & Reding 2001). Furthermore, patients with mixed cortical plus subcortical stroke tended to do better than patients with purely subcortical stroke despite the expected larger size of mixed lesions (Miyai et al. 1997). Although subcortical strokes are normally smaller than cortical strokes, they are more likely to involve both primary and secondary motor pathways; hence, that explains the findings by Miyai et al. (1997).

Taken together, neurological recovery post stroke is a complex process. Clinicians and researchers need to be mindful of various factors, such as integrity of CST, lesion size, lesion site, that can contribute to recovery. Gathering results from a combination of clinical, neurophysiological and neuroimaging measures is currently the best approach to understand stroke recovery and aid in the prediction of stroke outcomes.

7.4.2 Recovery of proximal versus distal segments of the upper extremity

Previous studies have demonstrated that distal arm muscles (wrist, fingers and thumb) are more severely impaired than those of proximal muscles (shoulder and elbow) and recovery of distal movements is slower (Hlustík & Mayer 2006; Lang et al. 2006). Therefore, the author (SKW) conducted a detailed analysis of the recovery pattern of the proximal (shoulder and elbow) and distal (wrist and hand) segments of the upper extremity to gain a deeper understanding of neurological recovery post stroke.

Results from this doctoral study demonstrated that the rate of recovery of FMA-SE was faster than the FMA-WH. This implies that the shoulder and elbow recovered faster than the wrist and hand. The FMA-SE appeared to continue to improve from the 3rd to 6th month while the FMA-WH started to slow down in progress from the 3rd month to 6th month. These findings can be explained by results from previous studies. The motor control of distal segment of the upper extremity relies on the contralateral primary motor cortex (Nirkko et al. 2001) while the proximal arm movement are controlled by bilateral motor cortices (Turton et al. 1996; Nirkko et al. 2001; Lemon 2008). In addition, alternate descending pathways, such as the ipsilateral corticospinal tract and the reticulospinal tract, are better able to drive motor units of the more proximal muscles than the more distal muscles (Nathan et al. 1996; Turton et al. 1996).

Another possible explanation to account for the faster recovery rate of the proximal segment of the upper extremity in this doctoral study could be related to the nature of the upper extremity rehabilitation programme. In the early phase of stroke rehabilitation, some therapists may be inclined to facilitate scapula, shoulder and elbow movements to practice reaching tasks with lesser emphasis on hand opening and grasping components. This is partly due to the challenges of controlling numerous degrees of freedom of the scapula, shoulder, elbow, wrist and hand simultaneously during upper extremity training. The presence of wrist and finger flexor muscle tightness and spasticity in some participants added even more challenges for the therapists to deliver hand rehabilitation optimally.

With more emphasis placed on the training of the proximal segment versus the distal segment of the upper extremity, it may further enhance the natural competition between the shoulder and hand representation in the cortex, possibly leading to larger shoulder representation area. Hence, this may be detrimental to recovery of the wrist and hand. This postulation by the author (SKW) was drawn from the seminal work of Nudo et al (1996a) and other studies (Hallet 2001; Mayer & Hluštík 2004; Hallet 2005; Hlustík & Mayer 2006). A systematic review suggests that most therapeutic effects from interventions are mainly driven by improvements in proximal motor control, whereas improvements for hand recovery are poor (Langhorne et al. 2009). Recovery does not proceed in a strict proximal-to-distal sequence as was traditionally believed by some therapists (Woodbury et al. 2007).

Cortical representation area of the body parts increases or decreases depending on use (Hallet 2001; Hallet 2005). Reading Braille is associated with expansion of the sensorimotor cortical representation of the reading finger (Pascual-Leone & Torres 1993) and this enlargement is at the expense of the representation of other fingers (Pascual-Leone et al. 1993). Similarly, if a body part is not used, the representation area will shrink in size. For example, the representation area of the hand was smaller after the arm was immobilized in a cast for 2 to 3 weeks (Lissek et al. 2009; Langer et al. 2012). Hence, these studies illustrate the existence of a natural competition among body parts for territorial representation in the cortex based on the extent of usage. Nudo et al. (1996b) showed that intensive hand rehabilitation can alter representational changes in the cortex. Retraining of skilled hand use in adult squirrel monkeys after cortical infarcts resulted in prevention of the loss of hand territory adjacent to the infarct. In some instances, the hand representations expanded into regions formerly occupied by representations of the shoulder and elbow (Nudo et al. 1996b).

In an investigation on 7 chronic stroke patients, Muellbacher et al. (2002) performed a regional anesthesia-induced deafferentation of the shoulder and upper arm, with sparing of the forearm and hand, during hand motor practice. The practice task involved metronome-paced pinch between index and thumb of the paretic hand. Post training, the patients demonstrated significant improvement in their grip force, grip acceleration and hand motor function.

The practice-induced increase in peak grip force was strongly correlated (r=0.86, p<0.03) with the increased in motor-evoked potential amplitude, as assessed by transcranial magnetic stimulation, of the paretic hand muscles. Patients also reported significant functional benefits in some activities of daily living, such as holding small objects, cup and pen. The gains in grip force were retained at 2 weeks follow-up. Hence, the animal and human studies illustrate that intensive and focused training of the hand can lead to better hand function.

Drawing from the findings of Muellbacher et al. (2002), another group of researchers conducted a pilot trial on 40 acute stroke patients to investigate the effects of intensive hand therapy on the outcome of hand and shoulder function (Mikulecká et al. 2005). All the patients in the treatment group (n=20) and control group (n=20) received standard physiotherapy based on Bobath concept. Those in the treatment group received an additional differentiated manual treatment and sensory stimulation of the hand and of the forearm which included rubbing, release of soft tissues, mobilization of the joints of the wrist, metacarpals and fingers and of digital pressure of selected points. Following 12 days of training, the treatment group demonstrated significantly greater improvement in hand function and shoulder function compared with the control group.

Taken together, the findings from previous studies (Muellbacher et al. 2002; Mikulecká et al. 2005) suggest that more emphasis should be placed on hand motor training in the early phases of stroke rehabilitation while shoulder and elbow training should be minimized. Hence, there is a need to re-examine how upper extremity training should be delivered in the light of the findings from this doctoral study about different recovery rates of the shoulder and elbow versus the wrist and hand in people with stroke; and also consideration of the principle of natural competition among body parts for territory in the sensorimotor cortex (Hallet 2001; Hallet 2005; Hlustík & Mayer 2006).

7.4.3 Recovery of trunk control and its association with the upper extremity of subacute stroke participants

There are only 2 publications related to the recovery of trunk control in stroke patients to date (Verheyden et al. 2008; Lee et al. 2015b). In these 2 studies,

trunk control as measured by the TIS reached between 63.2% and 70% of the maximum score of 23 by the first month post stroke. These results suggest that the most rapid recovery of trunk control occurred in the first month following stroke. In this doctoral study, the TIS reached 84.1% of the maximum score at first month.

This longitudinal study (Phase 2 study) showed the rate of recovery of TIS was largest in the first month and subsequently decreased over the next 5 months. Analysis revealed a similar rate of change of TIS and FMA in the first 6 months post stroke. In other words, the curvature of the recovery curves of TIS and FMA were very similar (Figure 6-41). Mathematical calculation of the gradients of the rate of change of the TIS and FMA recovery curves revealed values of -0.61 and -0.68 respectively, hence confirming the visual inspection of the graphs in Figure 6-41 with regard to similarity in the rate of change. The findings of a similar rate of recovery of trunk control and upper extremity impairment is in congruence with a previous study (Verheyden et al. 2008). Initially, Verheyden et al. (2008) hypothesized that the trunk may recover at a faster rate compared to the upper extremity in view of the bilateral innervation of trunk muscles. However, their final results proved otherwise. The results of this doctoral study also did not support the hypothesis of a more favorable recovery rate of the trunk compared to that of upper extremity.

As TIS scores improved over time, both the upper extremity impairment (FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS) improved almost in parallel with the TIS increase. From the Phase 1A and Phase 1B studies, FMA was found to correlate very strongly with the SWMFT-Time and SWMFT-FAS. This supports the notion that motor impairment and function of the upper extremity are closely linked (Lang et al. 2013). Hence, it is not surprising to observe the improvement in SWMFT-Time and SWMFT-FAS as the FMA improved in parallel with TIS over the 6 months.

Another key finding in this doctoral study was the demonstration of different rates of recovery of the TIS, FMA, FMA-SE, FMA-WH, SWMFT-Time and SWMFT-FAS based on the severity of trunk impairment level (Figures 6-6, 6-13, 6-19, 6-25, 6-33 and 6-39). The results clearly demonstrated that subacute stroke participants with poorer trunk control exhibited poorer upper extremity function, both in terms of performance time (SWMFT-Time) and score on the

functional ability scale (SWMFT-FAS). These findings further support the results from Phase 1A and Phase 1B studies about the existence of a strong association between trunk control and upper extremity function.

A closer examination of the recovery curves of FMA, FMA-SE, FMA-WH, SWMFT-Time and SWMFT-FAS revealed that each stratified group based on severity of trunk impairment followed its unique trajectory. Although all participants with poor, moderate and good trunk control improved over the 6-month period, the rate of recovery differs and the levels of their upper extremity function, on average, remained at that level based on the stratified groups. In other words, those participants with poor upper extremity function at 1st month remained at a lower level at 6th month compared to those with moderate upper extremity function and those with good upper extremity function.

This doctoral study is the first to analyse the recovery patterns of trunk control and upper extremity in people with stroke based on the stratification of the severity of upper extremity impairment and trunk impairment. Understanding the trajectory of the recovery curves of the stratified groups enable clinicians to prognosticate outcomes more accurately and aid in setting of realistic and achievable goals, treatment planning and intervention. The ability to predict an individual's potential for motor recovery allows for individually-tailored rehabilitation, management of patient and therapist expectations, and may result in more effective utilization of health resources (Stinear et al. 2014).

The TIS score over the 6-month period was found to be a significant predictor of the recovery of FMA, FMA-SE and FMA-WH. This implies that trunk control has a statistically significant impact on the recovery pattern of the upper extremity impairment. Analysis showed that trunk control exerts a stronger influence on the recovery pattern of FMA-SE (*F* statistic = 6.18; refer Table 6-16) than that of FMA-WH (*F* statistic = 4.75; refer Table 6-21). This finding is further supported by a larger correlation coefficient between TIS and FMA-SE (Spearman's $\rho = 0.70$) than between TIS and FMA-WH (Spearman's $\rho = 0.67$) (Table 5-11). This is not surprising in view that the trunk and shoulder are anatomically and biomechanically linked.

Similarly, the TIS score over the 6-month period was found to be a significant predictor of the recovery of SWMFT-Time and SWMFT-FAS. This implies that trunk control has a statistically significant impact on the recovery pattern of

the upper extremity function. Taken together, trunk control is associated with the trajectories of the recovery curves of the upper extremity and hence outcome.

One argument regarding the observation of upper extremity impairment and function improving in parallel with TIS improvement is whether it was trunk control having an influence on the upper extremity or the other way round. Both the cross-sectional studies, Phase 1A and Phase 1B studies, have provided concrete evidence that there is a strong association between trunk control and upper extremity; and stabilization of the trunk and improving its control has a positive and immediate effect on improving upper extremity function. Hence, it is the opinion of the author (SKW) that it is likely that trunk control that has an influence on the upper extremity function rather than the other way round, over the course of stroke recovery in the first 6 months. However, the reverse (i.e. hypothesis of supporting arm movement leading to improved trunk control) may also be true unless proven otherwise in future study. Another reason to support the author's (SKW) argument is that previous studies (Behm et al. 2010; Nadler et al. 2002) have demonstrated that a stable trunk provides a solid foundation for the torque generated by the extremities. In addition, the author (SKW) had drawn inferences from the research on developmental sciences. When appropriate support of the entire trunk was provided to newborn infants, emergence of reaching movements was observed (Rochat & Goubet 1995). Without such support, the reaching movement could not be performed. The findings suggest that stability of the trunk is key to enabling the dissociation of the upper extremities of the infant from the trunk for reaching. Emerging postural control of the head and trunk play an important role in the onset of successful reaching (Thelen & Spencer 1998). A recent longitudinal study confirmed a strong correlation between the development of trunk control and reaching performance in infants (Rachwani et al. 2015).

To the best of the author's knowledge, this is the first study that examined the recovery curves of trunk control and upper extremity closely and found a strong association between them over the time course of 6 months following stroke. This new knowledge has clinical implications that will be discussed further in the next section 7.5.

7.4.4 Intra-individual and inter-individual variability

Results from the final models of TIS, FMA, SWMFT-Time and SWMFT-FAS demonstrated statistically significant intra-individual difference across each wave of measurement. These findings suggest that there were significant improvements in TIS, FMA, SWMFT-Time and SWMFT-FAS for each individual at each time point.

In this doctoral study, results showed significant inter-individual variability in the initial status and rate of change over time. This finding underscores the considerable degree of heterogeneity in the stroke participants. Verheryden et al (2008) also reported a large degree of variability in the recovery pattern of the upper extremity. Prabhakaran et al. (2008) reported that inter-individual variability in stroke recovery is almost exclusively attributable to true inter-individual biologically meaningful variability. In that study (Prabhakaran et al. 2008), 95% of variance in recovery unexplained by clinical variables is attributable to true inter-individual variability. This implies that there are as-yet unidentified biological processes that account for the observed inter-individual differences.

7.5 Implications for clinical practice

A key finding of this PhD research is the demonstration of a strong association between trunk control and upper extremity impairment and function in people with stroke. Stabilization of the trunk with an external support led to a positive impact on the performance of upper extremity functional tasks. The performance time was significantly reduced; the movement smoothness was significantly improved; and the range of elbow extension improved significantly during reaching. In addition, results from the Phase 2 study have demonstrated that trunk control has an association with the recovery of upper extremity function in the first 6 months post stroke. Thus, there may be benefits to focus on early rehabilitation of the trunk.

Interventions that aim to promote neuroplasticity during the spontaneous recovery period, i.e. in the first 6 to 10 weeks post stroke (Kwakkel et al. 2006), may increase the rate of motor recovery (Stinear & Byblow 2014). Currently, it is unknown whether the rate of recovery of trunk control can be

accelerated with a focused trunk rehabilitation programme in the early phase of stroke recovery. If the rate of recovery of trunk control can be accelerated, that in turn may have an effect on improving the rate of recovery of the upper extremity based on the finding of a strong association between trunk control and upper extremity in the Phase 2 study. This may lead to a better upper extremity recovery in addition to improving the efficiency of rehabilitation.

The author (SKW) proposes that trunk rehabilitation should commence in the early phase of stroke rehabilitation. A focused trunk rehabilitation programme has the potential to promote upper extremity function and recovery as illustrated by this doctoral study. In the early phase of rehabilitation, stroke patients may exhibit poor trunk control and that can affect upper extremity practice during therapy sessions. Therapists may consider incorporation of an external trunk support during upper extremity practice in the early phase of rehabilitation. Results from this doctoral study and other studies (Michaelsen & Levin 2004; Michaelsen et al. 2006; Woodbury et al. 2009; Thielman 2010; Wu et al. 2012a; Wu et al. 2012b; Wee et al. 2014) support the thesis that stabilizing the trunk will facilitate the dissociation of the upper extremity from the trunk for better movement re-education and training. These evidence suggest that the most appropriate method of stabilization of the trunk, by external trunk support, chest harness or auditory feedback device, may depend on the level of trunk control post stroke. For those individuals with poor trunk control, an external trunk support or chest harness may be more suitable during rehabilitation.

As the trunk control improves, the trunk support should be removed and progression to an auditory feedback device may be considered. This is supported by findings that a training protocol of progressive fading of visual and verbal feedback was more effective in promoting motor learning than one that provides constant feedback (Cirstea et al. 2006; Cirstea & Levin 2007). In addition, training with an auditory feedback device requires the stroke patient to participate more actively to minimize compensatory trunk movements compared to the reliance on a trunk restraint. Thielman (2010) had demonstrated that stroke patients in the auditory feedback group improved significantly more on reaching ability than the trunk restraint group. This is consistent with findings of other studies that active motor training is more effective than passive motor training in eliciting performance improvements

(Lotze et al. 2003; Beets et al. 2012) and cortical reorganization (Lotze et al. 2003). These results highlight the pivotal role of voluntary drive in motor learning.

Trunk control of an individual involves a fine balance between maintaining stability and mobility. The author (SKW) postulates that an improvement in trunk control may also lead to an improvement in anticipatory postural adjustment (APA). In healthy individuals, APA occurs to counter the perturbation associated with the forthcoming voluntary movement of the upper extremity (Bouisset & Zattara 1981; Bouisset & Zattara 1987; Baldissera et al. 2008; Lee et al. 2009). The activities in the trunk muscles precede the arm movement which ensures that movement occurs against a background of dynamic stabilization of the body (Horak et al. 1984; Garland et al. 1997; Baldissera et al. 2008; Caronni & Cavallari 2009; Lee et al. 2009; Santos et al. 2010; Yiou et al. 2012). Hence, APA is essential for trunk stability (Pereira et al. 2014).

Major impairments in the activity of trunk muscles in hemiparetic subjects were manifested in the reduced activity level of the lateral trunk muscles (latissimus dorsi and external oblique), in delayed onset, and in reduced synchronization between activation of erector spinae and latissimus dorsi (Dickstein et al. 2004a; Dickstein et al. 2004b). Lower activity of paretic latissimus dorsi was found to be associated ($r = -0.408$) with a lower arm function score in people with stroke (Dickstein et al. 2004a). A recent study demonstrated a delay of APA in the muscles on both sides of the body of stroke subjects compared to healthy subjects. The delay was observed during performance of the reaching task with the fast and self-selected velocity (Pereira et al. 2014). The stroke subjects were also less capable of adapting their APA to different speeds, and always recruiting the same motor synergies.

It remains unknown whether APA will improve in parallel with trunk control. The author (SKW) postulated that a focused trunk rehabilitation programme may have influence on the postural muscles of the trunk and hence in turn influence the muscle activation as part of APA. Assuming that APA improves with an improvement in trunk control, it may have a positive effect to prepare the trunk for perturbation associated with the voluntary movement of the upper extremity. This assumption is supported by the existence of a

relationship between trunk muscle activity and upper extremity function (Hodges & Richardson 1997; Dickstein et al. 2004a). An improved APA may enable the distal and proximal segments of the upper extremity to act better against a background of stability of the trunk and therefore lead to better movement patterns. Future study may investigate the relationship between trunk control and APA. This can shed more light on muscle activation in relation to trunk control.

Another aspect when considering the relationship between trunk and upper extremity is from the musculoskeletal perspective on core stability. Core stability is defined as the ability to control the position and motion of the trunk over the pelvis and leg to allow optimum production, transfer and control of force and motion to the terminal segment in integrated kinetic chain activities (Kibler et al. 2006). In other words, a stable core in the form of good trunk control may influence the whole upper extremity due to the anatomical, biomechanical and kinetic chain linkage.

The musculoskeletal core of the body includes the spine, hips/pelvic girdle, deep and superficial abdominal structures (Kibler et al. 2006; Silfies et al. 2015). The thoracolumbar fascia consists of aponeurotic and fascial layers that interweave the paraspinal and abdominal muscles into a complex matrix stabilizing the lumbosacral spine (Vleeming et al. 2014). In essence, the core acts through the thoracolumbar fascia that serves as part of a ‘‘hoop’’ around the trunk that provides a connection between the upper extremity and lower extremity and enable effective load transfer between the spine, pelvis, arms and legs (Vleeming et al. 1995; Akuthota et al. 2008; Willard et al. 2012). With contraction of the core musculature, the thoracolumbar fascia also functions as a proprioceptor, providing feedback about trunk positioning (Akuthota et al. 2008).

Functional stability of the arm is associated with core control (Kibler et al. 2006). Ayhan et al. (2014) suggested that the incorporation of core stabilization into arm rehabilitation may improve neuromuscular coordination between the distal and proximal segments leading to better motor performance. This suggestion is supported by Kim et al. (2011) that demonstrated statistically significant improvement in functional reaching

ability of the upper extremity in people with stroke after an intervention consisting of trunk stability exercises.

The other reason for reinforcing trunk rehabilitation early in stroke recovery is the existence of strong evidence that trunk control is an important predictor of overall functional ability, balance and gait after stroke (Franchignoni et al. 1997; Duarte et al. 2002; Hsieh et al. 2002; Sebastia et al. 2006; Verheyden et al. 2006; Verheyden et al. 2007; Di Monaco et al. 2010; Gialanella et al. 2012; Kim et al. 2012; Jijimol et al. 2013). The variance of functional outcome post stroke explained by trunk control ranges from 45% to 71% (Franchignoni et al. 1997; Duarte et al. 2002; Hsieh et al. 2002).

Several researchers have investigated the effect of trunk rehabilitation exercises on the trunk control. Results from six randomised controlled trials (Verheyden et al. 2009; Karthikbabu et al. 2011a; Saeys et al. 2012; Chung et al. 2013; Cabanas-Valdes et al. 2015; Kılınç et al. 2015) and one pre-post design study (Karthikbabu et al. 2011b) demonstrated that specific trunk rehabilitation exercises which focused on trunk muscle strength, coordination, and selective movements of the upper and lower trunk, or the use of gym balls, yield positive outcomes in terms of improvement in selective activation of trunk muscles for function when compared to the control group that received conventional (usual care) rehabilitation. The carryover effect of such improvement is evident in positive improvement in sitting balance, standing balance, gait and overall functional outcome for stroke patients. A recent systematic review demonstrated a moderate level of evidence that trunk rehabilitation exercises can improve trunk performance and dynamic sitting balance in subacute and chronic stroke patients (Cabanas-Valdes et al. 2013). Trunk control has an impact on many facets of the recovery of stroke patients and emphasis should be placed on rehabilitation of the trunk early in the rehabilitation phase of stroke patients.

Taken together, the author (SKW) recommends a combined trunk and upper extremity rehabilitation programme with the aim of promoting a better trunk and upper extremity recovery for stroke patients.

In this doctoral study, the results demonstrated different trajectories of the recovery curves of TIS, FMA, FMA-SE, FMA-WH, SWMFT-Time and SWMFT-FAS based on the severity of the participant's upper extremity and trunk

impairment level. Hence, stratification of stroke participants based on their impairment level is important in terms of understanding the recovery pattern and prognostication of outcomes. This will assist clinicians to address the expectations of recovery in people with stroke and counsel them accordingly to help them cope with their disability post stroke.

Customised therapy should be delivered to people with stroke based on their impairment level and functional level. The effectiveness of therapy is not only determined by selecting the most effective therapy but also depends on selecting the most appropriate patients for that specific therapy (Kwakkel & Kollen 2013). In people with severe stroke, where remediation is not possible, therapists would implement compensatory strategies to promote independence (Govender & Kalra 2007). Compensatory treatment goals should be pursued only if there is an expected outcome of poor motor recovery (Foley et al. 2013). Hence, the knowledge of how an individual recovers over time based of the severity of the impairment level is critical in treatment planning and provision of appropriate therapy to yield best outcomes. In addition, the knowledge will enable clinicians to know the best therapeutic window period to introduce the most appropriate therapy.

7.6 Limitations of the study

7.6.1 Sample size

The initial research proposal entailed the stratification of the chronic stroke and subacute participants into three groups (TIS score 2-10, TIS score 11-19, and TIS score 20-23) based on their TIS scores. It was aimed to ensure that the samples for the Phase 1A, Phase 1B and Phase 2 studies comprised of stroke participants with various degree of trunk control for investigation.

It was challenging to recruit chronic stroke participants with low TIS score of between 2 to 10 for the Phase 1A study. Chronic stroke survivors with low TIS score have poor trunk control and hence, they are in a functionally dependent state and require carers to assist them in ADL. Thus, it would be challenging for this group of stroke survivors to participate in this study. Another possibility for the poor recruitment rate of participants with low TIS score can be due to the demands of the study. The setup time for the experimental

procedures, the Vicon calibration process and the assessment of TIS and SWMFT took an average of 2 to 2.5 hours. Some stroke survivors may feel that they cannot tolerate the long period in the laboratory and hence not keen to participate.

Only one chronic stroke participant with a TIS score of 10 was recruited into the Phase 1A study. This is a limitation of this study as it is important to analyse the clinical and kinematic outcome of a group of stroke participants with poor trunk control to shed light on the association between trunk control and upper extremity function. Future research study should include adequate sample size of chronic stroke participants with poor trunk control (TIS scores ≤10).

In the Phase 1B and Phase 2 studies, 13 subacute stroke participants with TIS score of ≤10 were recruited. Thus, the results offered some insights into the relationship between those participants with poor trunk control and their upper extremity function. There were 30 subacute stroke participants with TIS score between 11 to 19; and 2 participants with TIS score between 20 to 23.

As the author (SKW) recruited consecutive 45 subacute stroke participants who agreed to participate in the study, that led to an unbalanced sample number in each stratified TIS group. The ideal sample size in each stratified TIS group should be 15 for this study so that the study cohort comprises of stroke participants with various degree of trunk control. A method to consider in future studies to ensure equal number of participants in each stratified TIS group will be to assess each participant's TIS first and then allocate him/her to the respective TIS group till the desired sample size in each group is achieved.

Pooling the chronic stroke participants and subacute stroke participants together, there were a total of 14 participants in the group with TIS score 2-10; 43 participants in the group with TIS score 11-19; and 13 participants in the group with TIS score 20-23. Hence, there was a spread of stroke participants with poor, fair and good trunk control for this doctoral study.

7.6.2 Classification of trunk control based on the Trunk Impairment Scale (TIS) score

The range of TIS scores used in the stratification process were based partly on the study by Verheyden et al. (2005) and partly on the clinical experience of the author (SKW). The first group comprised of participants with TIS score between 2 to 10. Participants with TIS score of 0 were excluded from the study because they could not sit unsupported for 10 seconds. The second group included participants with TIS score between 11 to 19; and the last group with TIS score between 20 to 23.

Verheyden et al. (2005) found that the TIS has the ability to discriminate between stroke patients and healthy individuals. TIS score of 20 was the 90th percentile for the stroke patients and the 10th percentile for the healthy individuals. Hence, it is reasonable for the author (SKW) to consider participants with TIS score 20 to 23 to have good trunk control. Clinical observations, coupled with 18 years of physiotherapy work experience of the author led him to classify the group of participants with TIS score between 2 to 10 as having poor trunk control; and those with TIS score between 11 to 19 as having fair trunk control.

There is currently no study to determine the accuracy of this classification of trunk control in stroke patients. Verheyden et al. (2004) were the first group of researchers who developed the TIS to measure trunk control in stroke patients. They did not report any range of TIS score that can help clinicians to classify people with stroke into groups of various degree of trunk control.

The classification of trunk control based on the range of TIS score by the author (SKW) is considered arbitrary. This is one of the limitations of this doctoral study. This aspect of classification of the degree of trunk control with objective measures, for example with a motion capture system, can be recommended for future study.

7.6.3 Study design

The results of this study must be considered in the light of methodological limitations. As the Phase 1A and Phase 1B studies were of cross-sectional study design, the observations and assessment results were simply a snapshot of the

pool of participants at a single point in time and there was no follow-up phase. The performance of the participants may vary from day to day. However, the main problem with a cross-sectional study design is differentiating cause and effect from simple association (Mann 2003). Therefore, a causal relationship cannot be drawn from the results unless future randomised controlled trials are conducted to verify the associations reported in this study.

7.6.4 Observer bias

This study was conducted solely by the author (SKW). Due to absence of funding for the PhD research, the researcher conducted all assessments of TIS, FMA, SWMFT-Time and SWMFT-FAS to ensure standardisation in the administration of assessments. This presents an element of observer bias in the study.

Observer bias occurs when the observer unwittingly (or even intentionally) exercises more care about one type of responses or measurements such as those supporting a particular hypothesis than those opposing this hypothesis (Sica 2006; Pannucci & Wilkins 2010). Observer bias may arise out of unconscious assumptions or preconceptions harboured by the researcher (Agabegi & Stern 2008).

A notable finding in this doctoral study is the good level of agreement between the performance time (SWMFT-Time) measured with a stopwatch and the Vicon motion capture system (Chapter 5, section 5.13.1). Results from the Bland-Altman plot showed that the mean difference between the time measured with the stopwatch and the Vicon system ranged between -0.40 to 0.42 seconds. Hence, the findings help to rule out the element of observer bias partially. Ideally, with the availability of research funding, blinded research assistants who do not know the hypothesis of this study should be employed to assess all participants to reduce observer bias.

7.6.5 Hawthorne effect

Another limitation that might confound the observed improvements in the outcome measures in Phase 1 and Phase 2 studies is the Hawthorne effect. The Hawthorne effect concerns research participation, the consequent awareness of being observed and studied, or if they received additional attention and

possible impact on behavior (Fernald et al. 2012; McCambridge et al. 2014).

To minimize presence of any Hawthorne effect and performance bias, the participants were not informed of the hypotheses of the Phase 1 and Phase 2 studies. It would be very difficult to eliminate the Hawthorne effect completely in Phase 1A and Phase 1B studies as providing a sham condition would be difficult, but important for consideration in future studies. In the Phase 2 study that involved follow-up assessments till 6 months post stroke, the participants were not updated about their previous clinical scores and performance at each time point. This is a strategy adopted to minimize Hawthorne effect so that the participants could not compare previous results and attempt to outdo those scores during assessment at each time point.

7.6.6 Trunk support

The external trunk support and accessories (Figure 4-7) enable some degree of customisation, width-wise and depth-wise, to suit the body contour and size of the participants. However, the height of the trunk support is the same due to one standard size (height-wise). This implies that the superior part of the trunk support will be at different contact points on the posterior and lateral aspects of the trunk for the participants. Thus, the trunk of the participants was supported differently in this study. However, the height of the trunk support was designed so that no participants experienced restrictions as they performed lateral flexion of the trunk during the TIS assessment. To address this limitation however, future trunk supports could be created with different height dimensions. The author (SKW) acknowledged that the use of external trunk support would invalidate the administration of TIS. The reason for inclusion of trunk support in the experimental procedure in the Phase 1A and Phase 1B studies was to simulate the situation of having someone with a "better" TIS score, i.e. with a better trunk control within the same session, and then investigated that effect on upper extremity function.

7.6.7 Lack of kinematic data for the distal segment of the upper extremity in the Phase 1A study

In the Phase 1A study, the kinematics of the trunk, scapula, humerus and elbow were captured while the participants performed the 'lift can' task.

However, no reflective markers were placed on the individual digits to capture the kinematics of the wrist, fingers and thumb during the hand opening and grasping phase of the task. This is a limitation of this doctoral study.

The most prevalent muscle synergy observed in some individuals with stroke is the flexor synergy, which is expressed as an abnormal coupling between shoulder abductors and elbow/wrist/finger flexors in the paretic upper extremity (Dewald et al. 2001). Due to the flexor synergy, it can affect the individual's ability to generate volitional wrist and finger extension (Yao et al. 2015). Overall, it may affect the duration of task completion, i.e. movement duration, as well as the whole kinetic chain of the trunk, scapula, shoulder and elbow due to the anatomical and biomechanical links. Impairment of one or more kinetic chain links can create dysfunctional biomechanical output (Sciascia & Cromwell 2012). Michaelson et al. (2004) found that in patients with more severe distal impairments, the amount of trunk displacement was correlated with a more frontal hand orientation for grasping. In patients without distal impairments, the trunk movement was mostly related to proximal arm movements while in those with distal impairments, trunk movement was related to both proximal and distal arm movements.

In future studies on reach-to-grasp objects, it will be important to capture the kinematic data of the wrist and hand because the data will provide dynamic joint information (e.g. ROM, velocity of movement) of the fingers and thumb; and information about the coupling of hand transport with grip aperture (Baak et al. 2015) during the performance of task. In addition, the kinematic data can provide information on the maximum grip aperture size and percentage time of maximum grip aperture (Michaelson et al. 2004). Taken together, combination of the kinematics of the trunk, scapula, humerus, elbow and the kinematics of the wrist, fingers and thumb will provide a deeper insights into the movement strategies during task performance with the affected upper extremity in people with stroke.

7.6.8 Lack of kinematic data for the Phase 1B and Phase 2 studies

In the Phase 1B study, only clinical outcome measures were used. Similarly in the Phase 2 study, only clinical outcome measures were used to track the recovery pattern of the trunk and upper extremity in the subacute stroke

participants. No motion capture system was available at the study site (Rehabilitation Centre of Tan Tock Seng Hospital, Singapore). Clinical outcome measures are not suitable to assess the quality of motor performance and, with that, to distinguish between restitution and compensation (Buma et al, 2013). In addition, the clinical outcome measure, SWMFT, does not account for compensatory trunk movement in the final scoring system.

There were initial plans of using wearable inertial sensors (either Shimmer or Xsens sensors) to capture kinematic data in the Phase 1B and Phase 2 studies. However, the trial run of the Shimmer and Xsens sensors in the UK was unsuccessful due to technical problems (such as frequent break-up in data transmission and loss of synchronization between sensors) and the engineers could not fix them in time before the commencement of the Phase 1B and Phase 2 studies in Singapore. That was an unfortunate situation because serial kinematic measurement of the quality of motor performance would be valuable to shed light on the recovery mechanisms in the first 6 months following stroke. In addition, a recent study has demonstrated that acceleration metrics from wearable sensors are responsive to change in upper extremity function of people with stroke (Urbin et al. 2015). These information from the sensors will also provide insight into the amount of use of the affected upper extremity in real world activities (Bailey et al. 2014; Bailey et al. 2015).

Analysis at the kinematic level will enable differentiation between functional gains achieved through compensation versus those achieved through true recovery of motor control (Subramanian et al. 2010; Alt Murphy et al. 2013; Kitago et al. 2013; Frykberg & Vasa 2015). Kleim (2011) emphasized that distinguishing true recovery from compensation at both a neural and behavioural level is key towards understanding the relationship between neural plasticity and rehabilitation-dependent changes in function.

Kinematic analysis is sensitive enough to capture small changes and is influenced neither by the ceiling effect nor by subjective observation of clinicians and researchers (van Dokkum et al. 2014). Therefore, future study should capture longitudinal kinematic data in addition to the clinical outcome measures to provide a comprehensive understanding of neurological recovery post stroke.

7.6.9 Documentation of the average duration of therapy received per day

As many participants and carers found it challenging to keep track of the type and duration of therapy on a daily basis, the therapy log that was submitted monthly to the author (SKW) may not be entirely accurate. Moreover, the therapy log was self-reported. Thus, there was a possibility of recall bias. One possible solution to this problem is for the author to phone the participants weekly to improve the compliance and completion of the therapy log.

7.7 Generalizability of the results from this PhD work

The entire PhD work was conducted on groups of subacute stroke, chronic stroke and healthy participants who were age- and sex-matched. In the Phase 1A and Phase 1B studies, analysis confirmed no significant differences in the results of interest (i.e. TIS, SWMFT-Time and SWMFT-FAS) based on age, gender, hand dominance, type of stroke, side of affected upper extremity, and order of testing with the trunk support. In addition, the Phase 1A, Phase 1B and Phase 2 studies comprised of chronic and subacute stroke participants with different severity level of upper extremity impairment and trunk impairment, thus ensuring a spread of participants who were representative of the general stroke population. Hence, it is the opinion of the author (SKW) that the results gathered from the Phase 1A, Phase 1B and Phase 2 studies can be generalised to the wider stroke population.

These key findings can be generalised to other stroke populations:

1) the existence of a strong association between trunk control and upper extremity function;

2) stabilization of the trunk enables an improved ability of an individual to use the upper extremity for functional activities. A stable trunk under an unsupported condition implies a trunk with good degree of control. Hence, this finding supports the hypothesis that good trunk control enables a better dissociation of the upper extremity from the trunk for function;

3) trunk control has an association with the recovery pattern of the upper extremity impairment and function in the first 6 months post stroke. A better

degree of trunk control is associated with a better recovery of the upper extremity.

7.8 Recommendations for future research

This PhD work has established evidence of a strong association between trunk control and upper extremity impairment and function. In addition, the study has demonstrated that trunk control has an association with the recovery pattern of upper extremity function in the first 6 months post stroke. These findings suggest that improving trunk control in the early phase of stroke rehabilitation may potentially have an effect on improving upper extremity outcomes. However, this hypothesis needs to be tested in a properly designed study in the future. As an extension of the current PhD research, there are plans to conduct a clinical trial to evaluate whether improving trunk control early post-stroke leads to faster and better upper extremity functional recovery.

The author has also made some recommendations for future research. The observed improvement in trunk control and upper extremity function with the trunk support was an immediate effect; carry-over was not assessed as this was not the aim of the study. It remains unknown whether a period of UE training with the external trunk support for people with stroke will yield sustainable gains in the improvements observed in the trunk control or upper extremity function. A randomized controlled trial may be conducted to investigate the effectiveness of trunk support in improving upper extremity function in the future.

Future research studies may also consider investigating i) the effect of trunk support versus trunk restraint; ii) the effect of trunk support on trunk control and upper extremity in patients with trunk ataxia due to neurological disorders such as cerebellar stroke or brainstem stroke. Gaining a deeper understanding of the underlying mechanisms of trunk stability and trunk control may provide insights into a new therapeutic approach for the management of trunk ataxia and upper extremity in neurorehabilitation.

7.9 Original contributions to the body of knowledge in stroke rehabilitation

The following findings are the original contributions made to the body of knowledge in stroke rehabilitation that arise from the Phase 1 and Phase 2 studies:

1) There is a strong association between trunk control and upper extremity function in subacute and chronic stroke patients.

2) Stabilization of the trunk enables an improved ability to use the upper extremity for function in subacute and chronic stroke participants and healthy controls. It also helps to improve the smoothness of movement and elbow range of motion during reaching.

3) Trunk control has an association with the recovery pattern of the upper extremity impairment and function in the first 6 months following stroke. A better degree of trunk control is associated with a better recovery of the upper extremity. Therefore, improving active control of the trunk has the potential to facilitate better control and coordination of the upper extremity in subacute and chronic stroke patients and hence promote recovery.

4) In people with stroke, the rate of recovery of trunk control and upper extremity are different based on the stratification of the severity of upper extremity impairment and trunk impairment. Understanding the trajectory of the recovery curves of the stratified groups enable the clinicians to prognosticate outcomes more accurately and aid in setting of realistic and achievable goals, treatment planning and intervention.

7.10 Summary of Chapter 7

This Chapter has discussed the findings of this doctoral study, which provided answers to the research questions. Discussion of the issues related to trunk control and upper extremity of stroke patients were made in reference to the existing literature.

Results from the Phase 1A and Phase 1B studies have highlighted the strong association between trunk control and upper extremity in people with stroke.

The possible mechanisms for the association were discussed in depth. Stabilization of the trunk with the support assists in the facilitation of the movement of upper extremity to occur against a background of stabilized core of the body, thus improving the upper extremity function. Two other possible mechanisms include better postural alignment provided by the support and the reduction in the number of degrees of freedom.

The longitudinal study (Phase 2) study further confirmed the findings of the cross-sectional studies (Phase 1A and Phase 1B studies) about the existence of a strong association between trunk control and upper extremity in the first 6 months post stroke. The recovery pattern of the trunk and upper extremity impairment and function were analysed in detail, including the rate of change of each variable at each time point. The rate of change of the recovery curves of trunk control and upper extremity impairment was found to be similar over time. The improvements in the upper extremity impairment and function occurred in parallel with the improvement in trunk control. The difference in recovery pattern of the proximal and distal upper extremity was also discussed. In addition, the recovery patterns of trunk control and upper extremity based on the stratification of the severity of upper extremity impairment and trunk impairment were analysed and discussed. Understanding the trajectory of the recovery curves of the stratified groups enable the clinicians to prognosticate outcomes more accurately and aid in setting of realistic and achievable goals, treatment planning and intervention.

Implications of the findings to clinical practice and the limitations of this doctoral study were discussed, and recommendations for future research presented. The original contributions made to the body of knowledge in stroke rehabilitation that arise from the Phase 1 and Phase 2 studies were listed.

The next Chapter provides the conclusion for this PhD study.

Chapter 8: Conclusion

8. Conclusion

This Chapter will provide the conclusion for this PhD study; highlighting the original contributions to the body of knowledge in stroke rehabilitation.

The trunk is considered an important postural stabilizer which enables the dissociation of the upper and lower extremities from the trunk for function (Carr & Shepherd 1987; Davies 1990a; Mohr 1990; Gillen 1998; Davies 2000; Rosenblum & Josman 2003; Heyrman et al. 2013). However, this common assumption in neurorehabilitation has not been validated in clinical trials. The association of trunk control with upper extremity function in people with stroke was unknown. This knowledge is critical to the design of targeted rehabilitation programmes for the trunk and upper extremity so that optimal functional outcomes for stroke patients can be achieved. Hence, this is a gap in knowledge that warrants research to illuminate this relationship.

This PhD work investigated the relationship between trunk control and recovery of upper extremity function in stroke patients. In order to achieve the overarching aim, the author (SKW) conducted two cross-sectional studies (Phase 1A and Phase 1B studies) and a longitudinal study (Phase 2 study).

This doctoral study was the first to examine the impact of trunk control on upper extremity function in subacute and chronic stroke participants and healthy controls. Stabilization of the trunk with an external support led to statistically significant improvement in trunk control (TIS) and upper extremity function (SWMFT-Time and SWMFT-FAS). Further, the improvements in TIS, SWMFT-Time and SWMFT-FAS in the subacute stroke participants were considered clinically important difference as the scores were greater than the MCID of the respective variables.

The study also demonstrated that the external trunk support aids in the stabilization of the trunk that led to improvements in the smoothness of movement and elbow range of motion during reaching. Hence, this study supports the common assumption in neurorehabilitation that a stable trunk enables the dissociation of the upper extremity from the trunk for function. In other words, stabilization of the trunk via a better trunk control enables an improved ability to use the upper extremity for functional activities.

Due to the nature of cross-sectional study design of Phase 1A and Phase 1B studies, the results only provided a snapshot of the strong association between trunk control and upper extremity. The Phase 2 study with a longitudinal design further supports such a strong relationship in the first 6 months post stroke. Further, the Phase 2 study revealed a similar rate of change of TIS and FMA in the first 6 months following stroke. In other words, the trajectories of both TIS and FMA were very similar from the 1st to the 6th month post stroke. As TIS scores improved over time, both the upper extremity impairment (FMA) and upper extremity function (SWMFT-Time and SWMFT-FAS) improved almost in parallel with the TIS increase. In addition, the TIS score over the 6-month period was found to be a significant predictor of the recovery of FMA, FMA-SE, FMA-WH, SWMFT-Time and SWMFT-FAS. Taken together, the results imply that trunk control has an association with the recovery pattern of the upper extremity impairment. A better degree of trunk control is associated with a better recovery of the upper extremity. Therefore, improving active control of the trunk has the potential to facilitate better control and coordination of the upper extremity in subacute and chronic stroke patients and hence promote recovery.

This doctoral study was the first to analyse the recovery patterns of trunk control and upper extremity in people with stroke based on the stratification of the severity of upper extremity impairment and trunk impairment. The rate of recovery is dependent on the initial severity of impairment. Generally, those people with more severe stroke recover at a slower rate, in terms of trunk control and upper extremity, compared to those with moderate and mild level of impairment. Understanding the trajectory of the recovery curves of the stratified groups enable the clinicians to predict outcomes more accurately and aid in setting of realistic and achievable goals, treatment planning and intervention.

In conclusion, this PhD thesis has presented and discussed the findings of the Phase 1 and Phase 2 studies that investigated the relationship between trunk control and upper extremity function in subacute and chronic stroke participants and healthy participants; and investigated the relationship between trunk control and recovery of upper extremity function in subacute stroke participants in the first 6 months post stroke. The PhD research has deepened our understanding about trunk control and upper extremity in

people with stroke and provided valuable insights for rehabilitation professionals and researchers. The findings will assist therapists to design comprehensive programmes for rehabilitation of trunk control and upper extremity at different stages of stroke recovery. It will also aid in the prognostication of trunk and upper extremity recovery after stroke and therefore will have an impact on clinical practice.

END OF THESIS

References

Ada L, Canning C, Carr JH, Kilbreath SL and Shepherd RB (1994) Task specific training of reaching and manipulation IN: Bennett KMB and Castiello U (eds) *Advances in Psychology : Insights into Reach and Grasp Movement.* Oxford, UK: Elsevier 238-265

Agabegi SS and Stern PJ (2008) Bias in research. *American Journal of Orthopedics* 37(5): 242-248

Agarwal V, Mcrae MP, Bhardwaj A and Teasell RW (2003) A model to aid in the prediction of discharge location for stroke rehabilitation patients. *Archives of Physical Medicine and Rehabilitation* 84(11): 1703-1709

Akuthota V, Ferreiro A, Moore T and Fredericson M (2008) Core stability exercise principles. *Current Sports Medicine Reports* 7(1): 39-44

Akuthota V and Nadler SF (2004) Core strengthening. *Archives of Physical Medicine and Rehabilitation* 85(3 Suppl 1): 86-92

Albert SJ and Kesselring J (2012) Neurorehabilitation of stroke. *Journal of Neurology* 259(5): 817-832

Allan SM and Rothwell NJ (2003) Inflammation in central nervous system injury. *Philosophical Transactions of the Royal Society B: Biological Sciences* 358(1438): 1669-77

Allison GT and Morris SL (2008) Transversus abdominis and core stability: has the pendulum swung? *British Journal of Sports Medicine* 42(11): 930-931

Allison GT, Morris SL and Lay B (2008) Feedforward responses of transversus abdominis are directionally specific and act asymmetrically: implications for core stability theories. *Journal of Orthopaedic and Sports Physical Therapy* 38(5): 228-237

Allred RP, Cappellini CH and Jones TA (2010) The "good" limb makes the "bad" limb worse: experience-dependent interhemispheric disruption of functional outcome after cortical infarcts in rats. *Behavioral Neuroscience* 124(1): 124-132

Allred RP and Jones TA (2008a) Experience: a double-edged sword for restorative neural plasticity after brain damage. *Future Neurology* 3(2): 189-198

Allred RP and Jones TA (2008b) Maladaptive effects of learning with the less-affected forelimb after focal cortical infarcts in rats. *Experimental Neurology* 210(1): 172-181

Allred RP, Maldonado MA, Hsu JE and Jones TA (2005) Training the 'less-affected' forelimb after unilateral cortical infarcts interferes with functional recovery of the impaired forelimb in rats. *Restorative Neurology and Neuroscience* 23(5-6): 297-302

Alt Murphy M and Häger CK (2015) Kinematic analysis of the upper extremity after stroke – how far have we reached and what have we grasped? *Physical Therapy Reviews* 20(3): 137-155

Alt Murphy M, Willen C and Sunnerhagen KS (2011) Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass. *Neurorehabilitation and Neural Repair* 25(1): 71-80

Alt Murphy M, Willen C and Sunnerhagen KS (2013) Responsiveness of upper extremity kinematic measures and clinical improvement during the first

three months after stroke. *Neurorehabilitation and Neural Repair* 27(9): 844-853

Amasay T and Karduna AR (2009) Scapular kinematics in constrained and functional upper extremity movements. *Journal of Orthopaedic and Sports Physical Therapy* 39(8): 618-627

Amonoo-Kuofi H (1983) The density of muscle spindles in the medial, intermediate and lateral columns of human intrinsic postvertebral muscles. *Journal of Anatomy* 136(Pt 3): 509-519

Andersen KK, Andersen ZJ and Olsen TS (2010) Age- and gender-specific prevalence of cardiovascular risk factors in 40,102 patients with first-ever ischemic stroke: a Nationwide Danish Study. *Stroke* 41(12): 2768-2774

Anderson KG and Behm DG (2004) Maintenance of EMG activity and loss of force output with instability. *Journal of Strength and Conditioning Research* 18(3): 637-640

Andrews RJ (1991) Transhemispheric diaschisis. a review and comment. *Stroke* 22(7): 943-949

Ang JHY and Man DWK (2006) The discriminative power of the Wolf Motor Function Test in assessing upper extremity functions in persons with stroke. *International Journal of Rehabilitation Research* 29(4): 357-361

Appelboom G, Camacho E, Abraham ME, Bruce SS, Dumont EL, Zacharia BE, D'amico R, Slomian J, Reginster JY, Bruyere O and Connolly ES, Jr. (2014) Smart wearable body sensors for patient self-assessment and monitoring. *Archives of Public Health* 72(1): 28

Archambault P, Pigeon P, Feldman A and Levin M (1999) Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subjects. *Experimental Brain Research* 126(1): 55-67

Aruin AS (2002) The organization of anticipatory postural adjustments. *Journal of Automatic Control* 12(1): 31-37

Aruin AS and Latash ML (1995) Directional specificity of postural muscles in feedforward postural reactions during fast voluntary arm movements. *Experimental Brain Research* 103(2): 323-332

Arvidsson A, Collin T, Kirik D, Kokaia Z and Lindvall O (2002) Neuronal replacement from endogenous precursors in the adult brain after stroke. *Nature Medicine* 8(9): 963-970

Arya KN, Verma R and Garg RK (2011) Estimating the minimal clinically important difference of an upper extremity recovery measure in subacute stroke patients. *Topics in Stroke Rehabilitation* 18(Suppl 1): 599-610

Ayhan C, Unal E and Yakut Y (2014) Core stabilisation reduces compensatory movement patterns in patients with injury to the arm: a randomized controlled trial. *Clinical Rehabilitation* 28: 36-47

Baak B, Bock O, Dovern A, Saliger J, Karbe H and Weiss PH (2015) Deficits of reach-to-grasp coordination following stroke: comparison of instructed and natural movements. *Neuropsychologia* 77: 1-9

Babyar SR, Mccloskey KH and Reding M (2007) Surface electromyography of lumbar paraspinal muscles during seated passive tilting of patients with lateropulsion following stroke. *Neurorehabilitation and Neural Repair* 21(2): 127-136

Bailey RR, Klaesner JW and Lang CE (2014) An accelerometry-based methodology for assessment of real-world bilateral upper extremity activity. *PLoS One* 9(7): e103135

Bailey RR, Klaesner JW and Lang CE (2015) Quantifying real-world upper-Limb activity in nondisabled adults and adults With chronic stroke. . *Neurorehabilitation and Neural Repair*: Published online 20th April 2015

Baker K, Cano SJ and Playford ED (2011) Outcome measurement in stroke: a scale selection strategy. *Stroke* 42(6): 1787-1794

Baldissera F, Rota V and Esposti R (2008) Anticipatory postural adjustments in arm muscles associated with movements of the contralateral limb and their possible role in interlimb coordination. *Experimental Brain Research* 185(1): 63-74

Bang DH, Shin WS and Choi SJ (2015) The effects of modified constraint-induced movement therapy combined with trunk restraint in subacute stroke: a double-blinded randomized controlled trial. *Clinical Rehabilitation* 29(6): 561–569

Baraldi AN and Enders CK (2010) An introduction to modern missing data analyses. *Journal of School Psychology* 48(1): 5-37

Barker RN and Brauer SG (2005) Upper limb recovery after stroke: the stroke survivors' perspective. *Disability and Rehabilitation* 27(20): 1213-1223

Barnes MP (2001) An overview of the clinical management of spasticity IN*:* Barnes MP and Johnson GR (eds) *Upper motor neurone syndrome and spasticity: Clinical management and neurophysiology.* Cambridge, United Kingdom: Cambridge University Press 1-11

Barreca S, Gowland CK, Stratford P, Huijbregts M, Griffiths J, Torresin W, Dunkley M, Miller P and Masters L (2004) Development of the Chedoke Arm and Hand Activity Inventory: theoretical constructs, item generation, and selection. *Topics in Stroke Rehabilitation* 11(4): 31-42

Barreca S, Stratford P, Masters L, Lambert C, Griffiths J and Mcbay C (2006a) Validation of three shortened versions of the Chedoke Arm and Hand Activity Inventory. *Physiotherapy Canada* 58(2): 1-9

Barreca SR, Stratford PW, Lambert CL, Masters LM and Streiner DL (2005) Test-retest reliability, validity, and sensitivity of the Chedoke arm and hand activity inventory: a new measure of upper-limb function for survivors of stroke. *Archives of Physical Medicine and Rehabilitation* 86(8): 1616-1622

Barreca SR, Stratford PW, Masters LM, Lambert CL and Griffiths J (2006b) Comparing 2 versions of the Chedoke Arm and Hand Activity Inventory with the Action Research Arm Test. *Physical Therapy* 86(2): 245-253

Basagana X, Liao X and Spiegelman D (2011) Power and sample size calculations for longitudinal studies estimating a main effect of a time-varying exposure. *Statistical Methods in Medical Research* 20(5): 471-487

Basagana X and Spiegelman D (2010) Power and sample size calculations for longitudinal studies comparing rates of change with a time-varying exposure. *Statistics in Medicine* 29(2): 181-192

Baskett JJ, Marshall HJ, Broad JB, Owen PH and Green G (1996) The good side after stroke: Ipsilateral sensory-motor function needs careful assessment. *Age and Ageing* 25(3): 239-244

Bayona NA, Bitensky J and Teasell R (2005) Plasticity and reorganization of the uninjured brain. *Topics in Stroke Rehabilitation* 12(3): 1-10

Bazrgari B, Shirazi-Adl A and Lariviere C (2009) Trunk response analysis under sudden forward perturbations using a kinematics-driven model. *Journal of Biomechanics* 42(9): 1193-1200

Beebe JA and Lang CE (2008) Absence of a proximal to distal gradient of motor deficits in the upper extremity early after stroke. *Clinical Neurophysiology* 119(9): 2074-2085

Beebe JA and Lang CE (2009) Active range of motion predicts upper extremity function 3 months after stroke. *Stroke* 40(5): 1772-1779

Beer RF, Dewald JP, Dawson ML and Rymer WZ (2004) Target-dependent differences between free and constrained arm movements in chronic hemiparesis. *Experimental Brain Research* 156(4): 458-470

Beer RF, Dewald JPA and Rymer WZ (2000) Deficits in the coordination of multijoint arm movements in patients with hemiparesis: evidence for disturbed control of limb dynamics. *Experimental Brain Research* 131(3): 305-319

Beer RF, Ellis MD, Holubar BG and Dewald JP (2007) Impact of gravity loading on post-stroke reaching and its relationship to weakness. *Muscle & Nerve* 36(2): 242-250

Beets IA, Mace M, Meesen RL, Cuypers K, Levin O and Swinnen SP (2012) Active versus passive training of a complex bimanual task: is prescriptive proprioceptive information sufficient for inducing motor learning? *PLoS One* 7(5): e37687

Behm DG, Anderson K and Curnew RS (2002) Muscle force and activation under stable and unstable conditions. *Journal of Strength and Conditioning Research* 16(3): 416-422

Behm DG, Drinkwater EJ, Willardson JM and Cowley PM (2010) The use of instability to train the core musculature. *Applied Physiology, Nutrition, and Metabolism* 35(1): 91-108

Beloosesky Y, Streifler JY, Burstin A and Grinblat J (1995) The importance of brain infarct size and location in predicting outcome after stroke. *Age and Ageing* 24(6): 515-518

Bembenek JP, Kurczych K, Karlinski M and Czlonkowska A (2012) The prognostic value of motor-evoked potentials in motor recovery and functional outcome after stroke – a systematic review of the literature. *Functional Neurology* 27(2): 79-84

Benaim C, Perennou DA, Villy J, Rousseaux M and Pelissier JY (1999) Validation of a standardized assessment of postural control in stroke patients : The Postural Assessment Scale for Stroke Patients (PASS). *Stroke* 30(9): 1862-1868

Benecke B, Meyer BU and Freund HJ (1991) Reorganisation of descending motor pathways in patients after hemispherectomy and severe hemispheric lesions demonstrated by magnetic brain stimulation. *Experimental Brain Research* 83(2): 419-426

Benoit DL, Ramsey DK, Lamontagne M, Xu L, Wretenberg P and Renstrom P (2006) Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. *Gait & Posture* 24(2): 152-164

Bernstein N (2001) Motor control: Issues and theories IN*:* Shumway-Cook A and Woollacott MH (eds) *Motor Control: Theory and Practical Applications.* 2nd Edition Pennsylvania: Lippincott Williams & Wilkins 3-19

Bernstein NA (1967) The problem of the interrelation of co-ordination and localization *The co-ordination and regulation of movements.* Oxford: Pergamon Press

Berry J, Dyer A, Cai X, Garside D, Ning H, Thomas A, Greenland P, Horn L, Tracy R and Lloyd-Jones D (2012) Lifetime risks of cardiovascular disease. *New England Journal of Medicine* 366(4): 321-329

Bertenthal B and Von Hofsten C (1998) Eye, head and trunk control: the foundation for manual development. *Neuroscience and Biobehavioral Reviews* 22(4): 515-520

Bertucco M and Cesari P (2010) Does movement planning follow Fitts' law? Scaling anticipatory postural adjustments with movement speed and accuracy. *Neuroscience* 171(1): 205-213

Biernaskie J and Corbett D (2001) Enriched rehabilitative training promotes improved forelimb motor function and enhanced dendritic growth after focal ischemic injury. *Journal of Neuroscience* 21(14): 5272-5280

Biller J, Love BB, Marsh Ee I, Jones MP, Knepper LE, Jiang D, Adams HP and Gordon DL (1990) Spontaneous improvement after acute ischemic stroke. A pilot study. *Stroke* 21(7): 1008-1012

Binkofski F, Seitz RJ, Arnold S, Classen J, Benecke R and Freund HJ (1996) Thalamic metabolism and corticospinal tract integrity determine motor recovery in stroke. *Annals of Neurology* 39(4): 460-470

Binkofski F, Seitz RJ, Hacklander T, Pawelec D, Mau J and Freund HJ (2001) Recovery of motor functions following hemiparetic stroke: a clinical and magnetic resonance-morphometric study. *Cerebrovascular Diseases* 11(3): 273-281

Bobath B (1990) *Adult Hemiplegia: Evaluation and Treatment.* (3rd Edition) Oxford: Butterworth Heinemann

Bogard K, Wolf S, Zhang Q, Thompson P, Morris D and Nichols-Larsen D (2009) Can the Wolf Motor Function Test be streamlined? *Neurorehabilitation and Neural Repair* 23(5): 422-428

Bohannon R (1999) Motricity Index scores are valid indicators of paretic upper extremity strength following stroke. *Journal of Physical Therapy Science* 11(2): 59-61

Bohannon RW (1992) Lateral trunk flexion strength : impairment, measurement reliability and implications following unilateral brain lesions. *International Journal of Rehabilitation Research* 15(3): 249-251

Bohannon RW (1995) Recovery and correlates of trunk muscle strength after stroke. *International Journal of Rehabilitation Research* 18(2): 162-167

Bohannon RW, Cassidy D and Walsh S (1995) Trunk muscle strength is impaired multidirectionally after stroke. *Clinical Rehabilitation* 9(1): 47-51

Boissy P, Bourbonnais D, Carlotti MM, Gravel D and Arsenault BA (1999) Maximal grip force in chronic stroke subjects and its relationship to global upper extremity function. *Clinical Rehabilitation* 13(4): 354-362

Borsa PA, Timmons MK and Sauers EL (2003) Scapular-positioning patterns during humeral elevation in unimpaired shoulders. *Journal of Athletic Training* 38(1): 12-17

Bouisset S, Richardson J and Zattara M (2000) Are amplitude and duration of anticipatory postural adjustments identically scaled to focal movement parameters in humans? *Neuroscience Letters* 278(3): 153-156

Bouisset S and Zattara M (1981) A sequence of postural movements precedes voluntary movement. *Neuroscience Letters* 22(3): 263-270

Bouisset S and Zattara M (1987) Biomechanical study of the programming of anitcipatory postural adjustments associated with voluntary movement. *Journal of Biomechanics* 20(8): 735-742

Bourbonnais D and Noven SV (1989) Weakness in patients With hemiparesis. *American Journal of Occupational Therapy* 43(5): 313-319

Bovend'eerdt T, Dawes H, Johansen-Berg H and Wade D (2004) Evaluation of the Modified Jebsen Test of Hand Function and the University of Maryland Arm Questionnaire for Stroke. *Clinical Rehabilitation* 18(2): 195-202

Bradnam LV, Stinear CM and Byblow WD (2013) Ipsilateral motor pathways after stroke: implications for non-invasive brain stimulation. *Frontiers in Human Neuroscience* 7: 184

Brouwer BJ and Schryburt-Brown K (2006) Hand function and motor cortical output poststroke: are they related? *Archives of Physical Medicine and Rehabilitation* 87(5): 627-634

Brown RC (2002) Calcium dodulation of adherens and tight junction function: a potential mechanism for blood-brain barrier disruption after stroke. *Stroke* 33(6): 1706-1711

Brown SH and Potvin JR (2005) Constraining spine stability levels in an optimization model leads to the prediction of trunk muscle cocontraction and improved spine compression force estimates. *Journal of Biomechanics* 38(4): 745-754

Buma F, Kwakkel G and Ramsey N (2013) Understanding upper limb recovery after stroke. *Restorative Neurology and Neuroscience* 31(6): 707-722

Buma FE, Lindeman E, Ramsey NF and Kwakkel G (2010) Functional neuroimaging studies of early upper limb recovery after stroke: a systematic review of the literature. *Neurorehabilitation and Neural Repair* 24(7): 589-608

Burke E and Cramer SC (2013) Biomarkers and predictors of restorative therapy effects after stroke. *Current Neurology and Neuroscience Reports* 13(2): 329-338

Burridge JH, Turk R, Notley SV, Pickering RM and Simpson DM (2009) The relationship between upper limb activity and impairment in post-stroke hemiplegia. *Disability and Rehabilitation* 31(2): 109-117

Butefisch CM, Davis BC, Wise SP, Sawaki L, Kopylev L, Classen J and Cohen LG (2000) Mechanisms of use-dependent plasticity in the human motor cortex. *Proceedings of the National Academy of Sciences of the United States of America* 97(7): 3661-3665

Butler PB, Saavedra S, Sofranac M, Jarvis SE and Woollacott MH (2010) Refinement, reliability, and validity of the segmental assessment of trunk control. *Pediatric Physical Therapy* 22(3): 246-257

Buxbaum L, Ferraro M, Veramonti T, Farne A, Whyte J, Ladavas E, Frassinetti F and Coslett H (2004) Hemispatial neglect: subtypes, neuroanatomy, and disability. *Neurology* 62(5): 749-756

Cabanas-Valdes R, Bagur-Calafat C, Girabent-Farres M, Caballero-Gomez FM, Hernandez-Valino M and Urrutia Cuchi G (2015) The effect of additional core stability exercises on improving dynamic sitting balance and trunk control for subacute stroke patients: A randomized controlled trial. *Clinical Rehabilitation*: Published online 8 October 2015

Calautti C, Jones PS, Naccarato M, Sharma N, Day DJ, Bullmore ET, Warburton EA and Baron JC (2010) The relationship between motor deficit and primary motor cortex hemispheric activation balance after stroke: longitudinal fMRI study. *Journal of Neurology, Neurosurgery & Psychiatry* 81(7): 788-792

Canedo A (1997) Primary motor cortex influences on the descending and ascending systems. *Progress in Neurobiology* 51(3): 287-335

Carey JR, Kimberley TJ, Lewis SM, Auerbach EJ, Dorsey L, Rundquist P and Ugurbil K (2002) Analysis of fMRI and finger tracking training in subjects with chronic stroke. *Brain* 125(Pt 4): 773-388

Caronni A and Cavallari P (2009) Anticipatory postural adjustments stabilise the whole upper-limb prior to gentle index finger tap. *Experimental Brain Research* 194: 59-66

Carr J and Shepherd R (1987) *A motor relearning program for stroke.* (2nd Edition) Oxford: Butterworth-Heinemann

Carr JH, Shepherd RB, Nordholm L and Lynne D (1985) Investigation of a new motor assessment scale for stroke patients. *Physical Therapy* 65: 175-180

Carr LJ, Harrison LM and Stephens JA (1994) Evidence for bilateral innervation of certain homologous motoneurone pools in man. *Journal of Physiology* 475: 217-227

Cattaneo D, Ferrarin M, Frasson W and Casiraghi A (2005) Head control: volitional aspects of rehabilitation training in patients with multiple sclerosis compared with healthy subjects. *Archives of Physical Medicine and Rehabilitation* 86(7): 1381-1388

Cauraugh J, Light K, Kim S, Thigpen M and Behrman A (2000) Chronic motor dysfunction after stroke: recovering wrist and finger extension by electromyography-triggered neuromuscular stimulation. *Stroke* 31(6): 1360-1364

Chae J, Labatia I and Yang G (2003) Upper limb motor function in hemiparesis: concurrent validity of the Arm Motor Ability test. *American Journal of Physical Medicine and Rehabilitation* 82(1): 1-8

Chang L and Hasselkus BR (1998) Occupational therapists' expectations in rehabilitation following stroke: sources of satisfaction and dissatisfaction. *American Journal of Occupational Therapy* 52(8): 629-637

Chaudhuri G, Harvey RF, Sulton LD and Lambert RW (1988) Computerized tomography head scans as predictors of functional outcome of stroke patients. *Archives of Physical Medicine and Rehabilitation* 69(7): 496-498

Chen C, Leys D and Esquenazi A (2013a) The interaction between neuropsychological and motor deficits in patients after stroke. *Neurology* 80 (Suppl 2): S27–S34

Chen CL, Tang FT, Chen HC, Chung CY and Wong MK (2000) Brain lesion size and location: effects on motor recovery and functional outcome in stroke patients. *Archives of Physical Medicine and Rehabilitation* 81(4): 447-452

Chen H and Cohen P (2006) Using individual growth model to analyze the change in quality of life from adolescence to adulthood. *Health and Quality of Life Outcomes* 4: 10

Chen HF, Wu CY, Lin KC, Chen HC, Chen CP and Chen CK (2012) Rasch validation of the Streamlined Wolf Motor Function Test in people with chronic stroke and subacute stroke. *Physical Therapy* 92(8): 1017-1026

Chen HF, Wu CY, Lin KC, Jang Y, Lin SC, Cheng JW, Chung CY and Yan Y (2014) Measurement properties of Streamlined Wolf Motor Function Test in patients at subacute to chronic stages after stroke. *Neurorehabilitation and Neural Repair* 28(9): 839–846

Chen S, Lewthwaite R, Schweighofer N and Winstein CJ (2013b) Discriminant validity of a new measure of self-efficacy for reaching movements after stroke-induced hemiparesis. *Journal of Hand Therapy* 26(2): 116-123

Cheng J, Edwards LJ, Maldonado-Molina MM, Komro KA and Muller KE (2010) Real longitudinal data analysis for real people: building a good enough mixed model. *Statistics in Medicine* 29(4): 504-520

Cherney L, Halper A, Kwasnica C, Harvey R and Zhang M (2001) Recovery of functional status after right hemisphere stroke:relationship with unilateral neglect. *Archives of Physical Medicine and Rehabilitation* 82(3): 322-328

Chien CW, Hu MH, Tang PF, Sheu CF and Hsieh CL (2007) A comparison of psychometric properties of the Smart Balance Master system and the postural assessment scale for stroke in people who have had mild stroke. *Archives of Physical Medicine and Rehabilitation* 88(3): 374-380

Cho HM, Choi BY, Chang CH, Kim SH, Lee J, Chang MC, Son SM and Jang SH (2012) The clinical characteristics of motor function in chronic hemiparetic stroke patients with complete corticospinal tract injury. *NeuroRehabilitation* 31(2): 207-213

Cho SH, Kim DG, Kim DS, Kim YH, Lee CH and Jang SH (2007) Motor outcome according to the integrity of the corticospinal tract determined by diffusion tensor tractography in the early stage of corona radiata infarct. *Neuroscience Letters* 426(2): 123-127

Cholewicki J and Van Vliet JJ (2002) Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. *Clinical Biomechanics* 17(2): 99-105

Chollet F, Di Piero V, Wise RJS, Brooks DJ, Dolan RJ and Frackowiak RSJ (1991) The functional anatomy of motor recovery after stroke in humans: a study with positron emission tomography. *Annals of Neurology* 29(1): 63-71

Chopp M, Zhang ZG and Jiang Q (2007) Neurogenesis, angiogenesis, and MRI indices of functional recovery from stroke. *Stroke* 38(2 Suppl): 827-831

Chow W, Tin A and Meyyappan A (2010) Factors influencing costs of inpatient ischaemic stroke care in Singapore. *Proceedings of Singapore Healthcare* 19: 283-291

Chung E-J, Kim J-H and Lee B-H (2013) The effects of core stabilization exercise on dynamic balance and gait function in stroke patients. *Journal of Physical Therapy Science* 25(7): 803-806

Cicinelli P, Traversa R and Rossini PM (1997) Post-stroke reorganization of brain motor output to the hand- a 2–4 month follow-up with focal magnetic transcranial stimulation. *Electroencephalography and Clinical Neurophysiology* 105(6): 438-450

Cifu DX, Kreutzer JS, Kolakowsky-Hayner SA, Marwitz JH and Englander J (2003) The relationship between therapy intensity and rehabilitation outcomes after traumatic brain injury : a multicenter analysis. *Archives of Physical Medicine and Rehabilitation* 84: 1441-1448

Cillessen AH and Borch C (2006) Developmental trajectories of adolescent popularity: a growth curve modelling analysis. *Journal of Adolescence* 29(6): 935-599

Cioni M, Pisasale M, Abela S, Belfiore T and Micale M (2010) Physiological electromyographic activation patterns of trunk muscles during walking. *The Open Rehabilitation Journal* 3(1): 136-142

Cirstea CM, Ptito A and Levin MF (2006) Feedback and cognition in arm motor skill reacquisition after stroke. *Stroke* 37(5): 1237-1242

Cirstea MC and Levin MF (2000) Compensatory strategies for reaching in stroke. *Brain* 123(Pt 5): 940-953

Cirstea MC and Levin MF (2007) Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabilitation and Neural Repair* 21(5): 398-411

Cirstea MC, Mitnitski AB, Feldman AG and Levin MF (2003a) Interjoint coordination dynamics during reaching in stroke. *Experimental Brain Research* 151(3): 289-300

Cirstea MC, Ptito A and Levin MF (2003b) Arm reaching improvements with short-term practice depend on the severity of the motor deficit in stroke. *Experimental Brain Research* 152(4): 476-488

Clarke P (2002) Well-being after stroke in Canadian seniors: findings from the Canadian Study of Health and Aging. *Stroke* 33(4): 1016-1021

Clarkson AN and Carmichael ST (2009) Cortical excitability and post-stroke recovery. *Biochemical Society Transactions* 37(Pt 6): 1412-1414

Classen J, Liepert J, Wise SP, Hallett M and Cohen LG (1998) Rapid plasticity of human cortical movement representation induced by practice. *Journal of Neurophysiology* 79(2): 1117-1123

Cohen J (1988a) *Statistical power analysis for the behavioral sciences.* (2nd Edition) New Jersey: Lawrence Erlbaum

Cohen J (1988b) *Statistical power analysis for the behavioural sciences.* (2nd Edition) Hillsdale, NJ: Eribaum

Colebatch J and Gandevia S (1989) The distribution of muscular weakness in upper motor neuron lesions affecting the arm. *Brain* 112(Pt 3): 749–763

Colebatch JG, Rothwell JC, Day BL, Thompson PD and Marsden CD (1990) Cortical outflow to proximal arm muscles in man. *Brain* 113(Pt 6): 1843-1856

Colin C and Wade D (1990) Assessing motor impairment after stroke: a pilot reliability study. *Journal of Neurology, Neurosurgery & Psychiatry* 53(7): 576-579

Cordo PJ and Nashner LM (1982) Properties of postural adjustments associated with rapid arm movement. *Journal of Neurophysiology* 47(2): 287-302

Corti M, Patten C and Triggs W (2012) Repetitive transcranial magnetic stimulation of motor cortex after stroke: a focused review. *American Journal of Physical Medicine and Rehabilitation* 91(3): 254-270

Counsell C (2002) Predicting outcome after acute and subacute stroke: development and validation of new prognostic models. *Stroke* 33(4): 1041-1047

Counsell C (2004) Predicting functional outcome in acute stroke: comparison of a simple six variable model with other predictive systems and informal clinical prediction. *Journal of Neurology, Neurosurgery & Psychiatry* 75(3): 401-405

Coupar F, Pollock A, Rowe P, Weir C and Langhorne P (2012) Predictors of upper limb recovery after stroke: a systematic review and meta-analysis. *Clinical Rehabilitation* 26(4): 291-313

Crafton KR, Mark AN and Cramer SC (2003) Improved understanding of cortical injury by incorporating measures of functional anatomy. *Brain* 128(Pt 7): 1650-1659

Cramer SC (2004) Functional imaging in stroke recovery. *Stroke* 35(11 Suppl 1): 2695-2698

Cramer SC (2008) Repairing the human brain after stroke: I. Mechanisms of spontaneous recovery. *Annals of Neurology* 63(3): 272-287

Cramer SC, Nelles G, Benson RR, Kaplan JD, Parker RA, Kwong KK, Kennedy DN, Finklestein SP and Rosen BR (1997) A functional MRI study of subjects recovered from hemiparetic stroke. *Stroke* 28(12): 2518-2527

Cramer SC, Shah R, Juranek J, Crafton KR and Le V (2006) Activity in the peri-Infarct rim in relation to recovery from stroke. *Stroke* 37(1): 111-115

Cramer SC, Sur M, Dobkin BH, O'brien C, Sanger TD, Trojanowski JQ, Rumsey JM, Hicks R, Cameron J, Chen D, Chen WG, Cohen LG, Decharms C, Duffy CJ, Eden GF, Fetz EE, Filart R, Freund M, Grant SJ, Haber S, Kalivas PW, Kolb B, Kramer AF, Lynch M, Mayberg HS, Mcquillen PS, Nitkin R, Pascual-Leone A, Reuter-Lorenz P, Schiff N, Sharma A, Shekim L, Stryker M, Sullivan EV and Vinogradov S (2011) Harnessing neuroplasticity for clinical applications. *Brain* 134(Pt 4): 1591-1609

Cresswell A, Oddsson L and Thorstensson A (1994) The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Experimental Brain Research* 98(2): 336-341

Crosbie J, Kilbreath SL, Hollmann L and York S (2008) Scapulohumeral rhythm and associated spinal motion. *Clinical Biomechanics* 23(2): 184-192

Cuesta-Vargas AI, Galan-Mercant A and Williams JM (2010) The use of inertial sensors system for human motion analysis. *Physical Therapy Reviews* 15(6): 462-473

Curran PJ, Obeidat K and Losardo D (2010) Twelve frequently asked questions about growth curve modeling. *Journal of Cognition and Development* 11(2): 121-136

Curtis DJ, Butler P, Saavedra S, Bencke J, Kallemose T, Sonne-Holm S and Woollacott M (2015) The central role of trunk control in the gross motor function of children with cerebral palsy: a retrospective cross-sectional study. *Developmental Medicine & Child Neurology* 57(4): 351-357

Cutti AG, Giovanardi A, Rocchi L, Davalli A and Sacchetti R (2008) Ambulatory measurement of shoulder and elbow kinematics through inertial and magnetic sensors. *Medical & Biological Engineering & Computing* 46(2): 169-178

Danna-Dos-Santos A, Degani A and Latash M (2007) Anticipatory control of head posture. *Clinical Neurophysiology* 118(8): 1802-1814

Davare M, Duque J, Vandermeeren Y, Thonnard JL and Olivier E (2007) Role of the ipsilateral primary motor cortex in controlling the timing of hand muscle recruitment. *Cerebral Cortex* 17(2): 353-362

Davidoff RA (1990) The pyramidal tract. *Neurology* 40(2): 332-339

Davies PM (1990a) Problems associated with the loss of selective trunk activity in hemiplegia *Right in the Middle : Selective trunk activity in the treatment of adult hemiplegia.* Berlin Heidelberg, Germany: Springer-Verlag 31-65

Davies PM (1990b) *Right in the Middle : Selective trunk activity in the treatment of adult hemiplegia.* Berlin Heidelberg, Germany: Springer-Verlag

Davies PM (2000) *Steps to follow : the comprehensive treatment of patients with hemiplegia* (2nd Edition) Berlin: Springer

De Baets L, Jaspers E, Desloovere K and Van Deun S (2013a) A systematic review of 3D scapular kinematics and muscle activity during elevation in stroke subjects and controls. *Journal of Electromyography and Kinesiology* 23(1): 3-13

De Baets L, Van Deun S, Desloovere K and Jaspers E (2013b) Dynamic scapular movement analysis- is it feasible and reliable in stroke patients during arm elevation? *PLoS One* 8(11): e79046

De Graaf-Peters VB, Bakker H, Van Eykern LA, Otten B and Hadders-Algra M (2007) Postural adjustments and reaching in 4- and 6-month-old infants: an EMG and kinematical study. *Experimental Brain Research* 181(4): 647-656

De Oliveira Cacho R, Cacho EW, Ortolan RL, Cliquet A, Jr. and Borges G (2015) Trunk restraint therapy: the continuous use of the harness could promote feedback dependence in poststroke patients: a randomized trial. *Medicine (Baltimore)* 94(12): e641

De Oliveira R, Cacho EW and Borges G (2007) Improvements in the upper limb of hemiparetic patients after reaching movements training. *Int J Rehabil Res* 30(1): 67-70

Deakin A, Hill H and Pomeroy VM (2003) Rough guide to the Fugl-Meyer Assessment: upper limb section. *Physiotherapy* 89(12): 751-763

Delucia C and Pitts SC (2006) Applications of individual growth curve modeling for pediatric psychology research. *Journal of Pediatric Psychology* 31(10): 1002-1023

Demain S, Wiles R, Roberts L and Mcpherson K (2006) Recovery plateau following stroke: fact or fiction? *Disability and Rehabilitation* 28(13-14): 815-821

Denti L, Agosti M and Franceschini M (2008) Outcome predictors of rehabilitation for first stroke in the elderly. *European Journal of Physical and Rehabilitation Medicine* 44: 3-11

Desrosiers J, Bourbonnais D, Bravo G, Roy PM and Guay M (1996) Performance of the 'unaffected' upper extremity of elderly stroke patients. *Stroke* 27(9): 1564-1570

Desrosiers J, Malouin F, Bourbonnais D, Richards C, Rochette A and Bravo G (2003a) Arm and leg impairments and disabilities after stroke rehabilitation: relation to handicap. *Clinical Rehabilitation* 17(6): 666-673

Desrosiers J, Malouin F, Richards C, Bourbonnais D, Rochette A and Bravo G (2003b) Comparison of changes in upper and lower extremity impairments and disabilities after stroke. *Int J Rehabil Res* 26(2): 109-116

Devetten G, Coutts SB, Hill MD, Goyal M, Eesa M, O'brien B, Demchuk AM, Kirton A, Monitor and Groups VS (2010) Acute corticospinal tract Wallerian degeneration is associated with stroke outcome. *Stroke* 41(4): 751-756

Dewald J, Pope P, Given J, Buchanan T and Rymer W (1995) Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. *Brain* 118(Pt 2): 495-510

Dewald JP and Beer RF (2001) Abnormal joint torque patterns in the paretic upper limb of subjects with hemiparesis. *Muscle & Nerve* 24(2): 273-283

Dewald JP, Sheshadri V, Dawson ML and Beer RF (2001) Upper-limb discoordination in hemiparetic stroke: implications for neurorehabilitation. *Topics in Stroke Rehabilitation* 8(1): 1-12

Di Carlo A, Lamassa M, Pracucci G, Basile AM, Trefoloni G, Vanni P, Wolfe CDA, Tilling K, Ebrahim S and Inzitari D (1999) Stroke in the very old : clinical

presentation and determinants of 3-Month functional outcome: a European perspective. *Stroke* 30(11): 2313-2319

Di Fabio R and Emasithi A (1997) Aging and the mechanisms underlying head and postural control during voluntary motion. *Physical Therapy* 77: 458-475

Di Lazzaro V, Oliviero A, Profice P, Insola A, Mazzone P, Tonali P and Rothwell JC (1999) Direct demonstration of interhemispheric inhibition of the human motor cortex produced by transcranial magnetic stimulation. *Experimental Brain Research* 124(4): 520-524

Di Monaco M, Trucco M, Di Monaco R, Tappero R and Cavanna A (2010) The relationship between initial trunk control or postural balance and inpatient rehabilitation outcome after stroke: a prospective comparative study. *Clinical Rehabilitation* 24(6): 543-554

Di Piero V, Chollet FM, Maccarthy P, Lenzi GL and Frackowiak RS (1992) Motor recovery after acute ischaemic stroke: a metabolic study. *Journal of Neurology, Neurosurgery & Psychiatry* 55(11): 990-996

Dickstein R, Heffes Y, Laufer Y and Ben-Haim Z (1999) Activation of selected trunk muscles during symmetric functional activities in poststroke hemiparetic and hemiplegic patients. *Journal of Neurology, Neurosurgery & Psychiatry* 66(2): 218-221

Dickstein R, Sheffi S, Haim ZB, Shabtai E and Markovici E (2000) Activation of flexor and extensor trunk muscles in hemiparesis. *American Journal of Physical Medicine and Rehabilitation* 79(3): 228-234

Dickstein R, Shefi S, Marcovitz E and Villa Y (2004a) Anticipatory postural adjustment in selected trunk muscles in poststroke hemiparetic patients. *Archives of Physical Medicine and Rehabilitation* 85(2): 261-267

Dickstein R, Shefi S, Marcovitz E and Villa Y (2004b) Electromyographic activity of voluntarily activated trunk flexor and extensor muscles in post-stroke hemiparetic subjects. *Clinical Neurophysiology* 115(4): 790-796

Dipietro L, Krebs HI, Fasoli SE, Volpe BT and Hogan N (2009) Submovement changes characterize generalization of motor recovery after stroke. *Cortex* 45(3): 318-324

Dobkin BH (2005) Clinical practice: Rehabilitation after stroke. *New England Journal of Medicine* 352(16): 1677-1684

Dobkin BH and Dorsch A (2013) New evidence for therapies in stroke rehabilitation. *Current Atherosclerosis Reports* 15(6): 331-339

Donders AR, Van Der Heijden GJ, Stijnen T and Moons KG (2006) Review: a gentle introduction to imputation of missing values. *Journal of Clinical Epidemiology* 59(10): 1087-1091

Dounskaia N (2007) Kinematic invariants during cyclical arm movements. *Biological Cybernetics* 96(2): 147-163

Draganski B and May A (2008) Training-induced structural changes in the adult human brain. *Behavioural Brain Research* 192(1): 137-142

Dromerick AW and Reding MJ (1995) Functional outcome for patients with hemiparesis, hemihypesthesia, and hemianopsia: does Lesion location matter? *Stroke* 26(11): 2023-2026

Duarte E, Marco E, Muniesa JM, Belmonte R, Diaz P, Tejero M and Escalada F (2002) Trunk control test as a functional predictor in stroke patients. *Journal of Rehabilitation Medicine* 34(6): 267-272

Duncan PW, Goldstein LB, Horner RD, Landsman PB, Samsa GP and Matchar DB (1994) Similar motor recovery of upper and lower extremities after stroke. *Stroke* 25(6): 1181-1188

Duncan PW, Goldstein LB, Matchar D, Divine GW and Feussner J (1992) Measurement of motor recovery after stroke. Outcome assessment and sample size requirements. *Stroke* 23(8): 1084-1089

Duncan PW, Propst M and Nelson SG (1983) Reliability of the Fugl-Meyer assessment of sensorimotor recovery following cerebrovascular accident. *Physical Therapy* 63(10): 1606-1610

Duque J, Hummel F, Celnik P, Murase N, Mazzocchio R and Cohen LG (2005) Transcallosal inhibition in chronic subcortical stroke. *Neuroimage* 28(4): 940-946

Ebenbichler G and Oddsson L (2001) Sensory-motor control of the lower back: implications for rehabilitation. *Medicine & Science in Sports & Exercise* 33(11): 1889-1898

Edwards DF, Lang CE, Wagner JM, Birkenmeier R and Dromerick AW (2012) An evaluation of the Wolf Motor Function Test in motor trials early after stroke. *Archives of Physical Medicine and Rehabilitation* 93(4): 660-668

Edwards S (1996) An analysis of normal movement as the basis for the development of treament techniques IN*:* Edwards S (ed) *Neurological Physiotherapy : A problem-solving approach.* Edinburgh: Churchill Livingstone 15-40

Edwards WH (2010) *Motor Learning and Control: From Theory to Practice.* Belmont, CA, United States: Wadsworth, Cengage Learning

Edwardson MA, Lucas TH, Carey JR and Fetz EE (2013) New modalities of brain stimulation for stroke rehabilitation. *Experimental Brain Research* 224(3): 335-358

Efird J (2011) Blocked randomization with randomly selected block sizes. *International journal of Environmental Research and Public Health* 8(1): 15-20

Ellis MD, Acosta AM, Yao J and Dewald JP (2007) Position-dependent torque coupling and associated muscle activation in the hemiparetic upper extremity. *Experimental Brain Research* 176(4): 594-602

Endres M, Nyary I, Banhidi M and Deak G (1990) Stroke rehabilitation: A method and evaluation. *Int J Rehabil Res* 13(3): 225-236

Engels J (2003) Imputation of missing longitudinal data: a comparison of methods. *Journal of Clinical Epidemiology* 56(10): 968-976

English CK, Hillier SL, Stiller K and Warden-Flood A (2006) The sensitivity of three commonly used outcome measures to detect change amongst patients receiving inpatient rehabilitation following stroke. *Clinical Rehabilitation* 20(1): 52-55

Esparza DY, Archambault PS, Winstein CJ and Levin MF (2003) Hemispheric specialization in the co-ordination of arm and trunk movements during pointing in patients with unilateral brain damage. *Experimental Brain Research* 148(4): 488-497

Evans WJ and Campbell WW (1993) Sacropenia and age-related changes in body composition and functional capacity. *Journal of Nutrition* 123(2 Suppl): 465-468

Fallang B, Saugstad O and Hadders-Algra M (2000) Goal directed reaching and postural control in supine position in healthy infants. *Behavioural Brain Research* 115(1): 9-18

Fayad F, Roby-Brami A, Yazbeck C, Hanneton S, Lefevre-Colau MM, Gautheron V, Poiraudeau S and Revel M (2008) Three-dimensional scapular kinematics and scapulohumeral rhythm in patients with glenohumeral

osteoarthritis or frozen shoulder. *Journal of Biomechanics* 41(2): 326-332

Feeney DM and Baron JC (1986) Diaschisis. *Stroke* 17(5): 817-830

Feigin V, Barker-Collo S, Mcnaughton H, Brown P and Kerse N (2008) Long-term neuropsychological and functional outcomes in stroke survivors: current evidence and perspectives for new research. *International Journal of Stroke* 3(1): 33-40

Ferbert A, Caramia D, Priori A, Bertolasi L and Rothwell JC (1992) Cortical projection to erector spinae muscles in man as assessed by transcranial magnetic stimulation. *Electroencephalography and Clinical Neurophysiology* 85(6): 382-387

Fernald DH, Coombs L, Dealleaume L, West D and Parnes B (2012) An assessment of the Hawthorne Effect in practice-based research. *Journal of the American Board of Family Medicine* 25(1): 83-86

Feydy A (2002) Longitudinal study of motor recovery after stroke: recruitment and focusing of brain activation. *Stroke* 33(6): 1610-1617

Feys H, Hetebrij J, Wilms G, Dom R and De Weerdt W (2000) Predicting arm recovery following stroke: value of site of lesion. *Acta Neurologica Scandinavica* 102(6): 371-377

Feys HM, De Weerdt WJ, Selz BE, Cox Steck GA, Spichiger R, Vereeck LE, Putman KD and Van Hoydonck GA (1998) Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke : a single-blind, randomized, controlled multicenter trial. *Stroke* 29(4): 785-792

Field A (2009) *Discovering statistics using SPSS.* (3rd Edition) London: SAGE Publications Ltd

Finger S, Koehler PJ and Jagella C (2004) The Monakow concept of diaschisis: origins and perspectives. *Archives of Neurology* 61(2): 283-288

Finley M, Combs S, Carnahan K, Peacock S and Buskirk AV (2012) Comparison of “less affected limb” reaching kinematics in individuals with chronic stroke and healthy age-matched controls. *Physical & Occupational Therapy in Geriatrics* 30(3): 245-259

Fisher B (1987) Effect of trunk control and alignment on limb function. *Journal of Head Trauma Rehabilitation* 2(2): 72-79

Fitzek S, Fitzek C, Urban PP, Marx J, Hopf HC and Stoeter P (2001) Time course of lesion development in patients with acute brain stem infarction and correlation with NIHSS score. *European Journal of Radiology* 39(3): 180-185

Fitzmaurice GM, Laird NM and Ware JH (2004) *Applied longitudinal analysis.* Hoboken, New Jersey, USA: John Wiley & Sons

Foley N, Mcclure JA, Meyer M, Salter K, Bureau Y and Teasell R (2012) Inpatient rehabilitation following stroke : amount of therapy received and associations with functional recovery. *Disability and Rehabilitation* 34(25): 2132-2138

Foley N, Mehta S, Jutai J, Staines E and Teasell R (2013) Upper extremity interventions. *Evidence-based review of stroke rehabilitation* 2013:1-163 Available from: http://www.ebrsr.com/evidence-review/10-upper-extremity-interventions [Accessed 25th April 2015]

Font MA, Arboix A and Krupinski J (2010) Angiogenesis, neurogenesis and neuroplasticity in ischemic stroke. *Current Cardiology Reviews* 6(3): 238-244

Foroud A and Whishaw IQ (2006) Changes in the kinematic structure and non-kinematic features of movements during skilled reaching after stroke: a

Laban Movement Analysis in two case studies. *Journal of Neuroscience Methods* 158(1): 137-149

Forssberga H, Jucaitea A and Hadders-Algra M (1999) Shared memory representations for programming of lifting movements and associated whole body postural adjustments in humans. *Neuroscience Letters* 273(1): 9-12

Franchignoni F and Duarte E (2003) Psychometric properties and practical attributes of the trunk control test in stroke patients. *Journal of Rehabilitation Medicine* 35(3): 150-151

Franchignoni FP, Tesio L, Ricupero C and Martino MT (1997) Trunk control test as an early predictor of stroke rehabilitation outcome. *Stroke* 28(7): 1382-1385

Fridman EA, Hanakawa T, Chung M, Hummel F, Leiguarda RC and Cohen LG (2004) Reorganization of the human ipsilesional premotor cortex after stroke. *Brain* 127(Pt 4): 747-758

Fries W, Danek A, Scheidtmannl K and Hamburger C (1993) Motor recovery following capsular stroke: Role of descending pathways from multiple motor areas. *Brain* 116(Pt 2): 369-382

Fritz SL, Blanton S, Uswatte G, Taub E and Wolf SL (2009) Minimal detectable change scores for the Wolf Motor Function Test. *Neurorehabilitation and Neural Repair* 23(7): 662-667

Frykberg GE and Vasa R (2015) Neuroplasticity in action post-stroke: challenges for physiotherapists. *European Journal of Physiotherapy*: 1-10

Fuchs E and Flugge G (2014) Adult neuroplasticity: more than 40 years of research. *Neural Plasticity* 2014: 541870

Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S and Steglind S (1975) The poststroke hemiplegic patient : a method for evaluation of physical performance. *Scandinavian Journal of Rehabilitation Medicine* 7(1): 13-31

Fujita T, Sato A, Togashi Y, Kasahara R, Ohashi T and Yamamoto Y (2015) Contribution of abdominal muscle strength to various activities of daily living of stroke patients with mild paralysis. *Journal of Physical Therapy Science* 27(3): 815-818

Fujiwara T, Liu M, Tsuji T, Sonoda S, Mizuno K, Akaboshi K, Hase K, Masakado Y and Chino N (2004) Development of a new measure to assess trunk impairment after stroke (Trunk Impairment Scale). *American Journal of Physical Medicine and Rehabilitation* 83(9): 681-688

Fujiwara T, Sonoda S, Okajima Y and Chino N (2001) The relationships between trunk function and the findings of transcranial magnetic stimulation among patients with stroke. *Journal of Rehabilitation Medicine* 33(6): 249-255

Furlan M, Marchal M, Derlon J-M, Baron JC and Viade F (1996) Spontaneous neurological recovery after stroke and the fate of the ischemic penumbra. *Annals of Neurology* 40(2): 216-226

Gandavadi A and Ramsay J (2005) Effect of two seating positions on upper limb function in normal subjects. *International Journal of Therapy and Rehabilitation* 12(11): 485-490

Garland S, Stevenson T and Ivanova T (1997) Postural responses to unilateral arm perturbation in young, elderly, and hemiplegic subjects. *Archives of Physical Medicine and Rehabilitation* 78(10): 1072-1077

Gebruers N, Truijen S, Engelborghs S and De Deyn PP (2014) Prediction of upper limb recovery, general disability, and rehabilitation status by activity measurements assessed by accelerometers or the fugl-meyer score in acute stroke. *American Journal of Physical Medicine and Rehabilitation* 93(3): 245-252

Geyh S, Cieza A, Schouten J, Dickson H, Frommelt P, Omar Z, Kostanjsek N, Ring H and Stucki G (2004) ICF core sets for stroke. *Journal of Rehabilitation Medicine* (44 Suppl): 135-41

Ghafouri M and Feldman AG (2001) The timing of control signals underlying fast point-to-point arm movements. *Experimental Brain Research* 137(3-4): 411-423

Ghasemi A and Zahediasl S (2012) Normality tests for statistical analysis: a guide for non-statisticians. *International Journal of Endocrinology and Metabolism* 10(2): 486-489

Gialanella B, Santoro R and Ferlucci C (2012) Predicting outcome after stroke: the role of basic activities of daily living. *European Journal of Physical and Rehabilitation Medicine* 48(5): 1-9

Gibbons RD, Hedeker D and Dutoit S (2010) Advances in analysis of longitudinal data. *Annual Review of Clinical Psychology* 6: 79-107

Gillen G (1998) Trunk control : a prerequisite for functional independence IN*:* Gillen G and Burkhardt A (eds) *Stroke rehabilitation. A function-based approach.* St Louis: Mosby 69-89

Gillen G, Boiangiu C, Neuman M, Reinstein R and Schaap Y (2007) Trunk posture affects upper extremity function of adults. *Perceptual and Motor Skills* 104(2): 371-380

Gillick BT and Zirpel L (2012) Neuroplasticity: an appreciation from synapse to system. *Archives of Physical Medicine and Rehabilitation* 93(10): 1846-1855

Girolami GL, Shiratori T and Aruin AS (2011) Anticipatory postural adjustments in children with hemiplegia and diplegia. *Journal of Electromyography and Kinesiology* 21(6): 988-997

Gjelsvik BEB (2008) *The Bobath concept in adult neurology.* Stuttgart, Germany: Georg Thieme Vorlag

Gladstone DJ, Danells CJ and Black SE (2002) The Fugl-Meyer assessment of motor recovery after stroke : a critical review of its measurement properties. *Neurorehabilitation and Neural Repair* 16(3): 232-240

Glees P and Cole J (1950) Recovery of skilled motor functions after small repeated lesions of motor cortex in macaque. *Journal of Neurophysiology* 13(2): 137-148

Globas C, Lam JM, Zhang W, Imanbayev A, Hertler B, Becker C, Whitall J, Mccombe-Waller S, Mori S, Hanley DF and Luft AR (2011) Mesencephalic corticospinal atrophy predicts baseline deficit but not response to unilateral or bilateral arm training in chronic stroke. *Neurorehabilitation and Neural Repair* 25(1): 81-87

Goldstein LB and Davis JN (1990) Restorative neurology. Drugs and recovery following stroke. *Stroke* 21(11): 1636-1640

Goodvin C, Park EJ, Huang K and Sakaki K (2006) Development of a real-time three-dimensional spinal motion measurement system for clinical practice. *Medical & Biological Engineering & Computing* 44(12): 1061-1075

Goodwin N and Sunderland A (2003) Intensive, time-series measurement of upper limb recovery in the subacute phase following stroke. *Clinical Rehabilitation* 17(1): 69-82

Govender P and Kalra L (2007) Benefits of occupational therapy in stroke rehabilitation. *Expert Review of Neurotherapeutics* 7(8): 1013-1019

Gowland C, Stratford P, Ward M, Moreland J, Torresin W, Van Hullenaar S, Sanford J, Barreca S, Vanspall B and Plews N (1993) Measuring physical impairment and disability with the Chedoke-McMaster Stroke Assessment. *Stroke* 24(1): 58-63

Granacher U, Gollhofer A, Hortobágyi T, Kressig RW and Muehlbauer T (2013) The importance of trunk muscle strength for balance, functional performance, and fall prevention in seniors: a systematic review. *Sports Medcine* 43(7): 627-641

Granata KP, Slota GP and Bennett BC (2004) Paraspinal muscle reflex dynamics. *Journal of Biomechanics* 37(2): 241-247

Gray V, Rice CL and Garland SJ (2012) Factors that influence muscle weakness following stroke and their clinical implications: a critical review. *Physiotherapy Canada* 64(4): 415-426

Green JB (2003) Brain reorganization after stroke. *Topics in Stroke Rehabilitation* 10(3): 1-20

Greenwood N and Mackenzie A (2010) Informal caring for stroke survivors : Meta-ethnographic review of qualitative literature. *Maturitas* 66(3): 268-276

Grenier A and Amiel-Tison C (1981) Liberated-motricity by holding the head during the 1st weeks of life. *Archives Françaises de Pédiatrie* 38(8): 557-561

Groisser BN, Copen WA, Singhal AB, Hirai KK and Schaechter JD (2014) Corticospinal tract diffusion abnormalities early after stroke predict motor outcome. *Neurorehabilitation and Neural Repair* 28(8): 751-760

Hadjidj A, Souil M, Bouabdallah A, Challal Y and Owen H (2013) Wireless sensor networks for rehabilitation applications: Challenges and opportunities. *Journal of Network and Computer Applications* 36(1): 1-15

Hafer-Macko C, Ryan A, Ivey F and Macko R (2008) Skeletal muscle changes after hemiparetic stroke and potential beneficial effects of exercise intervention strategies. *Journal of Rehabilitation Research and Development* 45(2): 261-272

Hallet M (2001) Plasticity of the human motor cortex and recovery from stroke. *Brain Research Reviews* 36(2-3): 169-174

Hallet M (2005) Neuroplasticity and rehabilitation. *Journal of Rehabilitation Research and Development* 42(4): xvii-xxi

Hammond MC, Fitts SS, Kraft GH, Nutter PB, Trotter MJ and Robinson LM (1988) Co-contraction in the hemiparetic forearm: quantitative EMG evaluation. *Archives of Physical Medicine and Rehabilitation* 69(5): 348-351

Han CE, Kim S, Chen S, Lai YH, Lee JY, Osu R, Winstein CJ and Schweighofer N (2013) Quantifying arm nonuse in individuals poststroke. *Neurorehabilitation and Neural Repair* 27(5): 439-447

Hand PJ, Wardlaw JM, Rivers CS, Armitage PA, Bastin ME, Lindley RI and Dennis MS (2006) MR diffusion-weighted imaging and outcome prediction after ischemic stroke. *Neurology* 66(8): 1159-1163

Hardwick DD and Lang CE (2011a) Scapula and humeral movement patterns and their relationship with pain. *International Journal of Therapy and Rehabilitation* 18(4): 210-220

Hardwick DD and Lang CE (2011b) Scapular and humeral movement patterns of people with stroke during range-of-motion exercises. *Journal of Neurologic Physical Therapy* 35(1): 18-25

Harris JE and Eng JJ (2007) Paretic upper-limb strength best explains arm activity in people with stroke. *Physical Therapy* 87(1): 88-97

Harris JE and Eng JJ (2010) Strength training improves upper-limb function in individuals with stroke: a meta-analysis. *Stroke* 41(1): 136-140

Hart T, Kozlowski AJ, Whyte J, Poulsen I, Kristensen K, Nordenbo A and Heinemann AW (2014) Functional recovery after severe traumatic brain injury: an individual growth curve approach. *Archives of Physical Medicine and Rehabilitation* 95(11): 2103-2110

Hatakenaka M, Miyai I, Sakoda S and Yanagihara T (2007) Proximal paresis of the upper extremity in patients with stroke. *Neurology* 69(4): 348-355

Hayward KS, Barker RN, Carson RG and Brauer SG (2014) The effect of altering a single component of a rehabilitation programme on the functional recovery of stroke patients: a systematic review and meta-analysis. *Clinical Rehabilitation* 28(2): 107-117

Healthcare for London (2009) *Stroke rehabilitation guide: supporting London commissioners to commission quality services in 2010/11.* London: Healthcare for London

Hedeker D, Gibbons RD and Waternaux C (1999) Sample size estimation for longitudinal designs with attrition: comparing time-related contrasts between two groups. *Journal of Educational and Behavioral Statistics* 24(1): 70-93

Heller A, Wade DT, Wood VA, Sunderland A, Hewer RL and Ward E (1987) Arm function after stroke : measurement and recovery over the first three months. *Journal of Neurology, Neurosurgery & Psychiatry* 50(6): 714-719

Hendricks HT, Pasman JW, Van Limbeek J and Zwarts MJ (2003) Motor evoked potentials in predicting recovery from upper extremity paralysis after acute stroke. *Cerebrovascular Diseases* 16(3): 265-271

Hendricks HT, Van Limbeek J, Geurts AC and Zwarts MJ (2002) Motor recovery after stroke: A systematic review of the literature. *Archives of Physical Medicine and Rehabilitation* 83(11): 1629-1637

Hermsdorfer J, Laimgruber K, Kerkhoff G, Mai N and Goldenberg G (1999) Effects of unilateral brain damage on grip selection, coordination, and kinematics of ipsilesional prehension. *Experimental Brain Research* 128(1-2): 41-51

Heuschmann PU, Grieve AP, Toschke AM, Rudd AG and Wolfe CD (2008) Ethnic group disparities in 10-year trends in stroke incidence and vascular risk factors: the South London Stroke Register (SLSR). *Stroke* 39(8): 2204-2210

Hewett TE, Ford KR, Levine P and Page SJ (2007) Reaching kinematics to measure motor changes after mental practice in stroke. *Topics in Stroke Rehabilitation* 14(4): 23-29

Heyrman L, Desloovere K, Molenaers G, Verheyden G, Klingels K, Monbaliu E and Feys H (2013) Clinical characteristics of impaired trunk control in children with spastic cerebral palsy. *Research in Developmental Disabilities* 34(1): 327-334

Hidaka Y, Han CE, Wolf SL, Winstein CJ and Schweighofer N (2012) Use it and improve it or lose it: interactions between arm function and use in humans post-stroke. *PLoS Computational Biology* 8(2): e1002343

Higgins J, Mayo NE, Desrosiers J, Salbach NM and Ahmed S (2005) Upper-limb function and recovery in the acute phase poststroke. *Journal of Rehabilitation Research and Development* 42(1): 65-76

Higo N (2010) Training-induced recovery of manual dexterity after a lesion in the motor cortex. *Keio Journal of Medicine* 59(1): 4-9

Higo N (2014) Effects of rehabilitative training on recovery of hand motor function: A review of animal studies. *Neuroscience Ressearch* 78: 9-15

Hingtgen B, Mcguire JR, Wang M and Harris GF (2006) An upper extremity kinematic model for evaluation of hemiparetic stroke. *Journal of Biomechanics* 39(4): 681-688

Hinkle DE, Wiersma W and Jurs SG (2003) *Applied Statistics for the Behavioral Sciences.* (5th Edition) Boston, United States: Houghton Mifflin

Hlustík P and Mayer M (2006) Paretic hand in stroke: from motor cortical plasticity research to rehabilitation. *Cognitive and Behavioral Neurology* 19(1): 34-40

Hodges PW, Cresswell AG, Daggfeldt K and Thorstensson A (2000) Three dimensional preparatory trunk motion precedes asymmetrical upper limb movement. *Gait & Posture* 11(2): 92-101

Hodges PW and Richardson CA (1997) Relationship between limb movement speed and associated contraction of the trunk muscles. *Ergonomics* 40(11): 1220-1230

Hopkins B and RoNnqvist L (2002) Facilitating postural control: effects on the reaching behavior of 6-month-old infants. *Developmental Psychobiology* 40(2): 168-182

Horak F, Esselman P, Anderson M and Lynch M (1984) The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. *Journal of Neurology, Neurosurgery & Psychiatry* 47(9): 1020-1028

Horstman AM, Gerrits KH, Beltman MJ, Koppe PA, Janssen TW and De Haan A (2010) Intrinsic properties of the knee extensor muscles after subacute stroke. *Archives of Physical Medicine and Rehabilitation* 91(1): 123-128

Houwink A, Nijland RH, Geurts AC and Kwakkel G (2013) Functional recovery of the paretic upper limb after stroke: who regains hand capacity? *Archives of Physical Medicine and Rehabilitation* 94(5): 839-844

Howlett OA, Lannin NA, Ada L and Mckinstry C (2015) Functional electrical stimulation improves activity after atroke: a systematic review with meta-analysis. *Archives of Physical Medicine and Rehabilitation* 96(5): 934-943

Hoyer EH and Celnik PA (2011) Understanding and enhancing motor recovery after stroke using transcranial magnetic stimulation. *Restorative Neurology and Neuroscience* 29(6): 395-409

Hsieh C, Sheu C, Hsueh I and Wang C (2002) Trunk control as an early predictor of comprehensive activities of daily living function in stroke patients. *Stroke* 33(11): 2626-2630

Hsieh YW, Wu CY, Lin KC, Chang YF, Chen CL and Liu JS (2009) Responsiveness and validity of three outcome measures of motor function after stroke rehabilitation. *Stroke* 40(4): 1386-1391

Hsueh IP, Hsu MJ, Sheu CF, Lee S, Hsieh CL and Lin JH (2008) Psychometric comparisons of 2 versions of the Fugl-Meyer Motor Scale and 2 versions of the Stroke Rehabilitation Assessment of Movement. *Neurorehabilitation and Neural Repair* 22(6): 737-744

Hubbard IJ, Carey LM, Budd TW and Parsons MW (2015) Reorganizing therapy: changing the clinical approach to upper limb recovery post-stroke. *Occupational Therapy International* 22(1): 28-35

Hummel F, Kirsammer R and Gerloff C (2003) Ipsilateral cortical activation during finger sequences of increasing complexity: representation of movement difficulty or memory load? *Clinical Neurophysiology* 114(4): 605-613

Ibrahim JG and Molenberghs G (2009) Missing data methods in longitudinal studies: a review. *TEST* 18(1): 1-43

Infeld B, Davis SM, Lichtenstein M, Mitchell PJ and Hopper JL (1995) Crossed cerebellar diaschisis and brain recovery after stroke. *Stroke* 26(1): 90-95

Ingram JN, Kording KP, Howard IS and Wolpert DM (2008) The statistics of natural hand movements. *Experimental Brain Research* 188(2): 223-236

Inman VT, Saunders JB and Abbott LC (1944) Observations on function of the shoulder joint. *Journal of Bone and Joint Surgery* 26(330): 1-30

Jacobs K and Donoghue JP (1991) Reshaping the cortical motor map by unmasking latent intracortical connections. *Science* 251(4996): 944-947

Jang SH (2009a) A review of the ipsilateral motor pathway as a recovery mechanism in patients with stroke. *NeuroRehabilitation* 24(4): 315-320

Jang SH (2009b) The role of the corticospinal tract in motor recovery in patients with a stroke: a review. *NeuroRehabilitation* 24(3): 285-290

Jang SH (2012) Motor outcome and motor recovery mechanisms in pontine infarct: a review. *NeuroRehabilitation* 30(2): 147-152

Jang SH (2013) Motor function-related maladaptive plasticity in stroke: a review. *NeuroRehabilitation* 32(2): 311-316

Jang SH, Han BS, Chang Y, Byun WM, Lee J and Ahn SH (2002) Functional MRI evidence for motor cortex reorganization adjacent to a lesion in a primary motor cortex. *American Journal of Physical Medicine and Rehabilitation* 81(11): 844-847

Jang SH, Kim YH, Cho SH, Lee JH, Park JW and Kwon YH (2003) Cortical reorganization induced by task-oriented training in chronic hemiplegic stroke patients. *Neuroreport* 14(1): 137-141

Jette DU, Warren RL and Wirtalla C (2005) The relation between therapy intensity and outcomes of rehabilitation in skilled nursing facilities. *Archives of Physical Medicine and Rehabilitation* 86(3): 373-379

Jijimol G, Fayaz RK and Vijesh PV (2013) Correlation of trunk impairment with balance in patients with chronic stroke. *NeuroRehabilitation* 32(2): 323-325

Johansen-Berg H, Dawes H, Guy C, Smith SM, Wade DT and Matthews PM (2002) Correlation between motor improvements and altered fMRI activity after rehabilitative therapy. *Brain* 125(Pt 12): 2731-2742

Johnston S, Mendis S and Mathers C (2009) Global variation in stroke burden and mortality: estimates from monitoring, surveillance, and modelling. *Lancet Neurology* 8(4): 345-354

Jones RD, Donaldson IM and Parkin PJ (1989) Impairment and recovery of ipsilateral sensory-motor function following unilateral cerebral infarction. *Brain* 112(Pt 1): 113-132

Jorgensen H, Nakayama H, Raaschou H, Vive-Larsen J, Stoier M and Olsen T (1995) Outcome and time course of recovery in stroke. Part II: Time course of recovery. The Copenhagen Stroke Study. *Archives of Physical Medicine and Rehabilitation* 76(5): 406-412

Jung HY, Yoon JS and Park BS (2002) Recovery of proximal and distal arm weakness in the ipsilateral upper limb after stroke. *NeuroRehabilitation* 17(2): 153-159

Kaminski TR, Bock C and Gentile AM (1995) The coordination between trunk and arm motion during pointing movements. *Experimental Brain Research* 106(3): 457-466

Kamper DG, Mckenna-Cole AN, Kahn LE and Reinkensmeyer DJ (2002) Alterations in reaching after stroke and their relation to movement direction and impairment severity. *Archives of Physical Medicine and Rehabilitation* 83(5): 702-707

Kamper DG and Rymer WZ (2001) Impairment of voluntary control of finger motion following stroke : role of inappropriate muscle coactivation. *Muscle & Nerve* 24(5): 673-681

Kandel M, Beis JM, Le Chapelain L, Guesdon H and Paysant J (2012) Non-invasive cerebral stimulation for the upper limb rehabilitation after stroke: a review. *Annals of Physical and Rehabilitation Medicine* 55(9-10): 657-680

Karatas M, Cetin N, Bayramoglu M and Dilek A (2004) Trunk muscle strength in relation to balance and functional disability in unihemispheric stroke patients. *American Journal of Physical Medicine and Rehabilitation* 83(2): 81-87

Karduna AR, Mcclure PW and Michener LA (2000) Scapular kinematics: effects of altering the Euler angle sequence of rotations. *Journal of Biomechanics* 33: 1063-1068

Karnath H-O and Broetz D (2003) Understanding and treating 'pusher syndrome'. *Physical Therapy* 83(12): 1119-1125

Karni A, Meyer G, Jezzard P, Adams MM, Turner R and Ungerleider LG (1995) Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature* 377(6545): 155-158

Karthikbabu S, Nayak A, Vijayakumar K, Misri Z, Suresh B, Ganesan S and Joshua AM (2011a) Comparison of physio ball and plinth trunk exercises regimens on trunk control and functional balance in patients with acute stroke: a pilot randomized controlled trial. *Clinical Rehabilitation* 25(8): 709-719

Karthikbabu S, Rao BK, Manikandan N, Solomon JM, Chakrapani M and Nayak A (2011b) Role of trunk rehabilitation on trunk control, balance and gait in patients with chronic stroke: a pre-post design. *Neuroscience & Medicine* 2: 61-67

Katrak P, Bowring G, Conroy P, Chilvers M, Poulos R and Mcneil D (1998) Predicting upper limb recovery after stroke: the place of early shoulder and hand movement. *Archives of Physical Medicine and Rehabilitation* 79(7): 758-761

Kerr AL, Cheng SY and Jones TA (2011) Experience-dependent neural plasticity in the adult damaged brain. *Journal of Communication Disorders* 44(5): 538-548

Ketcham CJ, Rodriguez TM and Zihlman KA (2007) Targeted aiming movements are compromised in nonaffected limb of persons with stroke. *Neurorehabilitation and Neural Repair* 21(5): 388-397

Kibler B and Mcmullen J (2003) Scapular dyskinesis and its relation to shoulder pain. *Journal of the American Academy of Orthopaedic Surgeons* 11(2): 142-151

Kibler WB, Press J and Sciascia A (2006) The role of core stability in athletic function. *Sports Medicine* 36(3): 189-198

Kibler WB and Sciascia A (2010) Current concepts: scapular dyskinesis. *British Journal of Sports Medicine* 44(5): 300-305

Kılınç M, Avcu F, Onursal O, Ayvat E, Savcun Demirci C and Aksu Yildirim S (2015) The effects of Bobath-based trunk exercises on trunk control, functional capacity, balance, and gait: a pilot randomized controlled trial. *Topics in Stroke Rehabilitation*: Published online 10 Aug 2015

Kim BH, Lee SM, Bae YH, Yu JH and Kim TH (2012) The effect of a task-oriented training on trunk control ability, balance and gait of stroke patients. *Journal of Physical Therapy Science* 24(6): 519-522

Kim TJ, Seo KM, Kim DK and Kang SH (2015) The relationship between initial trunk performances and functional prognosis in patients with stroke. *Annals of Rehabilitation Medicine* 39(1): 66-73

Kim Y, Shim JK, Hong YK, Lee SH and Yoon BC (2013) Cutaneous sensory feedback plays a critical role in agonist-antagonist co-activation. *Experimental Brain Research* 229(2): 149-156

Kim YH, Jang SH, Byun WM, Han BS, Lee KH and Ahn SH (2004) Ipsilateral motor pathway confirmed by combined brain mapping of a patient with hemiparetic stroke: a case report. *Archives of Physical Medicine and Rehabilitation* 85(8): 1351-1353

Kim YH, Kim EJ and Gong WT (2011) The effects of trunk stability exercise using PNF on the Functional Reach Test and muscle activities of stroke patients. *Journal of Physical Therapy Science* 23: 699-702

Kinsella K and He W (2009) *An Aging World: 2008.* Washington, DC, United States of America: U.S. Government Printing Office

Kitago T and Krakauer JW (2013) Motor learning principles for neurorehabilitation. *Handbook of Clinical Neurology* 110: 93-103

Kitago T, Liang J, Huang VS, Hayes S, Simon P, Tenteromano L, Lazar RM, Marshall RS, Mazzoni P, Lennihan L and Krakauer JW (2013) Improvement after constraint-induced movement therapy: recovery of normal motor control or task-specific compensation? *Neurorehabilitation and Neural Repair* 27(2): 99-109

Kleim JA (2011) Neural plasticity and neurorehabilitation: teaching the new brain old tricks. *Journal of Communication Disorders* 44(5): 521-528

Kleim JA, Barbay S, Cooper NR, Hogg TM, Reidel CN, Remple MS and Nudo RJ (2002) Motor learning-dependent synaptogenesis is localized to functionally reorganized motor cortex. *Neurobiology of Learning and Memory* 77(1): 63-77

Kleim JA, Hogg TM, Vandenberg PM, Cooper NR, Bruneau R and Remple M (2004) Cortical synaptogenesis and motor map reorganization occur during late, but not early, phase of motor skill learning. *Journal of Neuroscience* 24(3): 628-633

Kleim JA and Jones TA (2008) Principles of experience-dependent neural plasticity- implications for rehabilitation after brain damage. *Journal of Speech, Language, and Hearing Research* 51(1): S225-S239

Kleim JA, Lussnig E, Schwarz ER, Comery TA and Greenough WT (1996) Synaptogenesis and FOS expression in the motor cortex of the adult rat after motor skill learning. *Journal of Neuroscience* 16(14): 4529-4535

Knapp M, Comas-Herrera A, Somani A and Banerjee S (2007) *Dementia: international comparisons (Summary report for the National Audit Office).* London: Personal Social Services Research Unit, London School of Economics and Political Science

Koh CL, Pan SL, Jeng JS, Chen BB, Wang YH, Hsueh IP and Hsieh CL (2015) Predicting recovery of voluntary upper extremity movement in subacute stroke patients with severe upper extremity paresis. *PLoS One* 10(5): e0126857

Kolb B and Muhammad A (2014) Harnessing the power of neuroplasticity for intervention. *Frontiers in Human Neuroscience* 8: 377

Konczak J and Dichgans J (1997) The development toward stereotypic arm kinematics during reaching in the first 3 years of life. *Experimental Brain Research* 117: 346-354

Kong KH, Chua KS and Lee J (2011) Recovery of upper limb dexterity in patients more than 1 year after stroke: Frequency, clinical correlates and predictors. *NeuroRehabilitation* 28(2): 105-111

Kong KH and Lee J (2013) Temporal recovery and predictors of upper limb dexterity in the first year of stroke: A prospective study of patients admitted to a rehabilitation centre. *NeuroRehabilitation* 13(2): 345-350

Konishi J, Yamada K, Kizu O, Ito H, Sugimura K, Yoshikawa K, Nakagawa M and Nishimura T (2005) MR tractography for the evaluation of functional recovery from lenticulostriate infarcts. *Neurology* 64(1): 108-113

Kontaxis A, Cutti AG, Johnson GR and Veeger HEJ (2009) A framework for the definition of standardized protocols for measuring upper-extremity kinematics. *Clinical Biomechanics* 24: 246-253

Kopp B, Kunkel A, Flor H, Platz T, Rose U, Mauritz KH, Gresser K, Mcculloch KL and Taub E (1997) The Arm Motor Ability Test: reliability, validity, and sensitivity to change of an instrument for assessing disabilities in activities of daily living. *Archives of Physical Medicine and Rehabilitation* 78(6): 615-620

Korner-Bitensky N (2013) When does stroke rehabilitation end? *International Journal of Stroke* 8(1): 8-10

Kou N, Park CH, Seghier ML, Leff AP and Ward NS (2013) Can fully automated detection of corticospinal tract damage be used in stroke patients? *Neurology* 80(24): 2242-2245

Koyama T, Matsumoto K, Okuno T and Domen K (2005) A new method for predicting functional recovery of stroke patients with hemiplegia: logarithmic modelling. *Clinical Rehabilitation* 19(7): 779-789

Kozlowski AJ and Heinemann AW (2013) Using individual growth curve models to predict recovery and activities of daily living after spinal cord injury: an SCIRehab project study. *Archives of Physical Medicine and Rehabilitation* 94(4 Suppl): S154-S164

Kozlowski AJ, Pretz CR, Dams-O'connor K, Kreider S and Whiteneck G (2013) An introduction to applying individual growth curve models to evaluate change in rehabilitation: a National Institute on Disability and Rehabilitation Research Traumatic Brain Injury Model Systems report. *Archives of Physical Medicine and Rehabilitation* 94(3): 589-596

Krebs C, Weinberg J and Akesson EJ (2012) Descending motor tracts IN*:* Harvey RA (ed) *Neuroscience (Lippincott's Illustrated Reviews Series).* Philadelphia, Pennsylvania, USA: Lippincott Williams & Wilkins

Kristian T and Siesjo BK (1998) Calcium in ischemic cell death. *Stroke* 29(3): 705-718

Kristián T and Siesjö BK (1997) Changes in ionic fluxes during cerebral ischaemia. *International Review of Neurobiology* 40: 27-45

Kung PC, Lin CCK, Ju MS and Chen SM (2012) Reducing abnormal synergies of forearm, elbow, and shoulder joints in stroke patients with neuro-rehabilitation robot treatment and assessment. *Journal of Medical and Biological Engineering* 32(2): 139-146

Kurtais Y, Kucukdeveci A, Elhan A, Yilmaz A, Kalli T, Tur BS and Tennant A (2009) Psychometric properties of the Rivermead Motor Assessment: its utility in stroke. *Journal of Rehabilitation Medicine* 41(13): 1055-1061

Kuypers HGJM (1981) Anatomy of the descending pathways IN*:* Brookhart JM, Mountcastle VB and Brooks VB (eds) *Handbook of physiology. Sect. 1, Vol. II, Pt. 1.* Bethesda: American Physiology Society 597-666

Kwakkel G and Kollen B (2007) Predicting improvement in the upper paretic limb after stroke: a longitudinal prospective study. *Restorative Neurology and Neuroscience* 25(5-6): 453-460

Kwakkel G, Kollen B and Lindeman E (2004) Understanding the pattern of functional recovery after stroke. *Restorative Neurology and Neuroscience* 22(3-5): 281-299

Kwakkel G, Kollen B and Twisk J (2006) Impact of time on improvement of outcome after stroke. *Stroke* 37(9): 2348-2353

Kwakkel G and Kollen BJ (2013) Predicting activities after stroke: what is clinically relevant? *International Journal of Stroke* 8(1): 25-32

Kwakkel G, Kollen BJ, Van Der Grond J and Prevo AJ (2003) Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke. *Stroke* 34(9): 2181-2186

Kwakkel G, Kollen BJ and Wagenaar RC (2002) Long-term effects of intensity of upper and lower limb training after stroke : a randomised trial. *Journal of Neurology, Neurosurgery & Psychiatry* 72(4): 473-479

Kwakkel G and Meskers CGM (2014) Effects of robotic therapy of the arm after stroke. *Lancet Neurology* 13(2): 132-133

Kwakkel G, Veerbeek JM, Van Wegen EEH and Wolf SL (2015) Constraint-induced movement therapy after stroke. *Lancet Neurology* 14(2): 224-234

Kwakkel G, Wagenaar RC, Twisk JW, Lankhorst GJ and Koetsier JC (1999) Intensity of leg and arm training after primary middle-cerebral-artery stroke : a randomized trial. *Lancet* 354(9174): 191-196

Kwon HY, Lee CH, Ahn SH, Lee MY, Yang DS, Byun WM, Park JW and Jang SH (2007a) Motor recovery via the peri-infarct area in patients with corona radiata infarct. *NeuroRehabilitation* 22(2): 105-108

Kwon YH, Lee MY, Park JW, Kang JH, Yang DS, Kim YH, Ahn SH and Jang SH (2007b) Differences of cortical activation pattern between cortical and corona radiata infarct. *Neuroscience Letters* 417(2): 138-142

Lai SM, Duncan PW, Keighley J and Johnson D (2002a) Depressive symptoms and independence in BADL and IADL. *Journal of Rehabilitation Research and Development* 39(5): 589-596

Lai SM, Studenski S, Duncan P and Perera S (2002b) Persisting consequences of stroke measured by the Stroke Impact Scale. *Stroke* 33(7): 1840-1844

Lang CE and Beebe JA (2007) Relating movement control at 9 upper extremity segments to loss of hand function in people with chronic hemiparesis. *Neurorehabilitation and Neural Repair* 21(3): 279-291

Lang CE, Bland MD, Bailey RR, Schaefer SY and Birkenmeier RL (2013) Assessment of upper extremity impairment, function, and activity after stroke: foundations for clinical decision making. *Journal of Hand Therapy* 26(2): 104-115

Lang CE, Dejong SL and Beebe JA (2009a) Recovery of thumb and finger extension and its relation to grasp performance after stroke. *Journal of Neurophysiology* 102(1): 451-459

Lang CE, Edwards DF, Birkenmeier RL and Dromerick AW (2008) Estimating minimal clinically important differences of upper-extremity measures early after stroke. *Archives of Physical Medicine and Rehabilitation* 89(9): 1693-1700

Lang CE, Macdonald JR, Reisman DS, Boyd L, Jacobson Kimberley T, Schindler-Ivens SM, Hornby TG, Ross SA and Scheets PL (2009b) Observation of amounts of movement practice provided during stroke rehabilitation. *Archives of Physical Medicine and Rehabilitation* 90(10): 1692-1698

Lang CE and Schieber MH (2003) Differential impairment of individuated finger movements in humans after damage to the motor cortex or the corticospinal tract. *Journal of Neurophysiology* 90(2): 1160-1170

Lang CE and Schieber MH (2004) Reduced muscle selectivity during individuated finger movements in humans after damage to the motor cortex or corticospinal tract. *Journal of Neurophysiology* 91(4): 1722-1733

Lang CE, Wagner JM, Bastian AJ, Hu Q, Edwards DF, Sahrmann SA and Dromerick AW (2005) Deficits in grasp versus reach during acute hemiparesis. *Experimental Brain Research* 166(1): 126-136

Lang CE, Wagner JM, Edwards DF, Sahrmann SA and Dromerick AW (2006) Recovery of grasp versus reach in people with hemiparesis poststroke. *Neurorehabilitation and Neural Repair* 20(4): 444-454

Langer N, Hanggi J, Muller NA, Simmen HP and Jancke L (2012) Effects of limb immobilization on brain plasticity. *Neurology* 78(3): 182-188

Langhorne P, Bernhardt J and Kwakkel G (2011) Stroke rehabilitation. *Lancet* 377(9778): 1693-1702

Langhorne P, Coupar F and Pollock A (2009) Motor recovery after stroke: a systematic review. *Lancet Neurology* 8(8): 741-754

Latash M, Levin M, Scholz J and Schoner G (2010) Motor control theories and their applications. *Medicina (Kaunas)* 46(6): 382–392

Latash ML and Anson J (1996) What are "normal movements in atypical populations? *Behavioural Brain Research* 19(1): 55-106

Lawrence ES, Coshall C, Dundas R, Stewart J, Rudd AG, Howard R and Wolfe CDA (2001) Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population. *Stroke* 32(6): 1279-1284

Lazar R, Dunn L, Schweber A, Manson D, Lendaris A and Marshall R (2014) Inter-individual variability in motor and language recovery during the acute stroke period *Neurology* 82(10): Supplement P1.136

Lee HM, Li PC and Fan SC (2015a) Delayed mirror visual feedback presented using a novel mirror therapy system enhances cortical activation in healthy adults. *Journal of NeuroEngineering & Rehabilitation* 12: 56

Lee KB, Lim SH, Kim KH, Kim KJ, Kim YR, Chang WN, Yeom JW, Kim YD and Hwang BY (2015b) Six-month functional recovery of stroke patients: a multi-time-point study. *International Journal of Rehabilitation Research* 38(2): 173-180

Lee L, Coppieters MW and Hodges PW (2009) Anticipatory postural adjustments to arm movement reveal complex control of paraspinal muscles in the thorax. *Journal of Electromyography and Kinesiology* 19(1): 46-54

Lee M, Hinder MR, Gandevia SC and Carroll TJ (2010) The ipsilateral motor cortex contributes to cross-limb transfer of performance gains after ballistic motor practice. *Journal of Physiology* 588(Pt 1): 201-212

Lee S, Shafe AC and Cowie MR (2011) UK stroke incidence, mortality and cardiovascular risk management 1999-2008: time-trend analysis from the General Practice Research Database. *British Medical Journal Open* 1(2): e000269

Lee WA (1989) A control systems framework for understanding normal and abnormal posture. *American Journal of Occupational Therapy* 43(5): 291-301

Lemon RN (2008) Descending pathways in motor control. *Annual Review of Neuroscience* 31: 195-218

Lenzenweger MF, Johnson MD and Willett JB (2004) Individual growth curve analysis illuminates stability and change in personality disorder features. *Archives of General Psychiatry* 61(10): 1015-1024

Levin M (1996a) Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain* 119(Pt 1): 281-293

Levin MF (1996b) Should stereotypic movement synergies seen in hemiparetic patients be considered adaptive? *Behavioural Brain Research* 19(1): 79-80

Levin MF, Cirstea CM, Archambault P, Son F and Roby-Brami A (2002a) Impairment and compensation of reaching in hemiparetic and cerebral palsied patients IN*:* Latash ML (ed) *Progress in Motor Control. Volume 2: Structure-Function Relations in Voluntary Movements.* Champaign, Illinois, United States: Human Kinetics 103-122

Levin MF, Desrosiers J, Beauchemin D, Bergeron N and Rochette A (2004) Development and validation of a scale for rating motor compensations used for reaching in patients with hemiparesis: the Reaching Performance Scale. *Physical Therapy* 84(1): 8-22

Levin MF, Kleim JA and Wolf SL (2009) What do motor "recovery" and "compensation" mean in patients following stroke? *Neurorehabilitation and Neural Repair* 23(4): 313-319

Levin MF, Michaelsen SM, Cirstea CM and Roby-Brami A (2002b) Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Experimental Brain Research* 143(2): 171-180

Levin MF, Musampa NK, Henderson AK and Knaut LA (2005) New approaches to enhance motor function of the upper limb in patients with hemiparesis. *Hong Kong Physiotherapy Journal* 23(1): 2-5

Levin MF, Selles RW, Verheul MHG and Meijer OG (2000) Deficits in the coordination of agonist and antagonist muscles in stroke patients: implications for normal motor control. *Brain Research* 853(2): 352-369

Levy CE, Nichols DS, Schmalbrock PM, Keller P and Chakeres DW (2001) Functional MRI evidence of cortical reorganization in upper-limb stroke hemiplegia treated with constraint-induced movement therapy. *American Journal of Physical Medicine and Rehabilitation* 80(1): 4-12

Li KY, Lin KC, Chen CK, Liing RJ, Wu CY and Chang WY (2015) Concurrent and predictive validity of arm kinematics with and without a trunk restraint during a reaching task in individuals with stroke. *Archives of Physical Medicine and Rehabilitation*: Publised online 1 May 2015

Li ZM (2006) Functional degrees of freedom. *Motor Contol* 10(4): 301-310

Liaw LJ, Hsieh CL, Lo SK, Chen HM, Lee S and Lin JH (2008) The relative and absolute reliability of two balance performance measures in chronic stroke patients. *Disability and Rehabilitation* 30(9): 656-661

Lie C, Hirsch JG, Rossmanith C, Hennerici MG and Gass A (2004) Clinicotopographical correlation of corticospinal tract stroke: a color-coded diffusion tensor imaging study. *Stroke* 35(1): 86-92

Liepert J, Bauder H, Miltner WHR, Taub E and Weiller C (2000) Treatment-induced cortical reorganization after stroke in humans. *Stroke* 31(6): 1210-1216

Liepert J, Miltner WH, Bauder H, Sommer M, Dettmers C, Taub E and Weiller C (1998) Motor cortex plasticity during constraint-induced movement therapy in stroke patients. *Neuroscience Letters* 250(1): 5-8

Liepert J, Tegenthoff M and Malin J-P (1995) Changes of cortical motor area size during immobilization. *Electroencephalography and Clinical Neurophysiology* 97(6): 382-386

Liepert J, Terborg C and Weiller C (1999) Motor plasticity induced by synchronized thumb and foot movements. *Experimental Brain Research* 125(4): 435-439

Likhi M, Jidesh V, Kanagaraj R and George J (2013) Does trunk, arm, or leg correlate best with overall function in stroke subjects? *Topics in Stroke Rehabilitation* 20(1): 62-67

Lima RC, Teixeira-Salmela L and Michaelsen SM (2012) Effects of trunk restraint in addition to home-based modified constraint-induced movement therapy after stroke: a randomized controlled trial. *International Journal of Stroke* 7(3): 258-264

Lin J, Hsu M, Sheu C, Wu T, Lin R, Chen C and Hsieh C (2009a) Psychometric comparisons of 4 measures for assessing upper-extremity function in people with stroke. *Physical Therapy* 89(8): 840-850

Lin KC, Hsieh YW, Wu CY, Chen CL, Jang Y and Liu JS (2009b) Minimal detectable change and clinically important difference of the Wolf Motor Function Test in stroke patients. *Neurorehabilitation and Neural Repair* 23(5): 429-434

Lincoln N and Leadbitter D (1979) Assessment of motor function in stroke patients. *Physiotherapy* 65(2): 48-51

Lindenberg R, Renga V, Zhu LL, Betzler F, Alsop D and Schlaug G (2010) Structural integrity of corticospinal motor fibers predicts motor impairment in chronic stroke. *Neuology* 74(4): 280-287

Lissek S, Wilimzig C, Stude P, Pleger B, Kalisch T, Maier C, Peters SA, Nicolas V, Tegenthoff M and Dinse HR (2009) Immobilization impairs tactile perception and shrinks somatosensory cortical maps. *Current Biology* 19(10): 837-842

Littell RC, Pendergast J and Natarajan R (2000) Modelling covariance structure in the analysis of repeated measures data. *Statistics in Medicine* 19(13): 1793-1819

Little RJA and Rubin DB (2002) *Statistical analysis with missing data.* (2nd Edition) Hoboken, New Jersey, USA: Wiley

Liu M, Chino N, Tuji T, Masakado Y, Hase K and Kimura A (2002) Psychometric properties of the Stroke Impairment Assessment Set (SIAS). *Neurorehabilitation and Neural Repair* 16(4): 339-351

Liu W, Mccombe Waller S, Kepple TM and Whitall J (2013) Compensatory arm reaching strategies after stroke: Induced position analysis. *Journal of Rehabilitation Research and Development* 50(1): 71-84

Lotze M, Beutling W, Loibl M, Domin M, Platz T, Schminke U and Byblow WD (2012) Contralesional motor cortex activation depends on ipsilesional

corticospinal tract integrity in well-recovered subcortical stroke patients. *Neurorehabilitation and Neural Repair* 26(6): 594-603

Lotze M, Braun C, Birbaumer N, Anders S and Cohen LG (2003) Motor learning elicited by voluntary drive. *Brain* 126(Pt 4): 866-872

Lövblad KO, Baird AE, Schlaug G, Benfield A, Siewert B, Voetsch B, Connor A, Burzynski C, Edelman RR and Warach S (1997) Ischemic lesion volumes in acute stroke by diffusion-weighted magnetic resonance imaging correlate with clinical outcome. *Annals of Neurology* 42(2): 164-170

Lucas SM, Rothwell NJ and Gibson RM (2006) The role of inflammation in CNS injury and disease. *British Journal of Pharmacology* 147 (Suppl 1): S232-S240

Ludewig PM and Reynolds JF (2009) The association of scapular kinematics and glenohumeral joint pathologies. *Journal of Orthopaedic and Sports Physical Therapy* 39(2): 90-104

Luke LM, Allred RP and Jones TA (2004) Unilateral ischemic sensorimotor cortical damage induces contralesional synaptogenesis and enhances skilled reaching with the ipsilateral forelimb in adult male rats. *Synapse* 54(4): 187-199

Lum PS, Mulroy S, Amdur RL, Requejo P, Prilutsky BI and Dromerick AW (2009) Gains in upper extremity function after stroke via recovery or compensation: potential differential effects on amount of real-world limb use. *Topics in Stroke Rehabilitation* 16(4): 237-253

Maaswinkel E, Veeger HE and Dieen JH (2014) Interactions of touch feedback with muscle vibration and galvanic vestibular stimulation in the control of trunk posture. *Gait & Posture* 39(2): 745-749

Mackay J and Mensah G.(2004) *The Atlas of Heart Disease and Stroke.* Geneva: World Health Organization

Mann CJ (2003) Observational research methods. Research design II - cohort, cross sectional, and case-control studies. *Emergency Medicine Journal* 20(1): 54-60

Mao HF (2002) Analysis and comparison of the psychometric properties of three balance measures for stroke patients. *Stroke* 33(4): 1022-1027

Marciniak C (2011) Poststroke hypertonicity: upper limb assessment and treatment. *Topics in Stroke Rehabilitation* 18(3): 179-194

Mark LS, Nemeth K, Gardner D, Dainoff MJ, Paasche J, Duffy M and Grandt K (1997) Postural dynamics and the preferred critical boundary for visually guided reaching. *Journal of Experimental Psychology: Human Perception and Performance* 23(5): 1365-1379

Martin-Schepers H, Roetenberg D and Veltink PH (2010) Ambulatory human motion tracking by fusion of inertial and magnetic sensing with adaptive actuation. *Medical & Biological Engineering & Computing* 48(1): 27-37

Massie CL and Malcolm MP (2012) Instructions emphasizing speed improves hemiparetic arm kinematics during reaching in stroke. *NeuroRehabilitation* 30(4): 341-350

Massie CL, Malcolm MP, Greene DP and Browning RC (2012) Kinematic motion analysis and muscle activation patterns of continuous reaching in survivors of stroke. *Journal of Motor Behavior* 44(3): 213-222

Massie CL, Malcolm MP, Greene DP and Browning RC (2014) Biomechanical contributions of the trunk and upper extremity in discrete versus cyclic reaching in survivors of stroke. *Topics in Stroke Rehabilitation* 21(1): 23-32

Mathiowetz V, Kashman N, Volland G, Weber K, Dowe M and Rogers S (1985) Grip and pinch strength: normative data for adults. *Archives of Physical Medicine and Rehabilitation* 66(2): 69-74

Mayer M and Hluštík P (2004) Hand in hemiparetic patient: neurophysiology, pathophysiology, rehabilitation *Rehabilitácia* 41: 9-13

Mayer NH and Esquenazi A (2003) Muscle overactivity and movement dysfunction in the upper motoneuron syndrome. *Physical Medicine and Rehabilitation Clinics of North America* 14(4): 855-883

Mayo NE, Wood-Dauphinee S, Ct R, Durcan L and Carlton J (2002) Activity, participation, and quality of life 6 months poststroke. *Archives of Physical Medicine and Rehabilitation* 83(8): 1035-1042

Mazzoleni S, Sale P, Tiboni M, Franceschini M, Carrozza MC and Posteraro F (2013) Upper limb robot-assisted therapy in chronic and subacute stroke patients: a kinematic analysis. *American Journal of Physical Medicine and Rehabilitation* 92(10 Suppl 1): e26-e37

Mccambridge J, Witton J and Elbourne DR (2014) Systematic review of the Hawthorne effect: new concepts are needed to study research participation effects. *Journal of Clinical Epidemiology* 67(3): 267-277

Mcclure PW, Michener LA, Sennett BJ and Karduna AR (2001) Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *Journal of Shoulder and Elbow Surgery* 10(3): 269-277

Mccoach DB and Kaniskan B (2010) Using time-varying covariates in multilevel growth models. *Frontiers in Psychology* 1: 17

Mccomas AJ (1994) Human neuromuscular adaptations that accompany changes in activity. *Medicine & Science in Sports & Exercise* 26(12): 1498-1509

Mccombe Waller S, Liu W and Whitall J (2008) Temporal and spatial control following bilateral versus unilateral training. *Human Movement Science* 27(5): 749-758

Mccrimmon CM, King CE, Wang PT, Cramer SC, Nenadic Z and Do AH (2015) Brain-controlled functional electrical stimulation therapy for gait rehabilitation after stroke: a safety study. *Journal of NeuroEngineering and Rehabilitation* 12: 57

Meldrum D, Pittock SJ, Hardiman O, Ni Dhuill C, O'regan M and Moroney JT (2004) Recovery of the upper limb post ischaemic stroke and the predictive value of the Orpington Prognostic Score. *Clinical Rehabilitation* 18(6): 694-702

Mercier L, Audet T, Hebert R, Rochette A and Dubois MF (2001) Impact of motor, cognitive, and perceptual disorders on ability to perform activities of daily living after stroke. *Stroke* 32(11): 2602-2608

Merdler T, Liebermann DG, Levin MF and Berman S (2013) Arm-plane representation of shoulder compensation during pointing movements in patients with stroke. *Journal of Electromyography and Kinesiology* 23(4): 938-947

Meskers CGM, Koppe PA, Konijnenbelt M, Veeger DEJ and Janssen TWJ (2005) Kinematic alterations in the ipsilateral shoulder of patients with hemiplegia due to stroke. *American Journal of Physical Medicine and Rehabilitation* 84(2): 97-105

Messier S, Bourbonnais D, Desrosiers J and Roy Y (2004) Dynamic analysis of trunk flexion after stroke. *Archives of Physical Medicine and Rehabilitation* 85(10): 1619-1624

Messier S, Bourbonnais D, Desrosiers J and Roy Y (2006) Kinematic analysis of upper limbs and trunk movement during bilateral movement after stroke. *Archives of Physical Medicine and Rehabilitation* 87(11): 1463-1470

Metrot J, Froger J, Hauret I, Mottet D, Van Dokkum L and Laffont I (2013) Motor recovery of the ipsilesional upper-limb in subacute stroke. *Archives of Physical Medicine and Rehabilitation* 94(11): 2283-2290

Meyer BU, Roricht S, Grafin Von Einsiedel H, Kruggel F and Weindl A (1995) Inhibitory and excitatory interhemispheric transfers between motor cortical areas in normal humans and patients with abnormalities of the corpus callosum. *Brain* 118(Pt 2): 429-440

Michaelsen SM, Dannenbaum R and Levin MF (2006) Task-specific training with trunk restraint on arm recovery in stroke: randomized control trial. *Stroke* 37(1): 186-192

Michaelsen SM, Jacobs S, Roby-Brami A and Levin MF (2004) Compensation for distal impairments of grasping in adults with hemiparesis. *Experimental Brain Research* 157(2): 162-173

Michaelsen SM and Levin MF (2004) Short-term effects of practice with trunk restraint on reaching movements in patients with chronic stroke: a controlled trial. *Stroke* 35(8): 1914-1919

Michaelsen SM, Luta A, Roby-Brami A and Levin MF (2001) Effect of trunk restraint on the recovery of reaching movements in hemiparetic patients. *Stroke* 32(8): 1875-1883

Mikulecká E, Petrušková L, Mayer M and Vlachová I (2005) Differentiated manual treatment of the hand and forearm in early rehabilitation of stroke patients: a controlled study. *Rehabilitácia* 52: 52-61

Milne DA, Chess DG, Johnson JA and King GJW (1996) Accuracy of an electromagnetic tracking device: a study of the optimal operating range and metal interference. *Journal of Biomechanics* 29(6): 791-793

Misawa S, Kuwabara S, Matsuda S, Honma K, Ono J and Hattori T (2008) The ipsilateral cortico-spinal tract is activated after hemiparetic stroke. *European Journal of Neurology* 15(7): 706-711

Miyai I, Blau AD, Reding MJ and Volpe BT (1997) Patients with stroke confined to basal ganglia have diminished response to rehabilitation efforts. *Neurology* 48(1): 95-101

Miyake Y, Kobayashi R, Kelepecz D and Nakajima M (2013) Core exercises elevate trunk stability to facilitate skilled motor behavior of the upper extremities. *Journal of Bodywork & Movement Therapies* 17(2): 259-265

Mohr J (1990) Management of the trunk in adult hemiplegia : the Bobath concept IN*:* Herdman S (ed) *Topics in Neurology.* Alexandria, Virginia: American Physical Therapy Association

Monfils MH and Teskey GC (2004) Skilled-learning-induced potentiation in rat sensorimotor cortex: a transient form of behavioural long-term potentiation. *Neuroscience* 125(2): 329-336

Montgomery LR, Herbert WJ and Buford JA (2013) Recruitment of ipsilateral and contralateral upper limb muscles following stimulation of the cortical motor areas in the monkey. *Experimental Brain Research* 230(2): 153-164

Morris JH and Van Wijck F (2012) Responses of the less affected arm to bilateral upper limb task training in early rehabilitation after stroke: a

randomized controlled trial. *Archives of Physical Medicine and Rehabilitation* 93(7): 1129-1137

Morris JH, Van Wijck F, Joice S and Donaghy M (2013) Predicting health related quality of life 6 months after stroke: the role of anxiety and upper limb dysfunction. *Disability and Rehabilitation* 35(4): 291-299

Muellbacher W, Facchini S, Boroojerdi B and Hallett M (2000) Changes in motor cortex excitability during ipsilateral hand muscle activation in humans. *Clinical Neurophysiology* 111(2): 344-349

Muellbacher W, Richards C, Ziemann U, Wittenberg G, Weltz D, Boroojerdi B, Cohen L and Hallett M (2002) Improving hand function in chronic stroke. *Archives of Neurology* 59: 1278-1282

Muller K, Kass-Iliyya F and Reitz M (1997) Ontogeny of ipsilateral corticospinal projections: a developmental study with transcranial magnetic stimulation. *Annals of Neurology* 42(5): 705-711

Murase N, Duque J, Mazzocchio R and Cohen LG (2004) Influence of interhemispheric interactions on motor function in chronic stroke. *Annals of Neurology* 55(3): 400-409

Murray C, Vos T, Lozano R, Naghavi M, Flaxman A, Michaud C, Ezzati M, Shibuya K, Salomon J, Abdalla S, Aboyans V and Others (2012) Disability-adjusted life years (DALYs) for 291 diseases and injuries in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* 380(9859): 2197–2223

Najib U, Bashir S, Edwards D, Rotenberg A and Pascual-Leone A (2011) Transcranial brain stimulation: clinical applications and future directions. *Neurosurgery Clinics of North America* 22(2): 233-251

Nakamura T, Abreu BC, Patterson RM, Buford Jr. WL and Ottenbacher KJ (2008) Upper-limb kinematics of the presumed-to-be-unaffected side after brain injury. *American Journal of Occupational Therapy* 62(1): 46-50

Nakayama H, Jorgensen H, Raaschou H and Ts O (1994a) Recovery of upper extremity function in stroke patients: the Copenhagen Stroke Study. *Archives of Physical Medicine and Rehabilitation* 75(4): 394-398

Nakayama H, Jorgensen HS, Raaschou HO and Olsen TS (1994b) Compensation in recovery of upper extremity function after stroke: the Copenhagen Stroke Study. *Archives of Physical Medicine and Rehabilitation* 75(4): 852-857

Nascimbeni A, Gaffuri A and Imazio P (2006) Motor evoked potentials: prognostic value in motor recovery after stroke. *Functional Neurology* 21(4): 199-203

Nascimento LR, Polese JC, Faria CD and Teixeira-Salmela LF (2012) Isometric hand grip strength correlated with isokinetic data of the shoulder stabilizers in individuals with chronic stroke. *Journal of Bodywork & Movement Therapies* 16(3): 275-280

Nathan PW, Smith M and Deacon P (1996) Vestibulospinal, reticulospinal and descending propriospinal nerve fibres in man. *Brain* 119(Pt 6): 1809-1833

National Audit Office (2010) *Progress in improving stroke care.* London: Department of Health

National Registry of Diseases Office (2012) *Trends in stroke in Singapore 2005-2010.* Singapore: Health Promotion Board

National Registry of Diseases Office (2013) *Trends in stroke in Singapore 2007-2011.* Singapore: Health Promotion Board

Nelles G, Jentzen W, Bockisch A and Diener HC (2011) Neural substrates of good and poor recovery after hemiplegic stroke: a serial PET study. *Journal of Neurology* 258(12): 2168-2175

Netz J, Lammers T and Homberg V (1997) Reorganization of motor output in the non-affected hemisphere after stroke. *Brain* 120(Pt 9): 1579-1586

Ng CS, Toh MPHS, Ng J and Ko Y (2015) Direct medical cost of stroke in Singapore. *International Journal of Stroke*: Published online 14 July 2015

Nichols-Larsen DS, Clark PC, Zeringue A, Greenspan A and Blanton S (2005) Factors influencing stroke survivors' quality of life during subacute recovery. *Stroke* 36(7): 1480-1484

Nielsen JB, Willerslev-Olsen M, Christiansen L, Lundbye-Jensen J and Lorentzen J (2015) Science-based neurorehabilitation: recommendations for neurorehabilitation from basic science. *Journal of Motor Behavior* 47(1): 7-17

Niessen M, Janssen T, Meskers C, Koppe P, Konijnenbelt M and Veeger D (2008) Kinematics of the contralateral and ipsilateral shoulder: a possible relationship with post-stroke shoulder pain. *Journal of Rehabilitation Medicine* 40(6): 482-486

Niessen MH, Veeger DH, Meskers CG, Koppe PA, Konijnenbelt MH and Janssen TW (2009) Relationship among shoulder proprioception, kinematics, and pain after stroke. *Archives of Physical Medicine and Rehabilitation* 90(9): 1557-1564

Nijland R, Van Wegen E, Verbunt J, Van Wijk R, Van Kordelaar J and Kwakkel G (2010a) A comparison of two validated tests for upper limb function after stroke: The Wolf Motor Function Test and the Action Research Arm Test. *Journal of Rehabilitation Medicine* 42(7): 694-696

Nijland RH, Van Wegen EE, Harmeling-Van Der Wel BC, Kwakkel G and Investigators E (2010b) Presence of finger extension and shoulder abduction within 72 hours after stroke predicts functional recovery: early prediction of functional outcome after stroke: the EPOS cohort study. *Stroke* 41(4): 745-750

Nirkko AC, Ozdoba C, Redmond SM, Burki M, Schroth G, Hess CW and Wiesendanger M (2001) Different ipsilateral representations for distal and proximal movements in the sensorimotor cortex: activation and deactivation patterns. *Neuroimage* 13(5): 825-835

Nishibe M, Urban ET, 3rd, Barbay S and Nudo RJ (2015) Rehabilitative training promotes rapid motor recovery but delayed motor map reorganization in a rat cortical ischemic infarct model. *Neurorehabilitation and Neural Repair* 29(5): 472-482

Norrving B and Kissela B (2013) The global burden of stroke and need for a continuum of care. *Neurology* 80(3 Suppl 2): S5-S12

Noskin O, Krakauer JW, Lazar RM, Festa JR, Handy C, O'brien KA and Marshall RS (2008) Ipsilaeral motor dysfunction from unilateral stroke : implications for functional neuroanatomy of hemiparesis. *Journal of Neurology, Neurosurgery & Psychiatry* 79(4): 401-406

Nowak DA, Grefkes C, Ameli M and Fink GR (2009) Interhemispheric competition after stroke: brain stimulation to enhance recovery of function of the affected hand. *Neurorehabilitation and Neural Repair* 23(7): 641-656

Nudo R (2003) Adaptive plasticity in motor cortex: implications for rehabilitation after brain injury. *Journal of Rehabilitation Medicine* 35(41 Suppl): 7-10

Nudo RJ (2006) Mechanisms for recovery of motor function following cortical damage. *Current Opinion in Neurobiology* 16(6): 638-644

Nudo RJ (2007) Postinfarct cortical plasticity and behavioral recovery. *Stroke* 38(2 Suppl): 840-845

Nudo RJ (2013) Recovery after brain injury: mechanisms and principles. *Frontiers in Human Neuroscience* 7: 887

Nudo RJ and Milliken GW (1996) Reorganization of movement representations in primary motor cortex following focal ischemic infarcts in adult squirrel monkeys. *Journal of Neurophysiology* 75(5): 2144-2149

Nudo RJ, Milliken GW, Jenkins WM and Merzenich MM (1996a) Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys. *Journal of Neuroscience* 16(2): 785-807

Nudo RJ, Plautz EJ and Frost SB (2001) Role of adaptive plasticity in recovery of function after damage to motor cortex. *Muscle & Nerve* 24(8): 1000-1019

Nudo RJ, Wise BM, Sifuentes F and Milliken GW (1996b) Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct. *Science* 272(5269): 1791-1794

O'dell MW, Kim G, Finnen LR and Polistena C (2011) Clinical implications of using the arm motor ability test in stroke rehabilitation. *Archives of Physical Medicine and Rehabilitation* 92(5): 830-836

O'dell MW, Kim G, Rivera L, Fieo R, Christos P, Polistena C, Fitzgerald K and Gorga D (2013) A psychometric evaluation of the Arm Motor Ability Test. *Journal of Rehabilitation Medicine* 45(6): 519-527

Ohab JJ, Fleming S, Blesch A and Carmichael ST (2006) A neurovascular niche for neurogenesis after stroke. *Journal of Neuroscience* 26(50): 13007-13016

Olsen TS (1989) Improvement of function and motor impairment after stroke. *Journal of Neurological Rehabilitation* 3: 187-192

Paci M, Nannetti L, Moretti S, Boccaletti E and Lombardi B (2012) Are there differences in motor recovery between upper and lower limbs in hemiplegic patients with hemorrhagic stroke? *Italian Journal of Physiotherapy* 2(2): 59-64

Page SJ, Fulk GD and Boyne P (2012a) Clinically important differences for the Upper-Extremity Fugl-Meyer Scale in people with minimal to moderate impairment due to chronic stroke. *Physical Therapy* 92(5): 791-798

Page SJ, Gater RR and Bach-Y-Rita P (2004) Reconsidering the motor recovery plateau in stroke rehabilitation. *Archives of Physical Medicine and Rehabilitation* 85(8)

Page SJ, Gauthier LV and White S (2013) Size doesn't matter: cortical stroke lesion volume is not associated with upper extremity motor impairment and function in mild, chronic hemiparesis. *Archives of Physical Medicine and Rehabilitation* 94(5): 817-821

Page SJ, Hade E and Persch A (2015) Psychometrics of the wrist stability and hand mobility subscales of the Fugl-Meyer Assessment in moderately impaired stroke. *Physical Therapy* 95(1): 103-108

Page SJ, Levine P and Hade E (2012b) Psychometric properties and administration of the wrist/hand subscales of the Fugl-Meyer Assessment in minimally impaired upper extremity hemiparesis in stroke. *Archives of Physical Medicine and Rehabilitation* 93(12): 2373-2376

Pain LM, Baker R, Richardson D and Agur AM (2015) Effect of trunk-restraint training on function and compensatory trunk, shoulder and elbow patterns during post-stroke reach: a systematic review. *Disability and Rehabilitation* 37(7): 553-562

Palmer E and Ashby P (1992) Corticospinal projections to upper limb motoneurones in humans. *Journal of Physiology* 448: 397-412

Palmer E, Ashby P and Hajek VE (1992) Ipsilateral fast corticospinal pathways do not account for recovery in stroke. *Annals of Neurology* 32(4): 519-525

Panjabi MM (1992) The stabilizing system of the spine. Part I Function, dysfunc- tion, adaptation and enhancement. *Journal of Spinal Disorders & Techniques* 5(4): 383-389

Pannucci CJ and Wilkins EG (2010) Identifying and avoiding bias in research. *Plastic and Reconstructive Surgery* 126(2): 619-625

Pantano P, Formisano R, Ricci M, Dipiero V, Sambatini U, Dipofi B, Rossi R, Bozzao L and Lenzi GL (1996) Motor recovery after stroke: morphological and functional brain alterations. *Brain* 119(Pt 6): 1849-1857

Paolucci S, Antonucci G, Grasso M and Pizzamiglio L (2001) The role of unilateral spatial neglect in rehabilitation of right brain-damaged ischemic stroke patients: a matched comparison *Archives of Physical Medicine and Rehabilitation* 82(6): 743-749

Park SH, Song KS, Ko M and Seo JH (2009) Motor evoked potentials of trunk muscles in stroke patients. *J Korean Acad Rehab Med* 33: 282-289

Parker VM, Wade DT and Langton Hewer R (1986) Loss of arm function after stroke: measurement, frequency, and recovery. *International Rehabilitation Medicine* 8(2): 69-73

Pascual-Leone A, Cammarota A, Wassermann EM, Brasil-Neto JP, Cohen LG and Hallett M (1993) Modulation of motor cortical outputs to the reading hand of Braille readers. *Annals of Neurology* 34(1): 33-37

Pascual-Leone A and Torres F (1993) Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers. *Brain* 116(Pt 1): 39-52

Patterson TS, Bishop MD, Mcguirk TE, Sethi A and Richards LG (2011) Reliability of upper extremity kinematics while performing different tasks in individuals with stroke. *Journal of Motor Behavior* 43(2): 121-130

Pearcy M and Hindle R (1989) New method for the noninvasive three-dimensional measurement of human back movement. *Clinical Biomechanics* 4(2): 73-79

Peiris CL, Taylor NF and Shields N (2011) Extra physical therapy reduces patient length of stay and improves functional outcomes and quality of life in people with acute or subacute conditions : a systematic review. *Archives of Physical Medicine and Rehabilitation* 92(9): 1490-1500

Pennisi G, Rapisarda G, Bella R, Calabrese V, Maertens De Noordhout A and Delwaide PJ (1999) Absence of response to early transcranial magnetic stimulation in ischemic stroke patients: prognostic value for hand motor recovery. *Stroke* 30(12): 2666-2670

Pereira LM, Marcucci FC, De Oliveira Menacho M, Garanhani MR, Lavado EL and Cardoso JR (2011) Electromyographic activity of selected trunk muscles in subjects with and without hemiparesis during therapeutic exercise. *Journal of Electromyography and Kinesiology* 21(2): 327-332

Pereira S, Silva CC, Ferreira S, Silva C, Oliveira N, Santos R, Vilas-Boas JP and Correia MV (2014) Anticipatory postural adjustments during sitting

reach movement in post-stroke subjects. *Journal of Electromyography and Kinesiology* 24(1): 165-171
Perez MA and Cohen LG (2008) Mechanisms underlying functional changes in the primary motor cortex ipsilateral to an active hand. *Journal of Neuroscience* 28(22): 5631-5640
Perry SB (1998) Clinical implications of a dynamic systems theory. *Neurology Report* 22(1): 4-10
Persch AC, Gugiu PC, Velozo CA and Page SJ (2015) Rasch analysis of the Wrist and Hand Fugl-Meyer: dimensionality and item-level characteristics. *Journal of Neurologic Physical Therapy* 39(3): 185-192
Peterson BW, Pitts NG and Fukushima K (1979) Reticulospinal connections with limb and axial motoneurons. *Experimental Brain Research* 36: 1-20
Peugh JL (2010) A practical guide to multilevel modeling. *Journal of School Psychology* 48(1): 85-112
Peugh JL and Enders CK (2005) Using the SPSS MIXED pocedure to fit cross-sectional and longitudinal multilevel models. *Educational and Psychological Measurement* 65(5): 717-741
Phadke V, Camargo P and Ludewig P (2009) Scapular and rotator cuff muscle activity during arm elevation: A review of normal function and alterations with shoulder impingement. *Revista Brasileira de Fisioterapia* 13(1): 1-9
Picerno P, Cereatti A and Cappozzo A (2008) Joint kinematics estimate using wearable inertial and magnetic sensing modules. *Gait & Posture* 28(4): 588-595
Pineiro R, Pendlebury ST, Smith S, Flitney D, Blamire AM, Styles P and Matthews PM (2000) Relating MRI changes to motor deficit after ischemic stroke by segmentation of functional motor pathways. *Stroke* 31(3): 672-679
Plassman BL and Gandevia SC (1989) Comparison of human motor cortical projections to abdominal muscles and instrinic muscles of the hand. *Experimental Brain Research* 78(2): 301-308
Platz T, Pinkowski C, Van Wijck F, Kim I-H, Di Bella P and Johnson G (2005a) Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: a multicentre study. *Clinical Rehabilitation* 19(4): 404-411
Platz T, Van Kaick S, Moller L, Freund S, Winter T and Kim IH (2005b) Impairment-oriented training and adaptive motor cortex reorganisation after stroke: a fTMS study. *Journal of Neurology* 252(11): 1363-1371
Plautz EJ, Milliken GW and Nudo RJ (2000) Effects of repetitive motor training on movement representations in adult squirrel monkeys: role of use versus learning. *Neurobiology of Learning and Memory* 74(1): 27-55
Polechonski J and Olex-Zarychta D (2012) The influence of tactile feedback on hand movement accuracy. *Human Movement* 13(3): 236–241
Pollock A, Farmer SE, Brady MC, Langhorne P, Mead GE, Mehrholz J and Van Wijck F (2014) Interventions for improving upper limb function after stroke. *Cochrane Database of Systematic Reviews* (11): 1-172
Porter MM, Vandervoort AA and Lexell J (1995) Ageing of human muscle : structure, junction and adaptability. *Scandinavian Journal of Medicine & Science in Sports* 5(3): 129-142
Prabhakaran S, Zarahn E, Riley C, Speizer A, Chong JY, Lazar RM, Marshall RS and Krakauer JW (2008) Inter-individual variability in the capacity for

motor recovery after ischemic stroke. *Neurorehabilitation and Neural Repair* 22(1): 64-71

Prager EM and Lang CE (2012) Predictive ability of 2-day measurement of active range of motion on 3-mo upper-extremity motor function in people with poststroke hemiparesis. *American Journal of Occupational Therapy* 66(1): 35-41

Pretz CR, Kozlowski AJ, Dams-O'connor K, Kreider S, Cuthbert JP, Corrigan JD, Heinemann AW and Whiteneck G (2013) Descriptive modeling of longitudinal outcome measures in traumatic brain injury: a National Institute on Disability and Rehabilitation Research Traumatic Brain Injury Model Systems study. *Archives of Physical Medicine and Rehabilitation* 94(3): 579-588

Price CI, Rodgers H, Franklin P, Curless RH and Johnson GR (2001) Glenohumeral subluxation, scapula resting position, and scapula rotation after stroke: a noninvasive evaluation. *Archives of Physical Medicine and Rehabilitation* 82(7): 955-960

Rabadi MH and Rabadi FM (2006) Comparison of the action research arm test and the Fugl-Meyer assessment as measures of upper-extremity motor weakness after stroke. *Archives of Physical Medicine and Rehabilitation* 87(7): 962-966

Rabin E, Dizio P, Ventura J and Lackner JR (2008) Influences of arm proprioception and degrees of freedom on postural control with light touch feedback. *Journal of Neurophysiology* 99(2): 595-604

Rabin E, Muratori L, Svokos K and Gordon A (2010) Tactile/proprioceptive integration during arm localization is intact in individuals with Parkinson's disease. *Neuroscience Letters* 470(1): 38-42

Rachwani J, Santamaria V, Saavedra SL, Wood S, Porter F and Woollacott MH (2013) Segmental trunk control acquisition and reaching in typically developing infants. *Experimental Brain Research* 228(1): 131-139

Rachwani J, Santamaria V, Saavedra SL and Woollacott MH (2015) The development of trunk control and its relation to reaching in infancy: a longitudinal study. *Frontiers in Human Neuroscience* 9: 94

Rangaraju S, Streib C, Aghaebrahim A, Jadhav A, Frankel M and Jovin TG (2015) Relationship Between Lesion Topology and Clinical Outcome in Anterior Circulation Large Vessel Occlusions. *Stroke* 46(7): 1787-1792

Rao A and Gordon A (2001) Contribution of tactile information to accuracy in pointing movements. *Experimental Brain Research* 138(4): 438-445

Rathore SS (2002) Characterization of Incident Stroke Signs and Symptoms: Findings From the Atherosclerosis Risk in Communities Study. *Stroke* 33(11): 2718-2721

Reeves NP, Narendra KS and Cholewicki J (2007) Spine stability: the six blind men and the elephant. *Clinical Biomechanics* 22(3): 266-274

Rehme AK, Eickhoff SB, Rottschy C, Fink GR and Grefkes C (2012) Activation likelihood estimation meta-analysis of motor-related neural activity after stroke. *Neuroimage* 59(3): 2771-2782

Rehme AK, Eickhoff SB, Wang LE, Fink GR and Grefkes C (2011a) Dynamic causal modeling of cortical activity from the acute to the chronic stage after stroke. *Neuroimage* 55(3): 1147-1458

Rehme AK, Fink GR, Von Cramon DY and Grefkes C (2011b) The role of the contralesional motor cortex for motor recovery in the early days after stroke assessed with longitudinal FMRI. *Cerebral Cortex* 21(4): 756-768

Reid JM, Dai D, Christian C, Reidy Y, Counsell C, Gubitz GJ and Phillips SJ (2012) Developing predictive models of excellent and devastating outcome after stroke. *Age and Ageing* 41(4): 560-564

Reid JM, Gubitz GJ, Dai D, Kydd D, Eskes G, Reidy Y, Christian C, Counsell CE, Dennis M and Phillips SJ (2010) Predicting functional outcome after stroke by modelling baseline clinical and CT variables. *Age and Ageing* 39(3): 360-366

Reinkensmeyer DJ, Cole AM, Kahn LE and Kamper DG (2002) Directional control of reaching is preserved following mild/moderate stroke and stochastically constrained following severe stroke. *Experimental Brain Research* 143(4): 525-530

Reinschmidt C, Van Den Bogert A, Nigg B, Lundberg A and Murphy N (1997) Effect of skin movement on the analysis of skeletal knee joint motion during running. *Journal of Biomechanics* 30(7): 729-732

Reisman DS and Scholz JP (2003) Aspects of joint coordination are preserved during pointing in persons with post-stroke hemiparesis. *Brain* 126: 2510-2527

Richards JG (1999) The measurement of human motion: a comparison of commercially available systems. *Human Movement Science* 18(5): 589-602

Richardson JTE (2011) Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review* 6(2): 135-147

Riley JD, Le V, Der-Yeghiaian L, See J, Newton JM, Ward NS and Cramer SC (2011) Anatomy of stroke injury predicts gains from therapy. *Stroke* 42(2): 421-426

Robertson JV and Roby-Brami A (2011) The trunk as a part of the kinematic chain for reaching movements in healthy subjects and hemiparetic patients. *Brain Research* 1382: 137-146

Roby-Brami A, Feydy A, Combeaud M, Biryukova EV, Bussel B and Levin MF (2003a) Motor compensation and recovery for reaching in stroke patients. *Acta Neurologica Scandinavica* 107(5): 369-381

Roby-Brami A, Fuchs S, Mokhtari M and Bussel B (1997) Reaching and grasping strategies in hemiparetic patients. *Motor Control* 1(1): 72-91

Roby-Brami A, Jacobs S, Bennis N and Levin MF (2003b) Hand orientation for grasping and arm joint rotation patterns in healthy subjects and hemiparetic stroke patients. *Brain Research* 969(1-2): 217-229

Rochat P and Goubet N (1995) Development of sitting and reaching in 5-6 month old infants. *Infant Behavior and Development* 18: 53-68

Roetenberg D, Slycke PJ and Veltink PH (2007) Ambulatory position and orientation tracking fusing magnetic and inertial sensing. *IEEE Transactions on Biomedical Engineering* 54(5): 883-890

Rogosa DR, Brandt D and Zimowski M (1982) A growth curve approach to the measurement of change. *Psychological Bulletin* 92(3): 726-748

Rogosa DR and Willett JB (1983) Demonstrating the reliability of the difference score In the measurement of change. *Journal of Educational Measurement* 20(4): 335-343

Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe BT, Frontera WR, Stein J and Hogan N (2002) Movement smoothness changes during stroke recovery. *Journal of Neuroscience* 22(18): 8297-8304

Rojas R and Iglesias A (2013) The language growth of Spanish-speaking English language learners. *Child Development* 84(2): 630-646

Roren A, Lefevre-Colau MM, Poiraudeau S, Fayad F, Pasqui V and Roby-Brami A (2015) A new description of scapulothoracic motion during arm movements in healthy subjects. *Manual Therapy* 20(1): 46-55

Roren A, Lefevre-Colau MM, Roby-Brami A, Revel M, Fermanian J, Gautheron V, Poiraudeau S and Fayad F (2012) Modified 3D scapular kinematic patterns for activities of daily living in painful shoulders with restricted mobility: a comparison with contralateral unaffected shoulders. *Journal of Biomechanics* 45(7): 1305-1311

Rosenblum S and Josman N (2003) The relationship between postural control and fine manual dexterity. *Physical & Occupational Therapy in Pediatrics* 23(4): 47-60

Rossi E, Mitnitski A and Feldman A (2002) Sequential control signals determine arm and trunk contributions to hand transport during reaching in humans. *Journal of Physiology* 538(Pt 2): 659-671

Rossini PM, Caltagirone C, Castriota-Scanderbeg A, Cicinelli P, Del Gratta C, Demartin M, Pizzella V, Traversa R and Romani GL (1998) Hand motor cortical area reorganization in stroke: a study with fMRI, MEG and TCS maps. *Neuroreport* 9(9): 2141-2146

Rossini PM and Pauri F (2000) Neuromagnetic integrated methods tracking human brain mechanisms of sensorimotor areas 'plastic' reorganisation. *Brain Research Reviews* 33(2-3): 131-154

Rosso C, Valabregue R, Attal Y, Vargas P, Gaudron M, Baronnet F, Bertasi E, Humbert F, Peskine A, Perlbarg V, Benali H, Lehericy S and Samson Y (2013) Contribution of corticospinal tract and functional connectivity in hand motor impairment after stroke. *PLoS One* 8(9): e73164

Rothrock JF, Clark WM and Lyden PD (1995) Spontaneous early improvement following ischemic stroke. *Stroke* 26(8): 1358-1360

Rothwell PM, Coull AJ, Giles MF, Howard SC, Silver LE, Bull LM, Gutnikov SA, Edwards P, Mant D, Sackley CM, Farmer A, Sandercock PaG, Dennis MS, Warlow CP, Bamford JM and Anslow P (2004) Change in stroke incidence, mortality, case-fatality, severity, and risk factors in Oxfordshire, UK from 1981 to 2004 (Oxford Vascular Study). *Lancet* 363(9425): 1925-1933

Rundquist P, Dumit M, Hartley J, Schultz K and Finley M (2012) Three-dimensional shoulder complex kinematics in individuals with upper extremity impairment from chronic stroke. *Disability and Rehabilitation* 34(5): 402-407

Ryerson S, Byl NN, Brown DA, Wong RA and Hidler JM (2008) Altered trunk position sense and its relation to balance functions in people post-stroke. *Journal of Neurologic Physical Therapy* 32(1): 14-20

Ryerson SD (2007) Hemiplegia IN*:* Umphred D (ed) *Neurological Rehabilitation.* 5th Edition St. Louis, Missouri, United States of America: Mosby Elsevier 857-901

Saeki S, Ogata H, Hachisuka K, Okubo T, Takahashi K and Hoshuyama T (1994) Association between location of the lesion and discharge status of ADL in first stroke patients. *Archives of Physical Medicine and Rehabilitation* 75(8): 858-860

Saeys W, Vereeck L, Truijen S, Lafosse C, Wuyts FP and Heyning PV (2012) Randomized controlled trial of truncal exercises early after stroke to improve balance and mobility. *Neurorehabilitation and Neural Repair* 26(3): 231-238

Saka O, Mcguire A and Wolfe C (2009) Cost of stroke in the United Kingdom. *Age and Ageing* 38(1): 27-32

Sanes JN, Donoghue JP, Thangaraj V, Edelman RR and Warach S (1995) Shared neural substrates controlling hand movements in human motor cortex. *Science* 268(5218): 1775-1777

Sanford J, Moreland J, Swanson LR, Stratford PW and Gowland C (1993) Reliability of the Fugl-Meyer Assessment for testing motor performance in patients following stroke. *Physical Therapy* 73(7): 447-454

Santos MJ, Kanekar N and Aruin AS (2010) The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. *Journal of Electromyography and Kinesiology* 20(3): 388-397

Sathian K, Buxbaum LJ, Cohen LG, Krakauer JW, Lang CE, Corbetta M and Fitzpatrick SM (2011) Neurological principles and rehabilitation of action disorders: common clinical deficits. *Neurorehabilitation and Neural Repair* 25(5 Suppl): 21S-32S

Saunders DE, Clifton AG and Brown MM (1995) Measurement of infarct size using MRI predicts prognosis in middle cerebral artery infarction. *Stroke* 26(12): 2272-2276

Scarborough P, Peto V, Bhatnagar P, Kaur A, Leal J, Luengo-Fernandez, Gray A, Rayner M and Allender S (2009) *Stroke statistics.* Oxford: Department of Public Health

Schaefer SY, Haaland KY and Sainburg RL (2009) Hemispheric specialization and functional impact of ipsilesional deficits in movement coordination and accuracy. *Neuropsychologia* 47(13): 2953-2966

Schieber MH, Lang CE, Reilly KT, Mcnulty P and Sirigu A (2009) Selective activation of human finger muscles after stroke or amputation. *Advances in Experimental Medicine and Biology* 629: 559-575

Schulz R, Koch P, Zimerman M, Wessel M, Bonstrup M, Thomalla G, Cheng B, Gerloff C and Hummel FC (2015) Parietofrontal motor pathways and their association with motor function after stroke. *Brain*

Schulz R, Park CH, Boudrias MH, Gerloff C, Hummel FC and Ward NS (2012) Assessing the integrity of corticospinal pathways from primary and secondary cortical motor areas after stroke. *Stroke* 43(8): 2248-2251

Schweighofer N, Han CE, Wolf SL, Arbib MA and Winstein CJ (2009) A functional threshold for long-term use of hand and arm function can be determined: predictions from a computational model and supporting data from the Extremity Constraint-Induced Therapy Evaluation (EXCITE) Trial. *Physical Therapy* 89(12): 1327-1336

Schwerin S, Dewald JP, Haztl M, Jovanovich S, Nickeas M and Mackinnon C (2008) Ipsilateral versus contralateral cortical motor projections to a shoulder adductor in chronic hemiparetic stroke: implications for the expression of arm synergies. *Experimental Brain Research* 185(3): 509-519

Sciascia A and Cromwell R (2012) Kinetic chain rehabilitation: a theoretical framework. *Rehabil Res Pract* 2012: 1-9

Scibek JS and Carcia CR (2012) Assessment of scapulohumeral rhythm for scapular plane shoulder elevation using a modified digital inclinometer. *World Journal of Orthopaedics* 3(6): 87-94

Scibek JS, Carpenter JE and Hughes RE (2009) Rotator cuff tear pain and tear size and scapulohumeral rhythm. *Journal of Athletic Training* 44(2): 148-159

Sebastia E, Duarte E, Boza R, Samitier B, Tejero M, Marco E, Muniesa JM, Belmonte R and Escalada F (2006) Cross-validation of a model for predicting functional status and length of stay in patients with stroke. *Journal of Rehabilitation Medicine* 38(3): 204-206

Sedgwick P (2013) Limits of agreement (Bland-Altman method). *British Medical Journal* 346: f1630

See J, Dodakian L, Chou C, Chan V, Mckenzie A, Reinkensmeyer DJ and Cramer SC (2013) A standardized approach to the Fugl-Meyer Assessment and its implications for clinical trials. *Neurorehabilitation and Neural Repair* 27(8): 732-741

Seitz RJ, Azari NP, Knorr U, Binkofski F, Herzog H and Freund HJ (1999) The role of diaschisis in stroke recovery. *Stroke* 30(9): 1844-1850

Ser G (2012) Determination of appropriate covariance structures in random slope and intercept model applied in repeated measures. *Journal of Animal and Plant Sciences* 22(3): 552-555

Serrien DJ, Strens LH, Cassidy MJ, Thompson AJ and Brown P (2004) Functional significance of the ipsilateral hemisphere during movement of the affected hand after stroke. *Experimental Neurology* 190(2): 425-432

Shaikh T, Goussev V, Feldman AG and Levin MF (2014) Arm-trunk coordination for beyond-the-reach movements in adults with stroke. *Neurorehabilitation and Neural Repair* 28(4): 355-366

Shek DTL and Ma CMS (2011) Longitudinal data analyses using linear mixed models in SPSS: concepts, procedures and illustrations. *Scientific World Journal* 11: 42-76

Shelton FDNaP and Reding MJ (2001) Effect of lesion location on upper limb motor recovery after stroke. *Stroke* 32(1): 107-112

Shumway-Cook A and Wollacott MH (2000) *Motor Control: Theory and Practical Applications* (2nd revised Edition) Philadelphia (USA): Lippincott Williams and Wilkins

Sica GT (2006) Bias in research studies. *Radiology* 238(3): 780-789

Silfies SP, Ebaugh D, Pontillo M and Butowicz CM (2015) Critical review of the impact of core stability on upper extremity athletic injury and performance. *Brazilian Journal of Physical Therapy* http://dx.doi.org/10.1590/bjpt-rbf.2014.0108

Silva-Couto Mde A, Prado-Medeiros CL, Oliveira AB, Alcantara CC, Guimaraes AT, Salvini Tde F, Mattioli R and Russo TL (2014) Muscle atrophy, voluntary activation disturbances, and low serum concentrations of IGF-1 and IGFBP-3 are associated with weakness in people with chronic stroke. *Physical Therapy* 94(7): 957-967

Simoneau M, Guillaud É and Blouin J (2013) Effects of underestimating the kinematics of trunk rotation on simultaneous reaching movements: predictions of a biomechanical model. *Journal of NeuroEngineering & Rehabilitation* 10(1): 54

Simpson LA and Eng JJ (2013) Functional recovery following stroke: capturing changes in upper-extremity function. *Neurorehabilitation and Neural Repair* 27(3): 240–250

Singer JD (1998) Using SAS PROC MIXED to fit multilevel models, hierarchical models, and individual growth models. *Journal of Educational and Behavioral Statistics* 24(4): 323-355

Singer JD and Willett JB (2003) *Applied longitudinal data analysis : modeling change and event occurence.* New York, United States of America: Oxford University Press, Inc.

Skilbeck CE, Wade DT, Hewer RL and Wood VA (1983) Recovery after stroke. *Journal of Neurology, Neurosurgery & Psychiatry* 46(1): 5-8

Slijper H, Latash M, Rao N and Aruin A (2002) Task-specific modulation of anticipatory postural adjustments in individuals with hemiparesis. *Clinical Neurophysiology* 113(5): 642-655

Smania N, Paolucci S, Tinazzi M, Borghero A, Manganotti P, Fiaschi A, Moretto G, Bovi P and Gambarin M (2007) Active finger extension: a simple movement predicting recovery of arm function in patients with acute stroke. *Stroke* 38(3): 1088-1090

Smutok MA, Grafman J, Salazar AM, Sweeney JK, Jonas BS and Dirocco PJ (1989) Effects of unilateral brain damage on contralateral and ipsilateral upper extremity function in hemiplegia. *Physical Therapy* 69(3): 195-203

Sohn YH, Jung HY, Kaelin-Lang A and Hallett M (2003) Excitability of the ipsilateral motor cortex during phasic voluntary hand movement. *Experimental Brain Research* 148(2): 176-185

Son SM, Kwon YH, Lee NK, Nam SH and Kim KY (2013) Deficits of movement accuracy and proprioceptive sense in the ipsi-lesional upper limb of patients with hemiparetic stroke. *Journal of Physical Therapy Science* 25(5): 567-569

Song CS (2013) Effects of scapular stabilization exercise on function of paretic upper extremity of chronic stroke patients. *Journal of Physical Therapy Science* 25(4): 403-405

Song J, Nair VA, Young BM, Walton LM, Nigogosyan Z, Remsik A, Tyler ME, Farrar-Edwards D, Caldera KE, Sattin JA, Williams JC and Prabhakaran V (2015) DTI measures track and predict motor function outcomes in stroke rehabilitation utilizing BCI technology. *Frontiers in Human Neuroscience* 9: 195

Spencer JP, Vereijken B, Diedrich FJ and Thelen E (2000) Posture and the emergence of manual skills. *Developmental Science* 3(2): 216-233

Sprigg N, Selby J, Fox L, Berge E, Whynes D and Bath PMW (2013) Very low quality of life after acute stroke: data from the Efficacy of Nitric Oxide in Stroke Trial. *Stroke* 44(12): 3458-3462

Stapleton CJ, Walcott BP, Fusco MR, Thomas AJ and Ogilvy CS (2015) Brain mapping for safe microsurgical resection of arteriovenous malformations in eloquent cortex. *World Neurosurg* 83(6): 1148-1156

Starkey ML and Schwab ME (2014) How plastic is the brain after a stroke? *Neuroscientist* 20(4): 359-371

Steenbergen B, Van Thiel E, Hulstijn W and Meulenbroek RGJ (2000) The coordination of reaching and grasping in spastic hemiparesis. *Human Movement Science* 19(1): 75-105

Steinskog DJ, Tjøstheim DB and Kvamstø NG (2007) A cautionary note on the use of the Kolmogorov–Smirnov test for normality. *American Meteorological Society* 135(3): 1151-1157

Sterr A, Shen S, Szameitat AJ and Herron KA (2010) The role of corticospinal tract damage in chronic motor recovery and neurorehabilitation: a pilot study. *Neurorehabilitation and Neural Repair* 24(5): 413-419

Stinear C (2010) Prediction of recovery of motor function after stroke. *Lancet Neurology* 9(12): 1228-1232

Stinear CM, Barber PA, Petoe M, Anwar S and Byblow WD (2012) The PREP algorithm predicts potential for upper limb recovery after stroke. *Brain* 135(Pt 8): 2527-2535

Stinear CM, Barber PA, Smale PR, Coxon JP, Fleming MK and Byblow WD (2007) Functional potential in chronic stroke patients depends on corticospinal tract integrity. *Brain* 130(Pt 1): 170-180

Stinear CM and Byblow WD (2014) Predicting and accelerating motor recovery after stroke. *Current Opinion in Neurology* 27(6): 624-630

Stinear CM, Byblow WD and Ward SH (2014) An update on predicting motor recovery after stroke. *Annals of Physical and Rehabilitation Medicine* 57(8): 489-498

Stoel RD and Van Den Wittenboer G (2004) Including time-invariant covariates in the latent growth curve model. *Structural Equation Modeling* 11(2): 155-167

Stokes IA, Gardner-Morse M, Churchill D and Laible JP (2002) Measurement of a spinal motion segment stiffness matrix. *Journal of Biomechanics* 35(4): 517-521

Stokes IA, Gardner-Morse M, Henry SM and Badger GJ (2000) Decrease in trunk muscular response to perturbation with preactivation of lumbar spinal musculature. *Spine (Phila Pa 1976)* 25(15): 1957-1964

Strens LHA, Fogelson N, Shanahan P, Rothwell JC and Brown P (2003) The ipsilateral human motor cortex can functionally compensate for acute contralateral motor cortex dysfunction. *Current Biology* 13(14): 1201-1205

Stroemer RP, Kent TA and Hulsebosch CE (1995) Neocortical neural sprouting, synaptogenesis, and behavioral recovery after neocortical infarction in rats. *Stroke* 26(11): 2135-2144

Subramanian SK, Yamanaka J, Chilingaryan G and Levin MF (2010) Validity of movement pattern kinematics as measures of arm motor impairment poststroke. *Stroke* 41(10): 2303-2308

Sugarman H, Avni A, Nathan R, Weisel-Eichler A and Tiran J (2002) Movement in the ipsilesional hand is segmented following unilateral brain damage. *Brain and Cognition* 48(2-3): 579-587

Sukal TM, Ellis MD and Dewald JP (2007) Shoulder abduction-induced reductions in reaching work area following hemiparetic stroke: neuroscientific implications. *Experimental Brain Research* 183(2): 215-223

Sullivan JE, Crowner BE, Kluding PM, Nichols D, Rose DK, Yoshida R and Pinto Zipp G (2013) Outcome measures for individuals with stroke: Recommendations from the American Physical Therapy Association Neurology Section Task Force. *Physical Therapy* 93(10): 1383-1396

Sullivan KJ, Tilson JK, Cen SY, Rose DK, Hershberg J, Correa A, Gallichio J, Mcleod M, Moore C, Wu SS and Duncan PW (2011) Fugl-Meyer assessment of sensorimotor function after stroke: standardized training procedure for clinical practice and clinical trials. *Stroke* 42(2): 427-432

Sun L, Yin D, Zhu Y, Fan M, Zang L, Wu Y, Jia J, Bai Y, Zhu B and Hu Y (2013) Cortical reorganization after motor imagery training in chronic stroke patients with severe motor impairment: a longitudinal fMRI study. *Neuroradiology* 55(7): 913-925

Sun MK, Hongpaisan J, Nelson TJ and Alkon DL (2008) Poststroke neuronal rescue and synaptogenesis mediated in vivo by protein kinase C in adult brains. *Proceedings of the National Academy of Sciences of the United States of America* 105(36): 13620-13625

Sunderland A, Fletcher D, Bradley L, Tinson D, Hewer R and Wade D (1994) Enhanced physical therapy for arm function after stroke : a one year

follow up study. *Journal of Neurology, Neurosurgery & Psychiatry* 57(7): 856-858

Sunderland A, Tinson D, Bradley L and Hewer RL (1989) Arm function after stroke.An evaluation of grip strength as a measure of recovery and a prognostic indicator. *Journal of Neurology, Neurosurgery & Psychiatry* 52(11): 1267-1272

Sunderland A and Tuke A (2005) Neuroplasticity, learning and recovery after stroke: a critical evaluation of constraint-induced therapy. *Neuropsychological Rehabilitation* 15(2): 81-96

Sveen U, Bautz-Holter E, Sodring K, Wyller T and Laake K (1999) Association between impairments, self-care ability and social activities 1 year after stroke. *Disability and Rehabilitation* 21(8): 372-377

Sveistrup H, Schneiberg S, Mckinley PA, Mcfadyen BJ and Levin MF (2008) Head, arm and trunk coordination during reaching in children. *Experimental Brain Research* 188(2): 237-247

Swinkels A and Dolan P (2000) Spinal position sense is independent of the magnitude of movement. *Spine (Phila Pa 1976)* 25(1): 98-105

Szaflarski JP, Page SJ, Kissela BM, Lee JH, Levine P and Strakowski SM (2006) Cortical reorganization following modified constraint-induced movement therapy: a study of 4 patients with chronic stroke. *Archives of Physical Medicine and Rehabilitation* 87(8): 1052-1058

Szameitat AJ, Shen S, Conforto A and Sterr A (2012) Cortical activation during executed, imagined, observed, and passive wrist movements in healthy volunteers and stroke patients. *Neuroimage* 62(1): 266-280

Takeuchi N and Izumi S (2012) Maladaptive plasticity for motor recovery after stroke: mechanisms and approaches. *Neural Plasticity* 2012: 359728

Takeuchi N, Tada T, Chuma T, Matsuo Y and Ikoma K (2007) Disinhibition of the premotor cortex contributes to a maladaptive change in the affected hand after stroke. *Stroke* 38(5): 1551-1556

Talelli P, Greenwood RJ and Rothwell JC (2006) Arm function after stroke: neurophysiological correlates and recovery mechanisms assessed by transcranial magnetic stimulation. *Clinical Neurophysiology* 117(8): 1641-1659

Tanaka S, Hachisuka K and Ogata H (1997) Trunk rotatory muscle performance in post-stroke hemiplegic patients. *American Journal of Physical Medicine and Rehabilitation* 76(5): 366-369

Tanaka S, Hachisuka K and Ogata H (1998) Muscle strength of the trunk flexion-extension in post-stroke hemiplegic patients. *American Journal of Physical Medicine and Rehabilitation* 77(4): 288-290

Taub E (2012) The behavior-analytic origins of constraint-induced movement therapy: an example of behavioral neurorehabilitation. *Behavior Analyst* 35(2): 155-178

Taub E and Uswatte G (2013) Constraint-induced movement therapy: a family of neurorehabilitation treatments that harnesses the plasticity of the central nervous system. *Neurologie & Rehabilitation* 19(3): 161-175

Taub E, Uswatte G, Mark V and Morris D (2006) The learned nonuse phenomenon: implications for rehabilitation. *Europa Medicophysica* 42(3): 241-255

Taub E, Uswatte G and Mark VW (2014) The functional significance of cortical reorganization and the parallel development of CI therapy. *Frontiers in Human Neuroscience* 8: 396

Taub E, Uswatte G, Mark VW, Morris DM, Barman J, Bowman MH, Bryson C, Delgado A and Bishop-Mckay S (2013) Method for enhancing real-world use of a more affected arm in chronic stroke: transfer package of constraint-induced movement therapy. *Stroke* 44(5): 1383-1388

Taylor D, Ashburn A and Ward C (1994) Asymmetrical trunk posture, unilateral neglect and motor performance following stroke. *Clinical Rehabilitation* 8(1): 48-52

Teasell R, Bayona NA and Bitensky J (2005) Plasticity and reorganization of the brain post stroke. *Topics in Stroke Rehabilitation* 12(3): 11-26

Teasell R, Mehta S, Pereira S, Mcintyre A, Janzen S, Allen L, Lobo L and Viana R (2012) Time to rethink long-term rehabilitation management of stroke patients. *Topics in Stroke Rehabilitation* 19(6): 457-462

Thelen E and Spencer JP (1998) Postural control during reaching in young infants: a dynamic systems approach. *Neuroscience and Biobehavioral Reviews* 22(4): 507-514

Thewlis D, Bishop C, Daniell N and Paul G (2013) Next-generation low-cost motion capture systems can provide comparable spatial accuracy to high-end systems. *Journal of Applied Biomechanics* 29(1): 112-117

Thielman G (2010) Rehabilitation of reaching poststroke: a randomized pilot investigation of tactile versus auditory feedback for trunk control. *Journal of Neurologic Physical Therapy* 34(3): 138-144

Thielman G (2013) Insights into upper limb kinematics and trunk control one year after task-related training in chronic post-stroke individuals. *Journal of Hand Therapy* 26(2): 156-161

Thielman G, Kaminski T and Gentile AM (2008) Rehabilitation of reaching after stroke: comparing 2 training protocols utilizing trunk restraint. *Neurorehabilitation and Neural Repair* 22(6): 697-705

Thijs VN, Lansberg MG, Beaulieu C, Marks MP, Moseley ME and Albers GW (2000) Is early ischemic lesion volume on diffusion-weighted imaging an independent predictor of stroke outcome? *Stroke* 31(11): 2597-2602

Thilmann AF, Fellows SJ and Ross HF (1991) Biomechanical changes at the ankle joint after stroke. *Journal of Neurology, Neurosurgery & Psychiatry* 54(2): 134-139

Timmermans AA, Seelen HA, Willmann RD and Kingma H (2009) Technology-assisted training of arm-hand skills in stroke: concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *Journal of NeuroEngineering & Rehabilitation* 6: 1

Todd NV, Picozzi P, Crockard A and Russell RW (1986) Duration of ischemia influences the development and resolution of ischemic brain edema. *Stroke* 17(3): 466-471

Toussaint HM, Michies Y, Faber MN, Commissaris DaCM and Van Dieen JH (1998) Scaling anticipatory postural adjustments dependent on confidence of load estimation in a bi-manual whole-body lifting task. *Experimental Brain Research* 120(1): 85-94

Traversa R, Cicinelli P, Bassi A, Rossini PM and Bernardi G (1997) Mapping of motor cortical reorganization after stroke. A brain stimulation study with focal magnetic pulses. *Stroke* 28(1): 110-117

Triandafilou KM and Kamper DG (2012) Investigation of hand muscle atrophy in stroke survivors. *Clinical Biomechanics* 27(3): 268-272

Trombly CA (1992) Deficits of reaching in subjects with left hemiparesis: a pilot study. *American Journal of Occupational Therapy* 46(10): 887-897

Tsuji T, Liu M, Hase K, Masakado Y and Chino N (2003) Trunk muscles in persons with hemiparetic stroke evaluated with computed tomography. *Journal of Rehabilitation Medicine* 35(4): 184-188

Tsuji T, Liu M, Sonoda S, Domen K and Chino N (2000) The stroke impairment assessment set: its internal consistency and predictive validity. *Archives of Physical Medicine and Rehabilitation* 81(7): 863-868

Tunstill SA, Wynn-Davies AC, Nowicky AV, Mcgregor AH and Davey NJ (2001) Corticospinal facilitation studied during voluntary contraction of human abdominal muscles. *Experimental Physiology* 86(1): 131-136

Turton A, Wroe S, Trepete N, Fraser C and Lemon RN (1996) Contralateral and ipsilateral EMG responses to transcranial magnetic stimulation during recovery of arm and hand function after stroke. *Electroencephalography and Clinical Neurophysiology* 101(4): 316-328

Twisk J and De Vente W (2002) Attrition in longitudinal studies: how to deal with missing data. *Journal of Clinical Epidemiology* 55(4): 329–337

Urbin MA, Waddell KJ and Lang CE (2015) Acceleration metrics are responsive to change in upper extremity function of stroke survivors. *Archives of Physical Medicine and Rehabilitation* 96(5): 854-861

Ustinova KI, Goussev VM, Balasubramaniam R and Levin MF (2004) Disruption of coordination between arm, trunk, and center of pressure displacement in patients with hemiparesis. *Motor Control* 8(2): 139-159

Vaartjes I, O'flaherty M, Capewell S, Kappelle J and Bots M (2013) Remarkable decline in ischemic stroke mortality is not matched by changes in incidence. *Stroke* 44(3): 591-597

Van Andel CJ, Wolterbeek N, Doorenbosch CA, Veeger DH and Harlaar J (2008) Complete 3D kinematics of upper extremity functional tasks. *Gait & Posture* 27(1): 120-127

Van Der Fits IBM, Otten E, Klip AWJ, Van Eykern LA and Hadders-Algra M (1999a) The development of postural adjustments during reaching in 6–18-month-old infants: evidence for two transitions. *Experimental Brain Research* 126(4): 517-528

Van Der Fits IBM, Otten E, Klip AWJ, Van Eykern LA and Hadders-Algra M (1999b) Postural adjustments during spontaneous and goal directed arm movement in the Wrst half year of life. *Behavioural Brain Research* 106(1-2): 75-90

Van Der Lee JH, Beckerman H, Lankhorst GJ and Boute RLM (2001) The responsiveness of the Action Research Arm test and the Fugl- Meyer Assessment scale in chronic stroke patients. *Journal of Rehabilitation Medicine* 33(3): 110-113

Van Der Putten J, Hobart J, Freeman J and Thompson A (1999) Measuring change in disability after inpatient rehabilitation- comparison of the responsiveness of the Barthel Index and the Functional Independence Measure. *Journal of Neurology, Neurosurgery & Psychiatry* 66(4): 480-484

Van Dokkum L, Hauret I, Mottet D, Froger J, MéTrot J and Laffont I (2014) The contribution of kinematics in the assessment of upper limb motor recovery early after stroke. *Neurorehabilitation and Neural Repair* 28(1): 4-12

Van Dommelen P, Van Buuren S, Zandwijken GR and Verkerk PH (2005) Individual growth curve models for assessing evidence-based referral criteria in growth monitoring. *Statistics in Medicine* 24(23): 3663-3674

Van Everdingen KJ, Van Der Grond J, Kappelle LJ, Ramos LMP and Mail WPTM (1998) Diffusion-weighted magnetic resonance imaging in acute stroke. *Stroke* 29(9): 1783-1790

Van Kordelaar J, Van Wegen EE and Kwakkel G (2012) Unraveling the interaction between pathological upper limb synergies and compensatory trunk movements during reach-to-grasp after stroke: a cross-sectional study. *Experimental Brain Research* 221(3): 251-262

Van Kuijk AA, Pasman JW, Hendricks HT, Zwarts MJ and Geurts AC (2009) Predicting hand motor recovery in severe stroke: the role of motor evoked potentials in relation to early clinical assessment. *Neurorehabilitation and Neural Repair* 23(1): 45-51

Vargas P, Gaudron M, Valabregue R, Bertasi E, Humbert F, Lehericy S, Samson Y and Rosso C (2013) Assessment of corticospinal tract (CST) damage in acute stroke patients: comparison of tract-specific analysis versus segmentation of a CST template. *Journal of Magnetic Resonance Imaging* 37(4): 836-845

Veale JF (2014) Edinburgh Handedness Inventory - Short Form: a revised version based on confirmatory factor analysis. *Laterality* 19(2): 164-177

Veeger HE (2000) The position of the rotation center of the glenohumeral joint *Journal of Biomechanics* 33(12): 1711-1715

Veerbeek JM, Kwakkel G, Van Wegen EE, Ket JC and Heymans MW (2011) Early prediction of outcome of activities of daily living after stroke: a systematic review. *Stroke* 42(5): 1482-1488

Velozo CA and Woodbury ML (2011) Translating measurement findings into rehabilitation practice: an example using Fugl-Meyer Assessment-Upper Extremity with patients following stroke. *Journal of Rehabilitation Research and Development* 48: 1211-1222

Venketasubramanian N, Tan LC, Sahadevan S, Chin JJ, Krishnamoorthy ES, Hong CY and Saw SM (2005) Prevalence of stroke among Chinese, Malay, and Indian Singaporeans: a community-based tri-racial cross-sectional survey. *Stroke* 36(3): 551-556

Verheyden G, Nieuwboer A, De Wit L, Feys H, Schuback B, Baert I, Jenni W, Schupp W, Thijs V and De Weerdt W (2007) Trunk performance after stroke: an eye catching predictor of functional outcome. *Journal of Neurology, Neurosurgery & Psychiatry* 78(7): 694-698

Verheyden G, Nieuwboer A, De Wit L, Thijs V, Dobbelaere J, Devos H, Severijns D, Vanbeveren S and De Weerdt W (2008) Time course of trunk, arm, leg, and functional recovery after ischemic stroke. *Neurorehabilitation and Neural Repair* 22(2): 173-179

Verheyden G, Nieuwboer A, Feys H, Thijs V, Vaes K and De Weerdt W (2005) Discriminant ability of the Trunk Impairment Scale: A comparison between stroke patients and healthy individuals. *Disability and Rehabilitation* 27(17): 1023-1028

Verheyden G, Nieuwboer A, Mertin J, Preger R, Kiekens C and De Weerdt W (2004) The Trunk Impairment Scale: a new tool to measure motor impairment of the trunk after stroke. *Clinical Rehabilitation* 18(3): 326-334

Verheyden G, Van Duijnhoven HJ, Burnett M, Littlewood J, Kunkel D, Ashburn AM and Stroke Association Rehabilitation Research C (2011) Kinematic analysis of head, trunk, and pelvis movement when people early after stroke reach sideways. *Neurorehabilitation and Neural Repair* 25(7): 656-663

Verheyden G, Vereeck L, Truijen S, Troch M, Herregodts I, Lafosse C, Nieuwboer A and De Weerdt W (2006) Trunk performance after stroke and the relationship with balance, gait and functional ability. *Clinical Rehabilitation* 20(5): 451-458

Verheyden G, Vereeck L, Truijen S, Troch M, Lafosse C, Saeys W, Leenaerts E, Palinckx A and De Weerdt W (2009) Additional exercises improve trunk performance after stroke: a pilot randomized controlled trial. *Neurorehabilitation and Neural Repair* 23(3): 281-286

Verstynen T, Diedrichsen J, Albert N, Aparicio P and Ivry RB (2005) Ipsilateral motor cortex activity during unimanual hand movements relates to task complexity. *Journal of Neurophysiology* 93(3): 1209-1222

Vleeming A, Pool-Goudzwaard AL, Stoeckart R, Van Wingerden JP and Snijders CJ (1995) The posterior layer of the thoracolumbar fascia: its function in load transfer from spine to legs. *Spine (Phila Pa 1976)* 20(7): 753-758

Vleeming A, Schuenke MD, Danneels L and Willard FH (2014) The functional coupling of the deep abdominal and paraspinal muscles: the effects of simulated paraspinal muscle contraction on force transfer to the middle and posterior layer of the thoracolumbar fascia. *Journal of Anatomy* 225(4): 447-462

Voelkle MC (2007) Latent growth curve modeling as an integrative approach to the analysis of change. *Psychological Science* 49(4): 375-414

Vogt G, Laage R, Shuaib A, Schneider A and Collaboration V (2012) Initial lesion volume is an independent predictor of clinical stroke outcome at day 90: an analysis of the Virtual International Stroke Trials Archive (VISTA) database. *Stroke* 43(5): 1266-1272

Von Hofsten C (1982) Eye-hand coordination in the newborn. *Developmental Psychology* 18(3): 450-461

Von Hofsten C (1991) Structuring of early reaching movements: a longitudinal study. *Journal of Motor Behavior* 23(4): 280-292

Wade D, Hewer R, Wood V, Skilbeck C and Ismail H (1983) The hemiplegic arm after stroke : measurement and recovery. *Journal of Neurology, Neurosurgery & Psychiatry* 46(6): 521-524

Wagner JM, Dromerick AW, Sahrmann SA and Lang CE (2007) Upper extremity muscle activation during recovery of reaching in subjects with post-stroke hemiparesis. *Clinical Neurophysiology* 118(1): 164-176

Wagner JM, Rhodes JA and Patten C (2008) Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Physical Therapy* 88(5): 652-663

Waites CL, Craig AM and Garner CC (2005) Mechanisms of vertebrate synaptogenesis. *Annual Review of Neuroscience* 28: 251-274

Wang C, Hsueh I, Sheu C and Hsieh C (2005) Discriminative, predictive, and evaluative properties of a trunk control measure in patients with stroke. *Physical Therapy* 85(9): 887-894

Wang H, Camicia M, Terdiman J, Mannava MK, Sidney S and Sandel ME (2013) Daily treatment time and functional gains of stroke patients during inpatient rehabilitation. *PM & R* 5(2): 122-128

Ward NS (2005) Mechanisms underlying recovery of motor function after stroke. *Postgraduate Medical Journal* 81(958): 510-514

Ward NS, Brown MM, Thompson AJ and Frackowiak RSJ (2003) Neural correlates of outcome after stroke: a cross-sectional fMRI study. *Brain* 126(Pt 6): 1430-1448

Ward NS and Cohen LG (2004) Mechanisms underlying recovery of motor function after stroke. *Archives of Neurology* 61(12): 1844-1848

Ward NS, Newton JM, Swayne OB, Lee L, Frackowiak RS, Thompson AJ, Greenwood RJ and Rothwell JC (2007) The relationship between brain activity and peak grip force is modulated by corticospinal system integrity after subcortical stroke. *European Journal of Neuroscience* 25(6): 1865-1873

Ward NS, Newton JM, Swayne OB, Lee L, Thompson AJ, Greenwood RJ, Rothwell JC and Frackowiak RS (2006) Motor system activation after subcortical stroke depends on corticospinal system integrity. *Brain* 129(Pt 3): 809-819

Warner MB, Chappell PH and Stokes MJ (2012) Measuring scapular kinematics during arm lowering using the acromion marker cluster. *Human Movement Science* 31(2): 386-396

Warner MB, Chappell PH and Stokes MJ (2015) Measurement of dynamic scapular kinematics using an acromion marker cluster to minimize skin movement artifact. *Journal of Visualized Experiments* 96: e51717

Warschausky S, Kay JB and Kewman DG (2001) Hierarchical linear modeling of FIM instrument growth curve characteristics after spinal cord injury. *Archives of Physical Medicine and Rehabilitation* 82(3): 329-334

Wassermann EM, Fuhr P, Cohen LG and Hallet M (1991) Effects of transcranial magnetic stimulation on ipsilateral muscles. *Neurology* 41(11): 1795-1799

Wee SK, Hughes AM, Warner M and Burridge JH (2014) Trunk restraint to promote upper extremity recovery in stroke patients: A systematic review and meta-analysis. *Neurorehabilitation and Neural Repair* 28(7): 660-677

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB and Burridge JH (2015a) Effect of trunk support on upper extremity function in people with chronic stroke and people who are healthy. *Physical Therapy* 95(8): 1163-1171

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH, Yeo SCD, Kong KH and Chan KF (2015b) Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. *Physiotherapy* 101(Supplement 1): eS1619

Weightman MM (1994) Motor unit behavior following cerebrovascular accident. *Neurology Report* 18(1): 26-28

Weiller C, Chollet F, Friston KJ, Wise RJ and Frackowiak RS (1992) Functional reorganization of the brain in recovery from striatocapsular infarction in man. *Annals of Neurology* 31(5): 463-472

Weiller C, Ramsay SC, Wise RJS, Friston KJ and Frackowiak RSJ (1993) Individual patterns of functional reorganization in the human cerebral cortex after capsular infarction. *Annals of Neurology* 33(2): 181-189

Wenzelburger R, Kopper F, Frenzel A, Stolze H, Klebe S, Brossmann A, Kuhtz-Buschbeck J, Golge M, Illert M and Deuschl G (2005) Hand coordination following capsular stroke. *Brain* 128(Pt 1): 64-74

Werhahn KJ, Conforto AB, Kadom N, Hallett M and Cohen LG (2003) Contribution of the ipsilateral motor cortex to recovery after chronic stroke. *Annals of Neurology* 54(4): 464-472

Werring DJ, Toosy AT, Clark CA, Parker GJM, Barker GJ, Miller DH and Thompson AJ (2000) Diffusion tensor imaging can detect and quantify corticospinal tract degeneration after stroke. *Journal of Neurology, Neurosurgery & Psychiatry* 69(2): 269-272

Willard FH, Vleeming A, Schuenke MD, Danneels L and Schleip R (2012) The thoracolumbar fascia: anatomy, function and clinical considerations. *Journal of Anatomy* 221(6): 507-536

Willett JB (1994) Measurement of change IN*:* Husen T and Postlethwaite TN (eds) *International Encyclopedia of Education.* 2nd Edition Oxford, UK: Elsevier Science Press 671-678

Willett JB (1997) Measuring change: what individual growth modeling buys you IN*:* Amsel E and Renninger KA (eds) *Change and Development: issues of Theory, Method, and Application.* Mahwah, NJ: Lawrence Erlbaum Associates 213-243

Winzeler-Mercay U and Mudie H (2002) The nature of the effects of stroke on trunk flexor and extensor muscles during work and at rest. *Disability and Rehabilitation* 24(17): 875-886

Witte OW (1998) Lesion-induced plasticity as a potential mechanism for recovery and rehabilitative training. *Current Opinion in Neurology* 11(6): 655-662

Witte OW, Bidmon HJ, Schiene K, Redecker C and Hagemann G (2000) Functional differentiation of multiple perilesional zones after focal cerebral ischemia. *Journal of Cerebral Blood Flow and Metabolism* 20(8): 1149-1165

Wittekind A, Raeder S and Grote G (2009) A longitudinal study of determinants of perceived employability. *Journal of Organizational Behavior* 31(4): 566-586

Wolf SL, Catlin PA, Ellis M, Archer AL, Morgan B and Piacentino A (2001) Assessing Wolf Motor Function Test as outcome measure for research in patients after stroke. *Stroke* 32(7): 1635-1639

Wolf SL, Mcjunkin JP, Swanson ML and Weiss PS (2006) Pilot normative database for the Wolf Motor Function Test. *Archives of Physical Medicine and Rehabilitation* 87(3): 443-445

Wolf SL, Thompson PA, Morris DM, Rose DK, Winstein CJ, Taub E, Giuliani C and Pearson SL (2005) The EXCITE trial: attributes of the Wolf Motor Function Test in patients with subacute stroke. *Neurorehabilitation and Neural Repair* 19(3): 194-205

Wolfinger RD (1996) Heterogeneous variance-covariance structures for repeated measures. *Journal of Agricultural, Biological, and Environmental Statistics* 1(2): 205-230

Woltman H, Feldstain A, Mackay JC and Rocchi M (2012) An introduction to hierarchical linear modeling. *Tutorials in Quantitative Methods for Psychology* 8(1): 52-69

Wong WY, Wong MS and Lo KH (2007) Clinical applications of sensors for human posture and movement analysis: a review. *Prosthetics and Orthotics International* 31(1): 62-75

Woodbury ML, Howland DR, Mcguirk TE, Davis SB, Senesac CR, Kautz S and Richards LG (2009) Effects of trunk restraint combined with intensive task practice on poststroke upper extremity reach and function: a pilot study. *Neurorehabilitation and Neural Repair* 23(1): 78-91

Woodbury ML, Velozo CA, Richards LG, Duncan PW, Studenski S and Lai SM (2007) Dimensionality and construct validity of the Fugl-Meyer Assessment of the upper extremity. *Archives of Physical Medicine and Rehabilitation* 88(6): 715-723

Woodbury ML, Velozo CA, Richards LG, Duncan PW, Studenski S and Lai SM (2008) Longitudinal stability of the Fugl-Meyer Assessment of the upper extremity. *Archives of Physical Medicine and Rehabilitation* 89(8): 1563-1569

Woodhouse G, Yang M, Goldstein H and Rasbash J (1996) Adjusting for measurement error in multilevel analysis. *Journal of the Royal Statistical Society: Series A* 159(2): 201-212

World Health Organisation (1988) The World Health Organization MONICA Project (monitoring trends and determinants in cardiovascular disease): a major international collaboration. *Journal of Clinical Epidemiology* 41(2): 105-114

World Health Organisation (2013) How to use the ICF: A Practical Manual for using the International Classification of Functioning, Disability and Health (ICF). Exposure draft for comment. 2013

Wright A, Hannon J, Hegedus EJ and Kavchak AE (2012) Clinimetrics corner: a closer look at the minimal clinically important difference (MCID). *Journal of Manual & Manipulative Therapy* 20(3): 160-166

Wu CY, Chen YA, Chen HC, Lin KC and Yeh IL (2012a) Pilot trial of distributed constraint-induced therapy with trunk restraint to improve poststroke reach to grasp and trunk kinematics. *Neurorehabilitation and Neural Repair* 26(3): 247-255

Wu CY, Chen YA, Lin KC, Chao CP and Chen YT (2012b) Constraint-induced therapy with trunk restraint for improving functional outcomes and trunk-arm control after stroke: a randomized controlled trial. *Physical Therapy* 92(4): 483-492

Wu CY, Fu T, Lin KC, Feng CT, Hsieh KP, Yu HW, Lin CH, Hsieh CJ and Ota H (2011) Assessing the Streamlined Wolf Motor Function Test as an outcome measure for stroke rehabilitation. *Neurorehabilitation and Neural Repair* 25(2): 194-199

Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'lima DD, Cristofolini L, Witte H, Schmid O, Stokes I and Standardization and Terminology Committee of the International Society of Biomechanics (2002) ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I- ankle, hip, and spine. *Journal of Biomechanics* 35(4): 543-548

Wu G, Van Der Helm FCT, Veeger HEJ, Makhsous M, Van Roy P, Anglin C, Nagels J, Karduna AR, Mcquade K, Wang X, Werner FW and Buchholz B (2005) ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics* 38(5): 981-992

Yang F and Feldman AG (2010) Reach-to-grasp movement as a minimization process. *Experimental Brain Research* 201(1): 75-92

Yao J, Sheaff C, Carmona C and Dewald JP (2015) Impact of shoulder abduction loading on brain-machine interface in predicting hand opening and closing in individuals with chronic stroke. *Neurorehabilitation and Neural Repair* Published online 27 July 2015

Yassi N, Churilov L, Campbell BC, Sharma G, Bammer R, Desmond PM, Parsons MW, Albers GW, Donnan GA, Davis SM, Epithet and Defuse Investigators

(2015) The association between lesion location and functional outcome after ischemic stroke. *International Journal of Stroke*

Yen S-C, Corkery MB, Chui KK, Manjourides J, Wang Y-C and Resnik LJ (2015) Risk adjustment for lumbar dysfunction: comparison of linear mixed models with and without inclusion of between-clinic variation as a random effect. *Physical Therapy*: Published online 23rd April 2015

Yeo SS and Jang SH (2012) Ipsilateral motor pathway without contralateral motor pathway in a stroke patient. *NeuroRehabilitation* 30(4): 303-306

Yiou E, Caderby T and Hussein T (2012) Adapatbility of anticipatory postural adjustments associated with voluntary movement. *World Journal of Orthopaedics* 3(6): 75-86

York DH (1987) Review of descending motor pathways involved with transcranial stimulation. *Neurosurgery* 20(1): 70-73

Young J and Forster A (2007) Review of stroke rehabilitation. *British Medical Journal* 334(7584): 86-90

Yozbatiran N, Der-Yeghiaian L and Cramer SC (2008) A standardized approach to performing the action research arm test. *Neurorehabilitation and Neural Repair* 22(1): 78-90

Yu WH, Hsueh IP, Hou WH, Wang YH and Hsieh CL (2012) A comparison of responsiveness and predictive validity of two balance measures in patients with stroke. *Journal of Rehabilitation Medicine* 44(2): 176-180

Yu X and Zuo Y (2011) Spine plasticity in the motor cortex. *Current Opinion in Neurobiology* 21(1): 169-174

Zakaria Y, Rashad U and Mohamed R (2010) Assessment of malalignment of trunk and pelvis in stroke patients. *Egyptian Journal of Neurology, Psychiatry and Neurosurgery* 47(4): 599-604

Zarahn E, Alon L, Ryan SL, Lazar RM, Vry MS, Weiller C, Marshall RS and Krakauer JW (2011) Prediction of motor recovery using initial impairment and fMRI 48 h poststroke. *Cerebral Cortex* 21(12): 2712-2721

Zatsiorsky VM (1998) *Kinematics of human motion.* Champaign, IL: Human Kinetics.

Zattara M and Bouisset S (1986) Chronometric analysis of posturo-kinetic programming of voluntary movement. *Journal of Motor Behavior* 18(2): 215-223

Zattara M and Bouisset S (1988) Posturo-kinetic organisation during the early phase of voluntary upper limb movement. 1. Normal subjects. *Journal of Neurology, Neurosurgery & Psychiatry* 51(7): 956-965

Zazulak B, Cholewicki J and Reeves P (2008) Neuromuscular control of trunk stability: clinical implications for sports injury prevention. *Journal of the American Academy of Orthopaedic Surgeons* 16(9): 497-505

Zazulak BT, Hewett TE, Reeves NP, Goldberg B and Cholewicki J (2007) Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *American Journal of Sports Medicine* 35(7): 1123-1130

Zeiler S and Krakauer JW (2013) The interaction between training and plasticity in the poststroke brain. *Current Opinion in Neurology* 26: 609-616

Zemke AC, Heagerty PJ, Lee C and Cramer SC (2003) Motor cortex organization after stroke is related to side of stroke and level of recovery. *Stroke* 34(5): e23-e26

Zhang J, Meng L, Qin W, Liu N, Shi FD and Yu C (2014) Structural damage and functional reorganization in Ipsilesional M1 in well-recovered patients with subcortical stroke. *Stroke* 45(3): 788-793

Zhang S, Boyd J, Delaney K and Murphy TH (2005) Rapid reversible changes in dendritic spine structure in vivo gated by the degree of ischemia. *Journal of Neuroscience* 25(22): 5333-5338

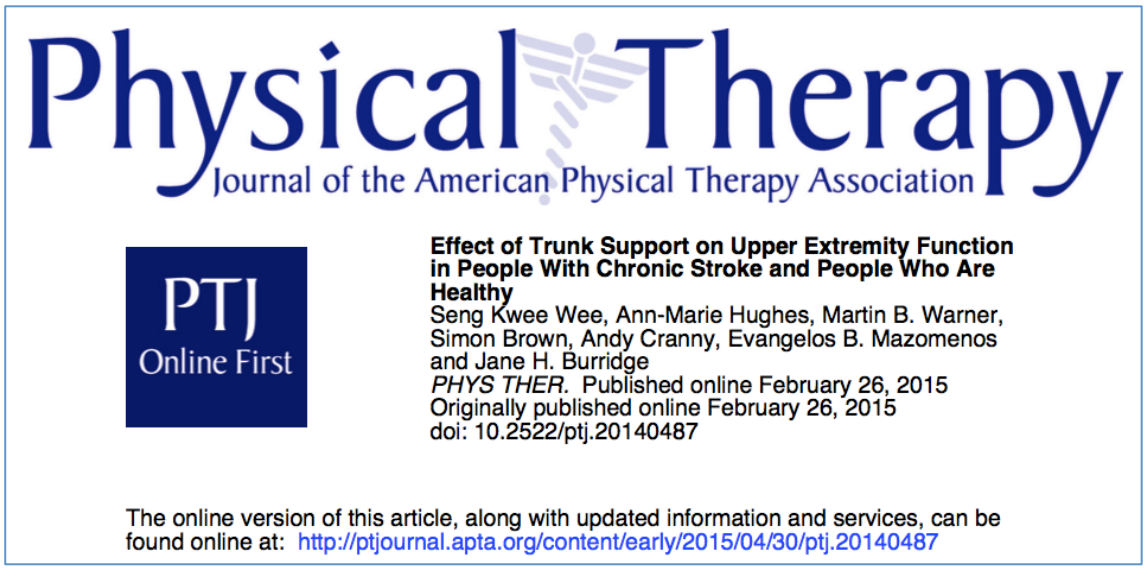
Zhang Y, Chapman AM, Plested M, Jackson D and Purroy F (2012) The incidence, prevalence, and mortality of stroke in France, Germany, Italy, Spain, the UK, and the US: a literature review. *Stroke Research and Treatment* 2012: 436125

Zhu LL, Lindenberg R, Alexander MP and Schlaug G (2010) Lesion load of the corticospinal tract predicts motor impairment in chronic stroke. *Stroke* 41(5): 910-915

Appendices

Appendix 1: Effect of trunk support on upper extremity function in people with chronic stroke and people who are healthy.

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH (2015) Effect of trunk support on upper extremity function in people with chronic stroke and people who are healthy. *Physical Therapy*. Published online February 26, 2015 doi: 10.2522/ptj.20140487



Appendix 2: Trunk restraint to promote upper extremity recovery in stroke patients: A systematic review and meta-analysis

Wee SK, Hughes AM, Warner MB and Burridge JH (2014) Trunk restraint to promote upper extremity recovery in stroke patients: A systematic review and meta-analysis. *Neurorehabil Neural Repair* 28(7): 660-677
DOI: 10.1177/1545968314521011.

Clinical Research Article

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Seng Kwee Wee, PT[1,2], Ann-Marie Hughes, PhD[1], Martin Warner, PhD[1], and Jane H. Burridge, PhD[1]

Abstract

Background. Many stroke patients exhibit excessive compensatory trunk movements during reaching. Compensatory movement behaviors may improve upper extremity function in the short-term but be detrimental to long-term recovery. *Objective.* To evaluate the evidence that trunk restraint limits compensatory trunk movement and/or promotes better upper extremity recovery in stroke patients. *Methods.* A search was conducted through electronic databases from January 1980 to June 2013. Only randomized controlled trials (RCTs) comparing upper extremity training with and without trunk restraint were selected for review. Three review authors independently assessed the methodological quality and extracted data from the studies. Meta-analysis was conducted when there was sufficient homogenous data. *Results.* Six RCTs involving 187 chronic stroke patients were identified. Meta-analysis of key outcome measures showed that trunk restraint has a moderate statistically significant effect on improving Fugl-Meyer Upper Extremity (FMA-UE) score, active shoulder flexion, and reduction in trunk displacement during reaching. There was a small, nonsignificant effect of trunk restraint on upper extremity function. *Conclusion.* Trunk restraint has a moderate effect on reduction of upper extremity impairment in chronic stroke patients, in terms of FMA-UE score, increased shoulder flexion, and reduction in excessive trunk movement during reaching. There is insufficient evidence to demonstrate that trunk restraint improves upper extremity function and reaching trajectory smoothness and straightness in chronic stroke patients. Future research on stroke patients at different phases of recovery and with different levels of upper extremity impairment is recommended.

Appendix 3: Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls

Wee SK, Hughes AM, Warner MB, Brown S, Cranny A, Mazomenos EB, Burridge JH, Yeo SCD, Kong KH and Chan KF (2015) Impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls. *Physiotherapy* 101(Supplement 1): eS1619

WCPT Congress 2015 / Physiotherapy 2015; Volume 101, Supplement 1 eS1238–eS1642 eS1619

Research Report Platform Presentation
Number: RR-PL-1198
Saturday 2 May 2015 16:00
Room 328–329

IMPACT OF TRUNK CONTROL ON UPPER EXTREMITY FUNCTION IN SUBACUTE AND CHRONIC STROKE PATIENTS AND HEALTHY CONTROLS

S.K. Wee [1,2], A.M. Hughes [1], M.B. Warner [1], S. Brown [1], A. Cranny [3], E.B. Mazomenos [3], J.H. Burridge [1], S.C. Doreen Yeo [2], K.H. Kong [2], K.F. Chan [2]

[1] *University of Southampton, Rehabilitation & Health Technologies Research Group, Faculty of Health Sciences, Southampton, United Kingdom*; [2] *Tan Tock Seng Hospital, Rehabilitation Centre, Singapore, Singapore*; [3] *University of Southampton, Electronics and Computer Science, Faculty of Physical Sciences and Engineering, Southampton, United Kingdom*

Background: Impaired trunk control is commonly observed following a stroke. The trunk is considered an important postural stabiliser that enables dissociation of upper extremity (UE) from the trunk for function. However, this common assumption in neurorehabilitation has not been validated in clinical trials. The relationship between trunk control and UE function in stroke patients is currently unknown. This knowledge is critical to the design of targeted rehabilitation programmes for the trunk and UE so that optimal functional outcomes for stroke patients can be achieved.

Purpose: To evaluate the impact of trunk control on upper extremity function in subacute and chronic stroke patients and healthy controls.

Methods: Twenty-five subacute and 25 chronic stroke patients, as well as 25 age- and sex-matched healthy controls were recruited. Trunk control was assessed using the Trunk Impairment Scale (TIS), UE impairment and function were assessed with Fugl-Meyer (FMA-UE) and Streamlined Wolf Motor Function Test (SWMFT) respectively. Participants performed the SWMFT tasks, with and without an external trunk support in random order.

Results: The split-plot analysis of variance revealed a significant main effect of trunk support on TIS ($F_{(1,72)} = 128.02$, $p < 0.001$), with a large effect size (partial Eta-squared = 0.64). With trunk support, the improvement in TIS was greatest for the subacute stroke group (from 13.12 to 18.08 points) as compared to the chronic stroke group (from 18.00 to 20.00 points) and the healthy group (from 22.48 to 22.80 points).

There was a significant main effect of trunk support on SWMFT performance time (SWMFT-Time) ($F_{(1,72)} = 6.08$, $p < 0.05$) of the affected UE, with a moderate effect size (partial Eta-squared = 0.08). With trunk support, the reduction in SWMFT-Time was greatest for the subacute stroke group (from 65.64 to 63.76 seconds) as compared to the chronic stroke group (from 29.39 to 27.99 seconds) and the healthy group (from 1.46 to 1.36 seconds).

The Wilcoxon signed rank test demonstrated that, with trunk support, there was a significant improvement in the affected UE function (SWMFT-Functional Ability Scale, SWMFT-FAS) from median 1.3 to 1.4 points ($p < 0.001$) for subacute stroke patients, and from median 3.3 to 3.4 points ($p < 0.01$) for chronic stroke patients.

In stroke patients and healthy controls (without trunk support), strong correlations were found between TIS and SWMFT-Time (Spearman's $\rho = -0.76$; $p < 0.001$); TIS and SWMFT-FAS (Spearman's $\rho = 0.81$; $p < 0.001$); TIS and FMA-UE (Spearman's $\rho = 0.66$; $p < 0.001$).

Conclusion(s): External trunk support improves trunk control and UE function in subacute and chronic stroke patients and healthy controls. Strong association was found between trunk control and UE function.

Stabilisation of the trunk with an external support may improve movement of the proximal and distal segments of the UE. Stabilisation reduces the number of degrees of freedom and therefore decreases the control demand on the motor system. In consequence, this may facilitate better coordinated movements and improve UE function.

Implications: Targeted rehabilitation programmes for the trunk may have an impact on the UE function in subacute and chronic stroke patients. Combined trunk and UE rehabilitation approaches have the potential to yield better functional outcomes.

Keywords: Trunk control; upper extremity; stroke rehabilitation

Funding acknowledgements: This work was partly supported by the European Union under the Seventh Framework Programme, grant agreement #288692, StrokeBack.

Ethics approval: (1) Institutional Review Board of University of Southampton, UK: Ethics number 7547. (2) Domain Specific Review Board of National Healthcare Group, Singapore: Ethics number 2014/00229.

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Appendix 4: Streamlined Wolf Motor Function Test (subacute stroke version)

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STREAMLINED WOLF MOTOR FUNCTION TEST
(Subacute Stroke version)

Participant ID : _____ Assessment : 1 / 2 / 3 / 4 / 5 / 6

Date of assessment : _____

Assessor : _____ Signature : _____

Arm tested : □ More affected □ Less affected

	TASK	TIME (seconds)	FUNCTIONAL ABILITY SCALE						Remarks
1	Hand to table (front)		0	1	2	3	4	5	
2	Hand to box (front)		0	1	2	3	4	5	
3	Lift can		0	1	2	3	4	5	
4	Lift pencil		0	1	2	3	4	5	
5	Fold towel		0	1	2	3	4	5	
6	Reach and retrieve		0	1	2	3	4	5	

Mean Time	Mean FAS

Score	Functional Ability Scale (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

Appendix 5: Streamlined Wolf Motor Function Test (chronic stroke version)

Health Sciences

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STREAMLINED WOLF MOTOR FUNCTION TEST
(Chronic Stroke version)

Participant ID : _____ Assessment : 1 / 2 / 3 / 4 / 5 / 6

Date of assessment : _____

Assessor : _____ Signature : _____

Arm tested : □ More affected □ Less affected

	TASK	TIME (seconds)	FUNCTIONAL ABILITY SCALE						Remarks
1	Hand to box (front)		0	1	2	3	4	5	
2	Lift can		0	1	2	3	4	5	
3	Lift pencil		0	1	2	3	4	5	
4	Fold towel		0	1	2	3	4	5	
5	Turn key in lock		0	1	2	3	4	5	
6	Extend elbow (1 lb weight)		0	1	2	3	4	5	

Mean Time	Mean FAS

Score	Functional Ability Scale (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

Appendix 6: Movement components of tasks in Streamlined Wolf Motor Function (subacute stroke version)

Task	Shoulder	Elbow	Wrist/Forearm	Fingers
Hand to table (front)	Flexion	Flexion Extension		
Hand to box (front)	Flexion	Flexion Extension		
Reach and retrieve	Internal rotation [Stabilization]	Flexion		
Lift can	Flexion [Stabilization]	Flexion Extension	Forearm neutral [Wrist stabilization]	Cylindrical grip
Life pencil	Flexion [Stabilization]	Flexion Extension	Wrist stabilization	Three-jaw chuck grip (thumb, index, middle fingers)
Fold towel	Flexion Extension Internal rotation Horizontal adduction [Stabilization]	Flexion Extension	Wrist extension/flexion Ulnar/radial deviation of wrist Forearm Pronation/supination	Pincer grip

Appendix 7: Movement components of Streamlined Wolf Motor Function Test (chronic stroke version)

Task	Shoulder	Elbow	Wrist/Forearm	Fingers
Hand to box (front)	Flexion	Flexion Extension		
Extend elbow (1 lb weight)	Slight external rotation [Stabilization]	Extension		
Lift can	Flexion [Stabilization]	Flexion Extension	Forearm neutral [Wrist stabilization]	Cylindrical grip
Life pencil	Flexion [Stabilization]	Flexion Extension	Wrist stabilization	Three-jaw chuck grip (thumb, index, middle fingers)
Fold towel	Flexion Extension Internal rotation Horizontal adduction [Stabilization]	Flexion Extension	Ulnar deviation of wrist Forearm Pronation/supination	Pincer grip
Turn key in lock	Flexion [Stabilization]	Flexion Extension	Ulnar/radial deviation of wrist Forearm Pronation/supination	Modified pincer grip (thumb and side of index finger)

Appendix 8: Streamlined Wolf Motor Function Test (combined version)

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STREAMLINED WOLF MOTOR FUNCTION TEST (without Trunk Support)

Participant ID : _____
Date of assessment : _____

Assessment : 1 / 2 / 3 / 4 / 5 / 6
Assessor : _____
Signature : _____

Hand dominance : □ Right □ Left
Affected side : □ Right □ Left

	TASK	RIGHT Time (seconds)	RIGHT Functional Ability Scale						LEFT Time (seconds)	LEFT Functional Ability Scale					
1	Hand to table (front)		0	1	2	3	4	5		0	1	2	3	4	5
2	Hand to box (front)		0	1	2	3	4	5		0	1	2	3	4	5
3	Lift can		0	1	2	3	4	5		0	1	2	3	4	5
4	Lift pencil		0	1	2	3	4	5		0	1	2	3	4	5
5	Fold towel		0	1	2	3	4	5		0	1	2	3	4	5
6	Turn key in lock		0	1	2	3	4	5		0	1	2	3	4	5
7	Reach and retrieve		0	1	2	3	4	5		0	1	2	3	4	5
8	Extend elbow (1 lb weight)		0	1	2	3	4	5		0	1	2	3	4	5
	MEAN														

Score	Functional Ability Scale (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

Health Sciences

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STREAMLINED WOLF MOTOR FUNCTION TEST (with Trunk Support)

Participant ID : _____
Date of assessment : _____

Assessment : 1 / 2 / 3 / 4 / 5 / 6
Assessor : _____
Signature : _____

Hand dominance : □ Right □ Left
Affected side : □ Right □ Left

		RIGHT							LEFT						
	TASK	Time (seconds)	Functional Ability Scale						Time (seconds)	Functional Ability Scale					
1	Hand to table (front)		0	1	2	3	4	5		0	1	2	3	4	5
2	Hand to box (front)		0	1	2	3	4	5		0	1	2	3	4	5
3	Lift can		0	1	2	3	4	5		0	1	2	3	4	5
4	Lift pencil		0	1	2	3	4	5		0	1	2	3	4	5
5	Fold towel		0	1	2	3	4	5		0	1	2	3	4	5
6	Turn key in lock		0	1	2	3	4	5		0	1	2	3	4	5
7	Reach and retrieve		0	1	2	3	4	5		0	1	2	3	4	5
8	Extend elbow (1 lb weight)		0	1	2	3	4	5		0	1	2	3	4	5
	MEAN														

Score	Functional Ability Scale (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

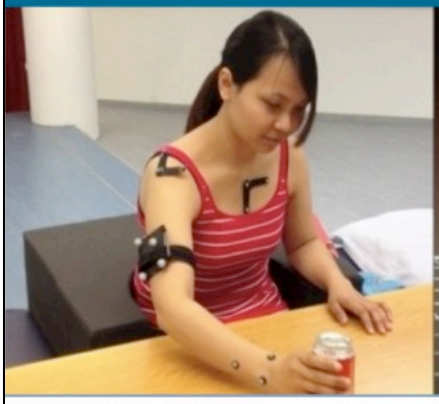
Appendix 9: Advertisement for recruitment of healthy participants (Phase 1A study)

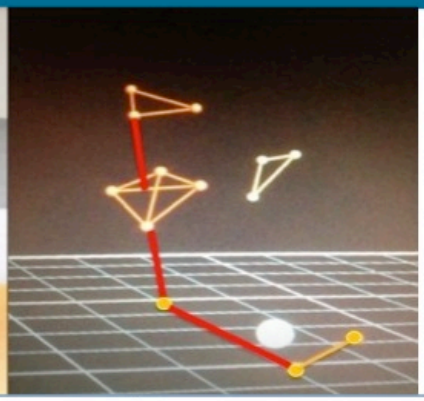
Health Sciences

UNIVERSITY OF Southampton

Ethics number : FoHS-ETHICS 7547

How does your body movement relate to ARM function?





Are you aged between 40 and 80 years?

Would you like to participate in research?

We are looking for healthy male and female individuals to help us gain a deeper understanding about the relationship between body movement and arm function.

What is involved?

- One visit to the motion analysis laboratory in the Faculty of Health Sciences (Building 45). A second visit may be required if you decide to participate in a sub-study of this research. The second visit is entirely voluntary.
- We will assess and capture your body and arm movement using a motion analysis system while you perform 8 simple arm tasks in a seated position.

Your participation would be greatly appreciated.
If you are interested, please contact Mr Seng-Kwee Wee
Email : skw1g12@soton.ac.uk Tel : 07583060106

Trunk Research
Seng-Kwee Wee
skw1g12@soton.ac.uk
Tel: 07583060106

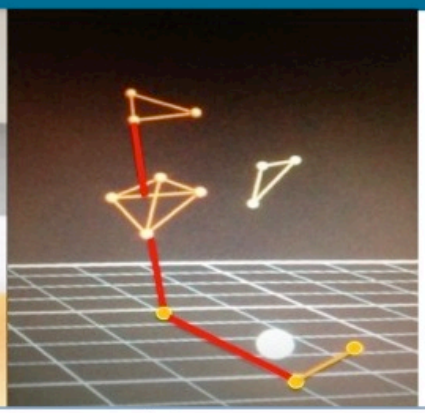
Appendix 10: Advertisement for recruitment of chronic stroke participants (Phase 1A study)

Health Sciences

UNIVERSITY OF Southampton

Ethics number : FoHS-ETHICS 7547

How does your body movement relate to ARM function?



Have you had a stroke?

Was your stroke more than 6 months ago?

Would you like to participate in research?

We are looking for people who have had a stroke to help us gain a deeper understanding about the relationship between body movement and arm function.

What is involved?

- One visit to the motion analysis laboratory in the Faculty of Health Sciences (Building 45). A second visit may be required if you decide to participate in a sub-study of this research. The second visit is entirely voluntary.
- We will assess and capture your body and arm movement using a motion analysis system while you perform 8 simple arm tasks in a seated position.

Your participation would be greatly appreciated.
If you are interested, please contact Mr Seng-Kwee Wee
Email : skw1g12@soton.ac.uk Tel : 07583060106

Trunk Research
Seng-Kwee Wee
skw1g12@soton.ac.uk
Tel: 07583060106

Appendix 11: Invite letter for participants (Phase 1A study)

UNIVERSITY OF Southampton

Date :

Dear Sir / Madam,

Re : Invitation to participate in a research study

I am writing to invite you to take part in a research study based at the University of Southampton. We are looking for people who have had a stroke and those who have not, to help us understand the recovery of trunk and arm after a stroke.

I would like to find out how movement of your arm affects how your trunk moves whilst you perform some simple tasks involving movement of your trunk and arm in a seated position. The assessment will be carried out in the Faculty of Health Sciences (Building 45). You will be required to make only one visit to the laboratory, which should last no longer than two hours. However, we may ask you if you would mind attending a second session, up to a week later, where you will repeat the assessments again.

Once you have read the information sheet, if you are interested in taking part in this study, please email or call me at the telephone number found at the end of this letter. I will answer any questions you may have and will ask you some general questions about your health (and your stroke, if applicable). These questions will help me determine if the assessment is suitable for you. I will then make an appointment for you to come in to the Faculty of Health Sciences, University of Southampton (Building 45) at a convenient day and time for you.

Thank you very much for time and your consideration to participate in the study.

Yours sincerely,

Seng Kwee Wee
PhD Student
Rehabilitation & Health Technologies Research Group
Faculty of Health Sciences
University of Southampton
Southampton SO17 1BJ
United Kingdom

Email : skw1g12@soton.ac.uk
Telephone : 07583060106

Appendix 12: Participant Information Sheet for healthy participants (Phase 1A study)

UNIVERSITY OF Southampton

Participant Information Sheet (Phase 1 study)

Study Title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher: Seng Kwee Wee **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 principal physiotherapist who has 17 years of experience working in brain injury and stroke rehabilitation, particularly for the arm and trunk. I am currently studying for a Doctor of Philosophy degree (PhD) at the University of Southampton and as part of this, I am conducting this research study.

It is important for you to understand why the research is being carried out and what it will involve before you decide. Please take time to read the following information carefully and discuss it with friends, relatives, and your GP if you wish. If something is not clear, or you would like further information, please do not hesitate to contact me at the address below or telephone number given at the end of this information sheet. Thank you for reading this.

What is the research about?
Many people have problems controlling their body, particularly their trunk and arm, after a stroke which can affect their ability to perform activities like sitting upright, being able to balance, and using their arms.

The purpose of this study is to investigate the relationship between being able to control the trunk on how well the arm functions in people who have suffered a stroke.

Gathering information from healthy individuals will help us in the comparison of the trunk and arm movement with the individuals with stroke. The results of this study will help healthcare professionals gain a better understanding of the recovery pattern of the trunk and arm after a stroke. It will assist therapists to predict outcome and to design better rehabilitation programmes to improve the recovery of the trunk and arm after a stroke.

Why have I been chosen?
You have been chosen to take part in this study as:

i) you are aged between 40 to 80 years
ii) you are healthy with no history of neurological, spinal, arm injury or disease

If you decide to take part, you will be one of 45 participants.

UNIVERSITY OF Southampton

Do I have to take part?
You do not have to agree to take part in the study. If you decide to take part you will be asked to sign a consent form. If you decide not to take part or you decide later to withdraw, you do not have to give a reason. This will not affect your current or future health care.

What will happen to me if I take part?
If you return the attached form saying you are interested in taking part then you will be contacted by telephone by the researcher. He will answer any questions you might have and will ask you some general questions about you. These questions will inform the researcher if the assessment is suitable for you. He will then make an appointment for you to come in to the Faculty of Health Sciences, University of Southampton (Building 45) at a convenient day and time for you.

You will be required to make only one visit to the laboratory, which should last no longer than two hours. Please kindly wear or bring along a loose fitting sleeveless T-shirt.

In the research laboratory, you will undergo a series of assessments by the researcher to look at your ability to control your trunk and arm function in a seated position. For the trunk assessment, you will be instructed to move your trunk in all directions, including bending sideways and twisting your body to the right and left side. For the assessment of arm function, you will be required to perform eight tasks such as lifting your arm onto a box on a table, picking up a canned drink, folding a tea towel.

These assessments will be performed twice, once whilst you are seated down with no support around your trunk and once with a foam support around your trunk (Figure 1). Your dominant arm (the arm you use to write with) will be tested first, and then your non-dominant arm will be tested. The researcher will use a stopwatch to time your ability to complete the tasks. If at any point you feel tired you may rest.

Figure 1: Trunk support

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During assessment, we will capture your movements using a motion capture system. This will aid our understanding of how you perform trunk and arm movements. Reflective markers, which are small plastic balls (about the size of a one-penny coin) wrapped in reflective tape, will be attached to your trunk and arm by double-sided adhesive tapes or straps (Figure 2).

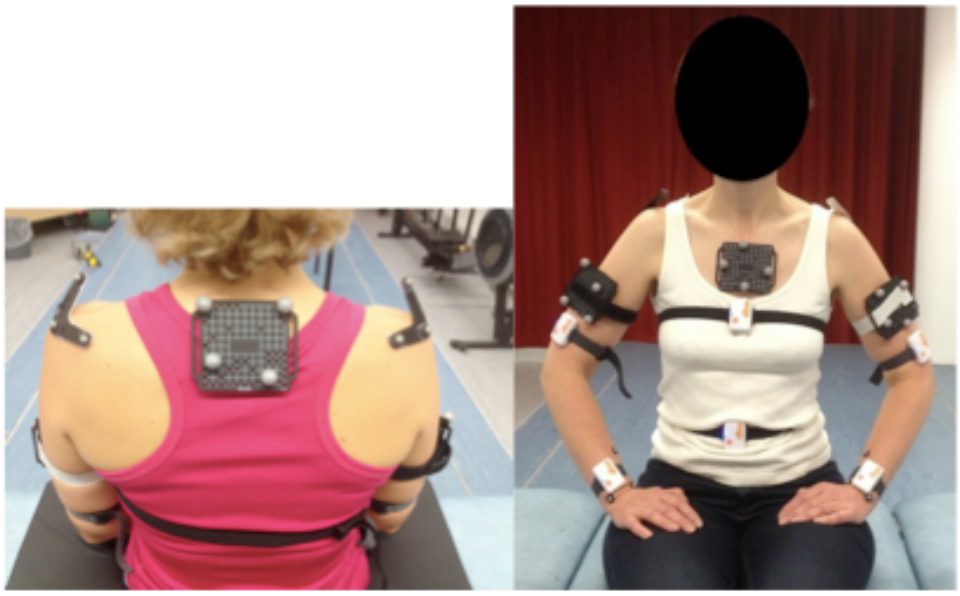

Figure 2: Placement of the reflective markers

Are there any benefits in my taking part?
There will be no direct benefit to you from taking part in the study. However, the data collected will be useful for healthcare professionals to gain a better understanding of the recovery of the trunk and arm after a stroke. It is hoped that this will lead to better rehabilitation programmes for stroke patients in the future.

Are there any risks involved?
There are unlikely to be any side effects or risks from the assessment session. Your arm may feel slightly tired at the end of the session. If at any point you feel tired, you may rest. If you feel unable to continue, you may withdraw. Throughout the session, the researcher will ensure that you are comfortable.

Will my participation be confidential?
All the information collected about you during the course of this research will be kept strictly confidential. Any information about you on research report forms or publications will have your name and address removed so that you cannot be identified from it. You will be assigned 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 study, will be held on a password protected computer or as paper records kept in a locked filing cabinet.

What happens if I change my mind?
You have the right to withdraw at any time without any obligation to state your reasons for withdrawal.

UNIVERSITY OF Southampton

What happens if something goes wrong?
If you become uncomfortable or distressed during the session, you will 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 the Governance Office, at the Research Governance Office (Address: University of Southampton, Building 37, Highfield, Southampton, SO17 1BJ ; Tel: +44 (0)23 8059 5058; Email: rgoinfo@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.

What will happen to the results of the research study?
On completion of the research study, the data collected will be securely stored at the University of Southampton for 10 years according to the University policy. The results will be used to inform research with people who have had a stroke. These results will be presented at scientific conferences and may be published in scientific journals. Please let us know if you would like a copy of the published results at the end of the study.

Who is organising the research study?
The research is organised through the University of Southampton.

Who has reviewed the study?
The Ethics Committee in the Research Governance Office of the University of Southampton have reviewed the research proposal and granted approval before commencement of this study.

Contact for further information
If you would like any further information, please contact:

1) Seng Kwee Wee
   PhD Student
   Rehabilitation & Health Technologies Research Group
   Faculty of Health Sciences (Building 45)
   University of Southampton
   Southampton SO17 1BJ
   United Kingdom

   Telephone :+44(0)7583060106
   Email : skw1g12@soton.ac.uk

2) Professor Jane Burridge
   Professor of Restorative Neuroscience
   Head of Rehabilitation & Health Technologies Research Group
   Faculty of Health Sciences (Building 45)
   University of Southampton
   Southampton SO17 1BJ
   United Kingdom

   Telephone : +44(0)2380598885
   Email : J.H.Burridge@soton.ac.uk

UNIVERSITY OF Southampton

3) Dr Ann-Marie Hughes
Senior Research Fellow
Rehabilitation & Health Technologies Research Group
Faculty of Health Sciences (Building 45)
University of Southampton
Southampton SO17 1BJ
United Kingdom

Telephone : +44(0)2380595191
Email : A.Hughes@soton.ac.uk

4) Dr Martin Warner
Senior Research Fellow (Musculoskeletal Biomechanics)
Arthritis Research UK Centre for Sport, Exercise and Osteoarthritis
Rehabilitation & Health Technologies Research Group
Faculty of Health Sciences (Building 45)
University of Southampton
Southampton SO17 1BJ
United Kingdom

Telephone : +44(0)2380598990
Email : m.warner@soton.ac.uk

Thank you for your consideration to take part in this study. You will be given a copy of the information sheet and a signed consent form to keep.

Appendix 13: Participant Information Sheet for chronic stroke participants (Phase 1A study)

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Participant Information Sheet (Phase 1 study)

Study Title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher: Seng Kwee Wee **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 principal physiotherapist who has 17 years of experience working in brain injury and stroke rehabilitation, particularly for the arm and trunk. I am currently studying for a Doctor of Philosophy degree (PhD) at the University of Southampton and as part of this, I am conducting this research study.

It is important for you to understand why the research is being carried out and what it will involve before you decide. Please take time to read the following information carefully and discuss it with friends, relatives, and your GP if you wish. If something is not clear, or you would like further information, please do not hesitate to contact me at the address below or telephone number given at the end of this information sheet. Thank you for reading this.

What is the research about?
Many people have problems controlling their body, particularly their trunk and arm, after a stroke which can affect their ability to perform activities like sitting upright, being able to balance, and using their arms.

The purpose of this study is to investigate the relationship between being able to control the trunk on how well the arm functions in people who have suffered a stroke. The results of this study will help healthcare professionals gain a better understanding of the recovery pattern of the trunk and arm after a stroke. It will assist therapists to predict outcome and to design better rehabilitation programmes to improve the recovery of the trunk and arm after a stroke.

Why have I been chosen?
You have been chosen to take part in this study as:

i) you had a stroke more than six months ago
ii) from your stroke you have some movement problems with your affected arm.

If you decide to take part, you will be one of 45 participants.

Do I have to take part?
You do not have to agree to take part in the study. If you decide to take part you will be asked to sign a consent form. If you decide not to take part or you decide later to withdraw, you do not have to give a reason. This will not affect your current or future health care.

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Do I have to take part?
You do not have to agree to take part in the study. If you decide to take part you will be asked to sign a consent form. If you decide not to take part or you decide later to withdraw, you do not have to give a reason. This will not affect your current or future health care.

What will happen to me if I take part?
If you return the attached form saying you are interested in taking part then you will be contacted by telephone by the researcher. He will answer any questions you might have and will ask you some general questions about you. These questions will inform the researcher if the assessment is suitable for you. He will then make an appointment for you to come in to the Faculty of Health Sciences, University of Southampton (Building 45) at a convenient day and time for you.

You will be required to make only one visit to the laboratory, which should last no longer than two hours. Please kindly wear or bring along a loose fitting sleeveless T-shirt.

In the research laboratory, you will undergo a series of assessments by the researcher to look at your ability to control your trunk and arm function in a seated position. For the trunk assessment, you will be instructed to move your trunk in all directions, including bending sideways and twisting your body to the right and left side. For the assessment of arm function, you will be required to perform eight tasks such as lifting your arm onto a box on a table, picking up a canned drink, folding a tea towel.

These assessments will be performed twice, once whilst you are seated down with no support around your trunk and once with a foam support around your trunk (Figure 1). Your dominant arm (the arm you use to write with) will be tested first, and then your non-dominant arm will be tested. The researcher will use a stopwatch to time your ability to complete the tasks. If at any point you feel tired you may rest.

Figure 1: Trunk support

UNIVERSITY OF Southampton

During assessment, we will capture your movements using a motion capture system. This will aid our understanding of how you perform trunk and arm movements. Reflective markers, which are small plastic balls (about the size of a one-penny coin) wrapped in reflective tape, will be attached to your trunk and arm by double-sided adhesive tapes or straps (Figure 2).

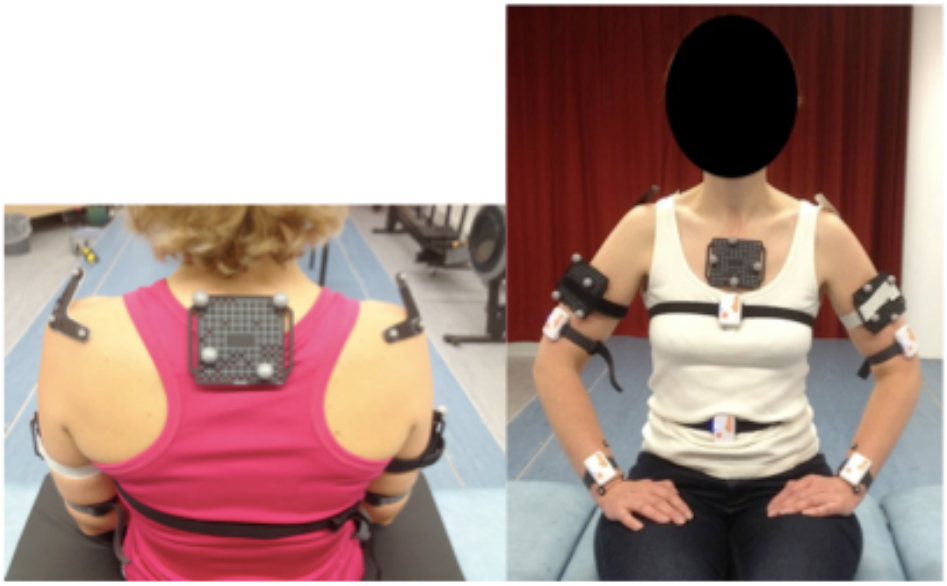

Figure 2: Placement of the reflective markers

Are there any benefits in my taking part?
There will be no direct benefit to you from taking part in the study. However, the data collected will be useful for healthcare professionals to gain a better understanding of the recovery of the trunk and arm after a stroke. It is hoped that this will lead to better rehabilitation programmes for stroke patients in the future.

Are there any risks involved?
There are unlikely to be any side effects or risks from the assessment session. Your arm may feel slightly tired at the end of the session. If at any point you feel tired, you may rest. If you feel unable to continue, you may withdraw. Throughout the session, the researcher will ensure that you are comfortable.

Will my participation be confidential?
All the information collected about you during the course of this research will be kept strictly confidential. Any information about you on research report forms or publications will have your name and address removed so that you cannot be identified from it. You will be assigned 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 study, will be held on a password protected computer or as paper records kept in a locked filing cabinet.

What happens if I change my mind?
You have the right to withdraw at any time without any obligation to state your reasons for withdrawal.

UNIVERSITY OF Southampton

What happens if something goes wrong?
If you become uncomfortable or distressed during the session, you will 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 the Governance Office, at the Research Governance Office (Address: University of Southampton, Building 37, Highfield, Southampton, SO17 1BJ ; Tel: +44 (0)23 8059 5058; Email: rgoinfo@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.

What will happen to the results of the research study?
On completion of the research study, the data collected will be securely stored at the University of Southampton for 10 years according to the University policy. The results will be used to inform research with people who have had a stroke. These results will be presented at scientific conferences and may be published in scientific journals. Please let us know if you would like a copy of the published results at the end of the study.

Who is organising the research study?
The research is organised through the University of Southampton.

Who has reviewed the study?
The Ethics Committee in the Research Governance Office of the University of Southampton have reviewed the research proposal and granted approval before commencement of this study.

Contact for further information
If you would like any further information, please contact:

1) Seng Kwee Wee
   PhD Student
   Rehabilitation & Health Technologies Research Group
   Faculty of Health Sciences (Building 45)
   University of Southampton
   Southampton SO17 1BJ
   United Kingdom

   Telephone :+44(0)7583060106
   Email : skw1g12@soton.ac.uk

2) Professor Jane Burridge
   Professor of Restorative Neuroscience
   Head of Rehabilitation & Health Technologies Research Group
   Faculty of Health Sciences (Building 45)
   University of Southampton
   Southampton SO17 1BJ
   United Kingdom

   Telephone : +44(0)2380598885
   Email : J.H.Burridge@soton.ac.uk

UNIVERSITY OF Southampton

3) Dr Ann-Marie Hughes
Senior Research Fellow
Rehabilitation & Health Technologies Research Group
Faculty of Health Sciences (Building 45)
University of Southampton
Southampton SO17 1BJ
United Kingdom

Telephone : +44(0)2380595191
Email : A.Hughes@soton.ac.uk

4) Dr Martin Warner
Senior Research Fellow (Musculoskeletal Biomechanics)
Arthritis Research UK Centre for Sport, Exercise and Osteoarthritis
Rehabilitation & Health Technologies Research Group
Faculty of Health Sciences (Building 45)
University of Southampton
Southampton SO17 1BJ
United Kingdom

Telephone : +44(0)2380598990
Email : m.warner@soton.ac.uk

Thank you for your consideration to take part in this study. You will be given a copy of the information sheet and a signed consent form to keep.

Appendix 14: Participant screening form for healthy participants (Phase 1A study)

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PARTICIPANT SCREENING FORM (Phase 1 study)

Study title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher name: Seng Kwee Wee
Study reference:
Ethics reference:

Name of participant _____

Date of screening _____

	Tick box
Inclusion criteria for healthy participants:	
1) Aged 18 years or over	☐
2) Able to understand the purpose of the study and follow instructions	☐
Exclusion criteria for healthy participants:	
1) History of neurological injury or disease	☐
2) Orthopaedic spinal pathology	☐
3) Orthopaedic upper extremity pathology	☐

Appendix 15: Participant screening form for chronic stroke participants (Phase 1A study)

UNIVERSITY OF Southampton

PARTICIPANT SCREENING FORM (Phase 1 study)

Study title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher name: Seng Kwee Wee

Ethics reference: 7547

Name of participant _____ Date of screening _____

	Tick box
Inclusion criteria for chronic stroke participants:	
1) Aged 18 years or over	☐
2) Clinical diagnosis of stroke	☐
3) More than 6 months post stroke	☐
4) Able to understand the purpose of the study and follow simple instructions	☐
5) Able to sit unsupported for 10 seconds	☐
Exclusion criteria for chronic stroke participants:	
1) Brainstem stroke	☐
2) Cerebellar stroke	☐
3) Orthopaedic spine pathology	☐
4) Orthopaedic upper extremity pathology such as fractures	☐
5) Acute low back pain	☐
6) Severe communication disorders -unable to follow simple instructions	☐
7) Unable to sit unsupported for ten seconds (verify in the laboratory: Score 0 on the Trunk Impairment Scale)	☐

Appendix 16: Reply slip (Phase 1A study)

UNIVERSITY OF Southampton

Reply slip for participation in research

Study title: **Relationship between trunk control and recovery of arm function in stroke patients**

Researcher: Seng Kwee Wee

Ethics reference: 7547

Please initial the box if you agree with the statement:

I am interested to take part in this research and agree for Seng Kwee Wee to contact me regarding this study ☐

Name of participant (print name) _____

Signature of participant _____

Age _____

Hand dominance _____

Have you had a stroke? ☐ No

☐ Yes When was your stroke? _____ (month and year)

Which of your arm is most affected? ☐Right ☐Left

Date _____

Email _____

Telephone _____

Preferred time for the researcher to call me: _____

Please return the reply slip in the pre-paid envelope. Thank you very much for your participation in this research.

Appendix 17: Consent form (Phase 1A study)

UNIVERSITY OF Southampton

CONSENT FORM (*Version 1*)

Study title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher name: Seng Kwee Wee
Study reference:
Ethics reference:

Please initial the box(es) if you agree with the statement(s):

I have read and understood the information sheet (insert date /version no. 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.....

[7/1/2013] [Version 1]

UNIVERSITY OF Southampton

CONSENT FORM (*Version 1*) : Photography and Video Recording

Study title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher name: Seng Kwee Wee
Study reference:
Ethics reference:

Please initial the box(es) if you agree with the statement(s):

I agree to photography or video recording during the session ☐

Photographs of me can be used in printed material such as scientific papers ☐

Photographs or videos of me can be used in presentations or educational activities ☐

Photographs or videos of me can be used on websites such as the university website ☐

Name of Participant _____ Signature _____

Date _____

Name of Researcher _____ Signature _____

Date _____

[7/1/2013] [Version 1]

Appendix 18: Invite letter for participant (Phase 1B and Phase 2 studies)

Tan Tock Seng HOSPITAL

UNIVERSITY OF Southampton

Date :

Dear Sir / Madam,

Re : Invitation to participate in a research study

I am writing to invite you to take part in a research study based at the Rehabilitation Centre of Tan Tock Seng Hospital. We are looking for people who have had a stroke less than six months ago to help us understand the recovery of trunk and arm after a stroke.

I would like to find out how movement of your arm affects how your trunk moves whilst you perform some simple tasks involving movement of your trunk and arm in a seated position. The assessment will be carried out in the research room within the therapy gymnasium of the Rehabilitation Centre. You will be required to make a total of six visits to the centre over a period of six months for the research. The visits will be scheduled one month apart. Each visit should last no longer than two hours.

Once you have read the information sheet, if you are interested in taking part in this study, please email or call me at the telephone number found at the end of this letter. I will answer any questions you may have and will ask you some general questions about your health and your stroke. These questions will help me determine if the assessment is suitable for you. I will then make an appointment for you to come in to the Rehabilitation Centre at a convenient day and time for you.

Thank you very much for time and your consideration to participate in the study.

Yours sincerely,

Wee Seng Kwee
PhD Student
Rehabilitation & Health Technologies Research Group
Faculty of Health Sciences
University of Southampton
Southampton SO17 1BJ
United Kingdom

Email : skw1g12@soton.ac.uk
Telephone : 98281449

Appendix 19: Informed Consent Form for subacute stroke participants (Phase 1B and Phase 2 studies)

OFFICIAL USE ONLY	
Doc Name : Consent Document Template	
Doc Number : 207-001	
Doc Version : 4	Date : 13 Aug 2012

INFORMED CONSENT FORM

1. Study Information

Protocol Title:

Relationship between trunk control and recovery of upper extremity function in subacute stroke patients

Principal Investigator & Contact Details:

Wee Seng Kwee
Principal Physiotherapist / PhD Student, University of Southampton, United Kingdom
Rehabilitation Centre
Tan Tock Seng Hospital
17 Ang Mo Kio Avenue 9
Singapore 569766

Email : seng_Kwee_wee@ttsh.com.sg
Tel : 64506181

2. Purpose of the Research Study

You are invited to participate in a research study. It is important to us that you first take time to read through and understand the information provided in this sheet. Nevertheless, before you take part in this research study, the study will be explained to you and you will be given the chance to ask questions. After you are properly satisfied that you understand this study, and that you wish to take part in the study, you must sign this informed consent form. You will be given a copy of this consent form to take home with you.

You are invited because:

i) you had a stroke less than six months ago
ii) from your stroke you have some movement problems with your affected arm.

This study is carried out to find out the relationship between your ability to control the trunk and how well the arm functions in people who have suffered a stroke. The results of this study will help healthcare professionals gain a better understanding of the recovery pattern of the trunk and arm after a stroke. It may assist therapists to predict outcome and to design better rehabilitation programmes to improve the recovery of the trunk and arm after a stroke.

This study will recruit 45 subjects from the Rehabilitation Centre of Tan Tock Seng Hospital over a period of one year from 1/4/2014 to 30/4/2015.

3. What procedures will be followed in this study

If you take part in this study, you will be offered two options:

Option 1: to make a total of six visits over a period of six months to the Rehabilitation Centre

for the research.

Option 2: to have the assessments conducted in your own home over a period of six months.

The assessments will be scheduled one month apart (see Table 1). Each visit to the hospital or home visit should last no longer than two hours. Please kindly wear or bring along a loose fitting sleeveless T-shirt for the assessments. You may have a carer or friend with you.

Visit 1	Week 0
Visit 2	Week 4
Visit 3	Week 8
Visit 4	Week 12
Visit 5	Week 16
Visit 6	Week 20

Table 1: Schedule of visits

For each visit to the Rehabilitation Centre / home visit, you will undergo a series of assessments by the Principal Investigator to look at your ability to control your trunk and arm function in a seated position. For the trunk assessment, you will be instructed to move your trunk in all directions, including bending sideways and twisting your body to the right and left side. For the assessment of arm function, you will be required to perform eight tasks: 1) lifting your arm onto table; 2) lifting your arm onto a box; 3) picking up a canned drink and bringing it to mouth; 4) lifting a pencil off the table; 5) folding a tea towel; 6) turning a key in the lock; 7) bringing a one-pound weight towards you; and 8) straightening your elbow against a one-pound weight.

These assessments will be performed twice, once whilst you are seated down with no support around your trunk and once with a foam support around your trunk (Figure 1). Your stronger arm will be tested first, and then your weaker arm will be tested. A stopwatch will be used to time your ability to complete the tasks. If at any point you feel tired you may rest.

Your consent will be sought before any photographs and video recordings will be captured during the session for detailed analysis and for educational purpose.

Figure 1: Trunk support

4. Your Responsibilities in This Study

If you agree to participate in this study, you should follow the advice given to you by the Principal Investigator. You should be prepared to visit the hospital 6 times and undergo all the procedures that are outlined above.

5. What Is Not Standard Care or Experimental in This Study

In this study, the procedures are only being performed for the purpose of the research, and are not part of your routine care.

6. Possible Risks and Side Effects

The assessment procedures used in this research may have the following side effects: your arm may feel slightly tired at the end of the session. If at any point you feel tired, you may rest. If you feel unable to continue, the remaining assessments will not be carried out. Throughout the session, the Principal Investigator will ensure that you are comfortable.

7. Possible Benefits from Participating in the Study

There is no known benefit from participation in this study. However, your participation in this study may add to the medical knowledge about the recovery pattern of the trunk and arm after a stroke. It is hoped that this will lead to better rehabilitation programmes for stroke patients in the future.

8. Alternatives to Participation

If you choose not to take part in this study, you will continue to receive standard care for your condition. In our institution, this would be medical care, nursing care and services provided by the allied health professionals.

9. Costs & Payments if Participating in the Study

You will be reimbursed for your time, inconvenience and transportation costs as follows:
If you choose to come to the Rehabilitation Centre for the assessments, you will be paid $30 after every visit. However, if you choose to have the assessments conducted in your own home, there will be no transportation allowance provided.

10. Voluntary Participation

Your participation in this study is voluntary. You may stop participating in this study at any time. Your decision not to take part in this study or to stop your participation will not affect your medical care or any benefits to which you are entitled. If you decide to stop taking part in this study, you should inform the Principal Investigator.

Your primary doctor or the Principal Investigator may stop your participation in the study at any time if they decide that it is in your best interests. They may also do this if you have other medical problems or any adverse side effects.

11. Compensation for Injury

If you follow the directions of the Principal Investigator in charge of this study and you are physically injured due to the procedure given under the plan for this study, Tan Tock Seng Hospital will pay the medical expenses for the treatment of that injury.

Tan Tock Seng Hospital without legal commitment will compensate you for the injuries arising from your participation in the study without you having to prove Tan Tock Seng Hospital is at fault. There are however conditions and limitations to the extent of the compensation provided. You may wish to discuss this with the Principal Investigator.

By signing this consent form, you will not waive any of your legal rights or release the parties involved in this study from liability for negligence.

12. Confidentiality of Study and Medical Records

Information collected for this study will be kept confidential. Your records, to the extent of the applicable laws and regulations, will not be made publicly available.

However, Tan Tock Seng Hospital Regulatory Agencies and NHG Domain-Specific Review Board and Ministry of Health will be granted direct access to your original medical records to check study procedures and data, without making any of your information public. By signing the Informed Consent Form attached, you (*or your legally acceptable representative, if relevant*) are authorizing such access to your study and medical records.

Data collected and entered into the Case Report Forms are the property of Tan Tock Seng Hospital. In the event of any publication regarding this study, your identity will remain confidential.

13. Who To Contact if You Have Questions

If you have questions about this research study, you may contact the Principal Investigator, Mr Wee Seng Kwee (email : seng_Kwee_wee@ttsh.com.sg Tel : 64506181).

In case of any injuries during the course of this study, you may also contact the Principal Investigator.

The study has been reviewed by the NHG Domain Specific Review Board (the central ethics committee) for ethics approval.

If you want an independent opinion of your rights as a research subject you may contact the NHG Domain Specific Review Board Secretariat at 6471-3266.

If you have any complaints about this research study, you may contact the Principal Investigator or the NHG Domain Specific Review Board Secretariat.

CONSENT FORM

Protocol Title:

Relationship between trunk control and recovery of upper extremity function in subacute stroke patients

Principal Investigator & Contact Details:

Wee Seng Kwee
Principal Physiotherapist / PhD Student, University of Southampton, United Kingdom
Rehabilitation Centre
Tan Tock Seng Hospital
17 Ang Mo Kio Avenue 9
Singapore 569766

Email : seng_Kwee_wee@ttsh.com.sg
Tel : 64506181

I voluntarily consent to take part in this research study. I have fully discussed and understood the purpose and procedures of this study. This study has been explained to me in a language that I understand. I have been given enough time to ask any questions that I have about the study, and all my questions have been answered to my satisfaction.

_____	_____	_____
Name of Participant	Signature	Date

☐ I agree to photography or video recording during the session.

☐ Photographs of me can be used in printed material such as scientific papers.

☐ Photographs or videos of me can be used in presentations or educational activities.

_____	_____	_____
Name of Participant	Signature	Date

_____	_____	_____
Name of Witness	Signature	Date

Investigator Statement

I, the undersigned, certify that I explained the study to the participant and to the best of my knowledge the participant signing this informed consent form clearly understands the nature, risks and benefits of her participation in the study.

_____	_____	_____
Name of Investigator / Person administering consent	Signature	Date

OFFICIAL USE ONLY	
Doc Name : Short Form Consent Document Template - Chinese	
Doc Number : 207-005	
Doc Version : 02	**Date** : 13 Aug 2012

Consent to Participate in Research

Study Title: Relationship between trunk control and recovery of upper extremity function in subacute stroke patients

You are being invited to participate in the above research study.

Before you agree, the investigator must tell you about:

i. the purpose, procedures, and duration of the research;
ii. any procedures which are experimental;
iii. any reasonably foreseeable risks or discomforts,
iv. any potential benefits of the research;
v. any alternative procedures or treatments; and
vi. how confidentiality will be maintained.

Where applicable, the investigator must also tell you about:

i. any available compensation or medical treatment if injury occurs;
ii. the possibility of unforeseeable risks;
iii. circumstances when the investigator may halt your participation;
iv. any added costs to you;
v. what happens if you decide to stop participating;
vi. when you will be told about new findings which may affect your willingness to participate; and
vii. how many people will be in the study.

If you agree to participate, you must be given a signed copy of this document and a written summary of the research.

If you have questions about this research study, you may contact the Principal Investigator, Wee Seng Kwee at 64506181.

In case of any injuries during the course of this study, you may contact the Principal Investigator, Wee Seng Kwee at 64506181.

If you want an independent opinion of your rights as a research subject, you may contact the NHG Domain Specific Review Board Secretariat at 64713266.

Your participation in this research is voluntary, and you will not be penalized or lose benefits if you refuse to participate or decide to stop.

Signing this document means that the research study, including the above information, has been described to you orally, and that you voluntarily agree to participate.

Consent to Participate in Research

Name of Participant	Signature of Participant	Date
Name of Witness	Signature of Witness	Date
Name of Investigator / Person Administering Consent	Signature of Person Administering Consent	Date

Appendix 20: Reply slip (Phase 1B and Phase 2 studies)

Tan Tock Seng HOSPITAL

Reply slip for participation in research

Study title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher: Seng Kwee Wee

Ethics reference: 2014/00229

Please initial the box if you agree with the statement:

I am interested to take part in this research and agree for Seng Kwee Wee to contact me regarding this study ☐

Name of participant (print name) _____

Signature of participant _____

Age _____

Hand dominance _____

Have you had a stroke? ☐ No

☐ Yes When was your stroke? _____ (month and year)

Which of your arm is most affected? ☐Right ☐Left

Date _____

Email _____

Telephone _____

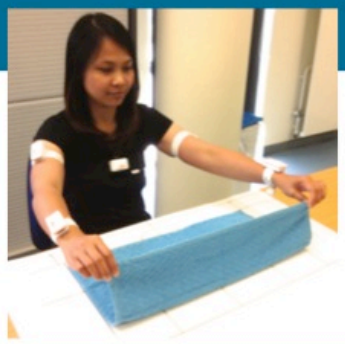
Preferred time for the researcher to call me: _____

Please return the reply slip in the pre-paid envelope. Thank you very much for your participation in this research.

Appendix 21: Advertisement for recruitment of subacute stroke participants (Phase 1B and Phase 2 studies)

Tan Tock Seng HOSPITAL

How does your body movement relate to ARM function ?



Are you aged 21 years or over?

Was your STROKE less than 6 months ago?

Would you like to participate in research?

Research study: Relationship between trunk control and recovery of upper extremity function in subacute stroke patients.

Principal Investigator: Mr Wee Seng Kwee, Principal Physiotherapist, TTSH

We are looking for people who have had a stroke to help us gain a deeper understanding about the relationship between body movement and arm function.

What is involved?

- Six visits to the Rehabilitation Centre of Tan Tock Seng Hospital. Each visit will be one-month apart.
- We will assess your body and arm movement while you perform 8 simple arm tasks in a seated position.

Poster Version 1, dated 23-04-2014

Your participation would be greatly appreciated.
If you are interested, please contact Mr Wee Seng Kwee
Email : seng_kwee_wee@ttsh.com.sg Tel : 98281449

Trunk Research
Wee Seng Kwee
seng_kwee_wee@ttsh.com.sg
Tel: 98281449

Appendix 22: Participant screening form for subacute stroke participants (Phase 1B and Phase 2 studies)

Tan Tock Seng HOSPITAL

PARTICIPANT SCREENING FORM (Phase 2 study)

Study title: Relationship between trunk control and recovery of arm function in stroke patients

Researcher: Seng Kwee Wee

Ethics reference:

Name of participant _____ Date of screening _____

	Tick box
Inclusion criteria for subacute stroke participants:	
1) Aged 18 years or over	☐
2) Clinical diagnosis of stroke	☐
3) Less than 6 months post stroke	☐
4) Able to understand the purpose of the study and follow simple instructions	☐
Exclusion criteria for subacute stroke participants:	
1) Brainstem stroke	☐
2) Cerebellar stroke	☐
3) Orthopaedic spine pathology	☐
4) Orthopaedic upper extremity pathology such as fractures	☐
5) Acute low back pain	☐
6) Severe communication disorders -unable to follow simple instructions	☐

Appendix 23: Trunk Impairment Scale

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TRUNK IMPAIRMENT SCALE

Participant ID : _____ Assessment : 1 / 2 / 3 / 4 / 5 / 6

Date of assessment : _____

Assessor : _____ Signature : _____

STATIC SITTING BALANCE		
1. Starting position : sit unsupported	• Patient falls or cannot maintain starting position for 10 seconds without arm support	0
	• Patient can maintain starting position for 10 seconds	2
2. Starting position : Therapist crosses the unaffected leg over the hemiplegic leg	• Patient falls or cannot maintain sitting position for 10 seconds without arm support	0
	• Patient can maintain starting position for 10 seconds	2
3. Starting position : Patient crosses the unaffected leg over the hemiplegic leg	• Patient falls	0
	• Patient cannot cross the legs without arm support on bed	1
	• Patient crosses the legs but displaces the trunk more than 10cm backwards or assists crossing with the hand	2
	• Patient crosses the legs without trunk displacement	3
	Subtotal (max 7)	

DYNAMIC SITTING BALANCE		
1. Starting position : Patient is instructed to touch the bed with the hemiplegic elbow (by shortening the hemiplegic side and lengthening the unaffected side) and return to starting position	• Patient falls, needs support from an upper extremity or the elbow does not touch the bed ** If score = 0, then items 2 and 3 score 0*	0
	• Patient moves actively without help, elbow touches bed	1
2. Repeat item 1	• Patient demonstrates no or opposite shortening / lengthening ** If score = 0, then item 3 scores 0*	0
	• Patient demonstrates appropriate shortening / lengthening	1
3. Repeat item 1	• Patient compensates. Possible compensations are : i) use of upper extremity ii) contralateral hip abduction iii) hip flexion iv) elbow touches bed further than proximal half of femur v) knee flexion vi) sliding of feet	0
	• Patient moves without compensation	1

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DYNAMIC SITTING BALANCE		
4. Starting position : Patient is instructed to touch the bed with the unaffected elbow (by shortening the unaffected side and lengthening the hemiplegic side) and return to starting position	• Patient falls, needs support from an upper extremity or the elbow does not touch the bed ** If score = 0, then items 5 and 6 score 0*	0
	• Patient moves actively without help, elbow touches bed	1
5. Repeat item 4	• Patient demonstrates no or opposite shortening / lengthening ** If score = 0, then item 6 scores 0*	0
	• Patient demonstrates appropriate shortening / lengthening	1
6. Repeat item 4	• Patient compensates. Possible compensations are : i) use of upper extremity ii) contralateral hip abduction iii) hip flexion iv) elbow touches bed further than proximal half of femur v) knee flexion vi) sliding of feet	0
	• Patient moves without compensation	1
7. Starting position : Patient is instructed to lift pelvis from bed at hemiplegic side (by shortening the hemiplegic side and lengthening the unaffected side) and return to starting position	• Patient demonstrates no or opposite shortening / lengthening ** If score = 0, then item 8 scores 0*	0
	• Patient demonstrates appropriate shortening / lengthening	1
8. Repeat item 7	• Patient compensates. Possible compensations are : i) use of upper extremity ii) pushing off with the ipsilateral foot (heel loses contact with the floor)	0
	• Patient moves without compensation	1
9. Starting position : Patient is instructed to lift pelvis from bed at unaffected side (by shortening the unaffected side and lengthening the hemiplegic side) and return to starting position	• Patient demonstrates no or opposite shortening / lengthening ** If score = 0, then item 10 scores 0*	0
	• Patient demonstrates appropriate shortening / lengthening	1
10. Repeat item 9	• Patient compensates. Possible compensations are : i) use of upper extremity ii) pushing off with the ipsilateral foot (heel loses contact • with the floor)	0
	• Patient moves without compensation	1
	Subtotal (max 10)	

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COORDINATION		
1. Starting position : Patient is instructed to rotate upper trunk 6 times (every shoulder should be moved forward 3 times), first side that moves must be hemiplegic side, head should be fixated in starting position	• Hemiplegic side not moved 3 times ** If score = 0, then item 2 scores 0*	0
	• Rotation is asymmetrical	1
	• Rotation is symmetrical	2
2. Repeat item 1 within 6 seconds	• Rotation is asymmetrical	0
	• Rotation is symmetrical	1
3. Starting position : Patient is instructed to rotate lower trunk 6 times (every knee should be moved forward 3 times), first side that moves must be hemiplegic side, upper trunk should be fixated in starting position	• Hemiplegic side not moved 3 times ** If score = 0, then item 4 scores 0*	0
	• Rotation is asymmetrical	1
	• Rotation is symmetrical	2
4. Repeat item 3 within 6 seconds	• Rotation is asymmetrical	0
	• Rotation is symmetrical	1
	Subtotal (max 6)	

Total Trunk Impairment Scale (TIS) score

Appendix 24: Fugl-Meyer Upper Extremity

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FUGL-MEYER ASSESSMENT-UPPER EXTREMITY

Participant ID : _____ Assessment : 1 / 2 / 3 / 4 / 5 / 6

Date of assessment : _____ Assessor : _____ Signature : _____

A. SHOULDER / ELBOW / FOREARM			
I Reflex activity	none	can be elicited	
Flexors : biceps	0	2	
Extensors : triceps	0	2	
Subtotal (max 4)			
II Flexor synergy : hand from contralateral knee to ipsilateral ear	none	partial	full
Shoulder retraction	0	1	2
Shoulder elevation	0	1	2
Shoulder abduction	0	1	2
Shoulder external rotation	0	1	2
Elbow flexion	0	1	2
Forearm supination	0	1	2
III Extensor synergy : hand from ipsilateral ear to contralateral knee	none	partial	full
Shoulder adduction / internal rotation	0	1	2
Elbow extension	0	1	2
Forearm pronation	0	1	2
Subtotal (max 18)			
IV Volitional movement mixing synergies	none	partial	full
Hand to lumbar spine	0	1	2
Shoulder flexion 0^o – 90^o (elbow 0^o , pronation-supination 0^o)	0	1	2
Forearm pronation / supination (elbow 90^o , shoulder 0^o)	0	1	2
Subtotal (max 6)			
V Volitional movement with little or no synergy	none	partial	full
Shoulder abduction 0^o – 90^o (elbow 0^o , forearm pronated)	0	1	2
Shoulder flexion 90^o – 180^o (elbow 0^o , pronation-supination 0^o)	0	1	2
Pronation / supination (elbow 0^o , shoulder flexion 30^o – 90^o)	0	1	2
Subtotal (max 6)			
VI Normal reflex activity – evaluated only if full score of 6 points in part V			
Test reflexes in Biceps, Finger flexors and Triceps Score 0 = 2 or 3 reflexes markedly hyperactive Score 1 = 1 reflex markedly hyperactive or at least 2 reflexes lively Score 2 = 1 reflex lively, none hyperactive	0	1	2
Subtotal (max 2)			

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B. WRIST	none	partial	full
Stability at 15° wrist extension : maintain position (shoulder flexion 0°, **elbow 90°**, forearm pronated) against resistance	0	1	2
Wrist flexion / extension (elbow 90°)	0	1	2
Stability at 15° wrist extension : maintain position (shoulder flexion 30°, **elbow 0°**, forearm pronated) against resistance	0	1	2
Wrist flexion / extension (shoulder flexion 30°, **elbow 0°**, forearm pronated)	0	1	2
Wrist circumduction (shoulder flexion 0°, **elbow 90°**, forearm pronated)	0	1	2
Subtotal (max 10)			
C. HAND	none	partial	full
Finger mass flexion	0	1	2
Finger mass extension	0	1	2
GRASP (maintain position against resistance)			
i. Distal finger grasp : extend the MCP joints of digits 2nd to 5th, flex the proximal and distal IP joints	0	1	2
ii. Thumb adduction grasp : grip paper between thumb and index finger	0	1	2
iii. Grasping a pen between thumb and index finger pad	0	1	2
iv. Cylinder grasp : small can (thumb & index finger)	0	1	2
v. Spherical grasp : tennis ball	0	1	2
Subtotal (max 14)			
D. COORDINATION & SPEED (tip of index finger from knee to nose, 5 repetitions)	marked	slight	none
Tremor	0	1	2
Dysmetria	0	1	2
	> 6 s	2 – 6 s	< 2 s
Time	0	1	2
Subtotal (max 6)			

Total FMA-UE score (max 66)

Appendix 25: Normative data for the Wolf Motor Function Test (Wolf et al. 2006)

The items of Streamlined Wolf Motor Function Test (Subacute Stroke and Chronic Stroke versions) are highlighted within red boundaries

Timed and Strength WMFT Tasks by Age Group

Tasks	40–49y		50–59y		60–69y		>70y	
	Right	Left	Right	Left	Right	Left	Right	Left
1. Forearm to table	0.6±0.1	0.5±0.1	0.5±0.1	0.5±0.1	0.7±0.1	0.7±0.2	0.7±0.2	0.7±0.1
2. Forearm to box	0.7±0.2	0.7±0.1	0.7±0.2	0.7±0.1	0.8±0.2	0.8±0.3	0.9±0.3	0.8±0.2
3. Extend elbow	0.4±0.1	0.4±0.1	0.4±0.1	0.4±0.1	0.5±0.1	0.5±0.2	0.5±0.1	0.4±0.1
4. Extend elbow with weight	0.4±0.1	0.4±0.1	0.4±0.1	0.4±0.1	0.4±0.1	0.4±0.1	0.5±0.2	0.4±0.1
5. Hand to table	0.5±0.1	0.5±0.1	0.4±0.1	0.5±0.1	0.5±0.1	0.5±0.2	0.5±0.1	0.5±0.1
6. Hand to box	0.5±0.1	0.5±0.1	0.5±0.1	0.5±0.1	0.6±0.1	0.6±0.2	0.6±0.1	0.6±0.1
7. Weight to box: male	20.0±0.0*	20.0±0.0*	20.0±0.0*	20.0±0.0*	20.0±0.0*	20.0±0.0*	19.0±2.2	19.4±0.9
7. Weight to box: female	18.9±2.5	18.5±2.5	16.0±3.1	14.9±3.5	17.2±3.1	16.0±3.1	13.8±4.3	11.6±1.5
8. Reach/retrieve	0.6±0.2	0.6±0.2	0.5±0.1	0.6±0.1	0.6±0.2	0.6±0.1	0.6±0.2	0.5±0.1
9. Lift can	0.9±0.2	0.9±0.2	0.9±0.2	1.0±0.2	1.1±0.4	1.1±0.3	1.2±0.2	1.1±0.2
10. Lift pencil	0.7±0.2	0.7±0.1	0.8±0.2	0.9±0.1	0.9±0.3	0.9±0.2	1.0±0.1	1.0±0.2
11. Lift paper clip	0.8±0.1	0.9±0.2	1.0±0.2	1.0±0.2	1.0±0.2	1.0±0.2	1.2±0.3	1.1±0.2
12. Stack checkers	2.1±0.6	2.1±0.3	2.4±0.4	2.5±0.5	2.7±0.6	2.7±0.6	2.9±0.6	2.9±0.5
13. Flip cards	2.7±0.4	2.7±0.5	2.8±0.7	2.9±0.6	3.1±0.8	3.1±0.7	3.1±0.4	3.0±0.4
14. Grip strength: male	34.5±5.8	33.0±4.2	45.8±7.7	38.3±8.9	40.5±9.0	39.3±5.8	38.8±7.1	34.4±4.1
14. Grip strength: female	19.6±7.1	17.8±4.5	20.5±5.4	16.9±5.7	24.1±7.9	19.3±7.1	18.9±6.9	18.3±5.1
15. Turn key in lock	1.7±0.3	1.7±0.4	1.8±0.4	1.8±0.4	2.2±0.6	2.2±0.6	2.1±0.6	2.0±0.5
16. Fold towel	2.5±0.5	2.4±0.4	2.6±0.5	2.7±0.6	3.0±0.6	3.0±0.8	3.2±0.7	3.0±0.4
17. Lift basket	1.5±0.3	1.6±0.2	1.6±0.3	1.6±0.3	1.7±0.4	1.8±0.5	1.9±0.3	1.8±0.2
Mean time per timed task	1.1±0.2	1.1±0.1	1.2±0.2	1.2±0.2	1.3±0.3	1.3±0.3	1.4±0.2	1.3±0.2
Mean male	1.0±0.1	1.1±0.1	1.1±0.1	1.2±0.2	1.2±0.2	1.2±0.3	1.3±0.2	1.4±0.2
Mean female	1.1±0.2	1.1±0.2	1.2±0.2	1.2±0.1	1.4±0.3	1.4±0.3	1.5±0.2	1.3±0.2

Appendix 26: Components of the Streamlined Wolf Motor Function Test (SWMFT) tasks for kinematic analysis

Task	Starting position	Start	Detected by	End	Detected by
(1) Hand to table (front)	Hand on lap, feet flat on ground. Distance of chair from the table is measured as follows: Position the box (used for the Streamlined Wolf Motor Function Test) at the 20-cm line on the template. Place the participant's hand flat on the top of the box with the wrist crease at the edge of box, shoulder at 90^0 flexion and elbow fully extended. With the arm in this position, place the chair so that the participant's hips and back are fully against the back of the chair.	Hand leaves the lap	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand lands on table – The heel of the hand must rest beyond the 2-cm line. Note: Trial will be repeated if the heel does not rest beyond the 2 cm line.	Ulnar styloid marker crosses the markers at 2-cm line and the ulnar styloid marker velocity returns to 2% of the peak velocity

Task	Starting position	Start	Detected by	End	Detected by
(2) Hand to box (front)	Hand on table, feet flat on ground. Distance of chair from the table is measured as follows: Position the box (used for the Streamlined Wolf Motor Function Test) at the 20-cm line on the template. Place the participant's hand flat on the top of the box with the wrist crease at the edge of box, shoulder at 90^{0} flexion and elbow fully extended. With the arm in this position, place the chair so that the participant's hips and back are fully against the back of the chair.	Hand leaves the table	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand lands on box – The heel of the hand must be placed past the front edge of box Note: Trial will be repeated if the heel of the hand does not past the front edge of box	Ulnar styloid marker crosses the markers at edge of the box and the ulnar styloid marker velocity returns to 2% of the peak velocity

Task	Starting position	Start	Detected by	End	Detected by
(3) Lift can					
i) Reaching (includes grasping)	Hand on lap, feet flat on ground. Distance of chair from the table is measured as follows: Position the box (used for the Streamlined Wolf Motor Function Test) at the 20-cm line on the template. Place the participant's hand flat on the top of the box with the wrist crease at the edge of box, shoulder at 90° flexion and elbow fully extended. With the arm in this position, place the chair so that the participant's hips and back are fully against the back of the chair.	Hand leaves the lap	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand begins to move the can towards the mouth	Can and ulnar styloid markers move simultaneously: Displacement between the can marker and ulnar styloid marker is constant
ii) Forward transport (bring can to mouth)		Hand begins to move the can towards the mouth	Can and ulnar styloid markers move simultaneously: Displacement between the can marker and ulnar styloid marker is constant	The can is brought close to mouth, without touching lips	Displacement between the can marker and sternal notch (IJ) thorax marker reaches its minimum point
iii) Back transport		Hand begins to move to put the can back to table	Displacement between the can marker and IJ marker increases from the minimum point	Hand releases the can and begins to move back to initial position	Displacement between the can marker and ulnar styloid marker increases beyond 2% of the distance observed whilst the can is grasped
iv) Return hand to initial position		Hand releases the can and begins to move back to initial position	Displacement between the can marker and ulnar styloid marker increases beyond 2% of the distance observed whilst the can is grasped	Hand back on the lap	Ulnar styloid marker velocity returns to 2% of the peak velocity

Task	Starting position	Start	Detected by	End	Detected by
(4) Lift pencil					
i) Reaching (includes 3-jaw grasp with thumb and first two fingers)	Hand on lap, feet flat on ground. Distance of chair from the table is measured as follows: Position the box (used for the Streamlined Wolf Motor Function Test) at the 20-cm line on the template. Place the participant's hand flat on the top of the box with the wrist crease at the edge of box, shoulder at 90° flexion and elbow fully extended. With the arm in this position, place the chair so that the participant's hips and back are fully against the back of the chair.	Hand leaves the lap	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand begins to lift the pencil at least 0.5 inch off the table	Displacement between the pencil marker and ulnar styloid marker is constant
ii) Lift the pencil		Hand begins to lift the pencil at least 0.5 inch off the table	Displacement between the pencil marker and ulnar styloid marker is constant	The pencil is lifted off the table	The point of maximum displacement of the pencil marker in the vertical axis
iii) Lower pencil back to the table		Hand begins to lower to put the pencil back to table	The point of maximum displacement of the pencil marker in the vertical axis	Hand releases the pencil and begins to move back to initial position	Displacement between the pencil marker and ulnar styloid marker increases beyond 2% of the distance observed whilst the pencil is grasped
iv) Return hand to initial position		Hand releases the pencil and begins to move back to initial position	Displacement between the pencil marker and ulnar styloid marker increases beyond 2% of the distance observed whilst the pencil is grasped	Hand back on the lap	Ulnar styloid marker velocity returns to 2% of the peak velocity

Task	Starting position	Start	Detected by	End	Detected by
(5) Fold towel					
i) Reaching (includes grasping the far corners of the towel)	Hands on lap, feet flat on ground. Distance of chair from the table is measured as follows: Position the box (used for the Streamlined Wolf Motor Function Test) at the 20-cm line on the template. Place the participant's hand flat on the top of the box with the wrist crease at the edge of box, shoulder at 90° flexion and elbow fully extended. With the arm in this position, place the chair so that the participant's hips and back are fully against the back of the chair.	Hands leave the lap	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hands begins to grasp the far corners of the towel	Maximum anterior displacement of ulnar styloid marker
ii) Folding towel into half lengthwise		Hands begins to fold towel into half lengthwise	Maximum anterior displacement of ulnar styloid marker	The towel is folded into half lengthwise	Minimum anterior displacement of ulnar styloid marker at a time point beyond the maximum anterior displacement
iii) Folding towel into half again across its centre (widthwise) - done from the side of the towel corresponding to the hand being tested		The tested hand begins to fold towel into half again across its centre (widthwise)	Minimum anterior displacement of ulnar styloid marker at a time point beyond the maximum anterior displacement	The towel is folded into half across its centre (widthwise). Hand releases the towel after folding.	Maximum medial displacement of ulnar styloid marker
iv) Return hand to initial position		Hand releases the towel and begins to move back to initial position	Maximum medial displacement of ulnar styloid marker	Hand back on the lap	Ulnar styloid marker velocity returns to 2% of the peak velocity following the maximum medial displacement of the ulnar styloid marker

Task	Starting position	Start	Detected by	End	Detected by
(6) Turn key in lock					
i) Reaching (includes lateral pincer grasp on the key)	Hands on lap, feet flat on ground. Distance of chair from the table is measured as follows: Position the box (used for the Streamlined Wolf Motor Function Test) at the 20-cm line on the template. Place the participant's hand flat on the top of the box with the wrist crease at the edge of box, shoulder at 90° flexion and elbow fully extended. With the arm in this position, place the chair so that the participant's hips and back are fully against the back of the chair.	Hand leaves the lap	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand performs lateral pincer grasp on the key	Ulnar styloid marker velocity returns to 2% of the peak velocity
ii) Turn the key 90 degrees to the side being tested		Hand starts to turn the key in the lock from the vertical position to the side being tested	Angular velocity of the key markers go above 2% of peak velocity	The key is turned 90 degrees to the side being tested	Angular velocity of the key markers fall below 2% of peak velocity
iii) Turn the key 90 degrees to the opposite side		Hand starts to turn the key 180 degrees to the opposite side	Angular velocity of the key markers go above 2% of peak velocity	The key is turned 180 degrees to the opposite side	Angular velocity of the key markers fall below 2% of peak velocity
iv) Turn the key to the vertical position		Hand starts to turn the key back to the vertical position	Angular velocity of the key markers go above 2% of peak velocity	The key is turned back to the vertical position. Hand releases the key and begins to move back to initial position.	Angular velocity of the key markers fall below 2% of peak velocity
iv) Return hand to initial position		Hand releases the key and begins to move back to initial position	Displacement between the key markers and ulnar styloid marker increases beyond 2% of the distance observed whilst the key is grasped	Hand back on the lap	Ulnar styloid marker velocity returns to 2% of the peak velocity

Task	Starting position	Start	Detected by	End	Detected by
(7) Reach and retrieve	Distance of chair from the table is measured as follows: Place the participant's wrist crease at the 40-cm line with the elbow fully extended. With the arm in this position, place the chair so that the participant's hips and back are fully against the back of the chair. 1-lb weight is placed just beyond 40-cm line. Elbow extended, forearm in mid-position of pronation and supination and palm of hand in contact with weight. Feet flat on ground	Hand movement begins - slides 1-lb weight towards the 8-cm line	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand slides 1-lb weight past the 8-cm line	Ulnar styloid marker crosses the markers at 8-cm line and the ulnar styloid marker velocity returns to 2% of the peak velocity

Task	Starting position	Start	Detected by	End	Detected by
(8) Extend elbow 1-lb weight	Distance of chair from the table is measured as follows: Chair placed sideways to the table. Position the box lengthwise at the 14 cm line. Place the participant's forearm flat on the box, with the wrist hanging over the edge. Height of box should be such that the patient's hips and back are against the back of the chair. Ensure that the trunk is straight and participant is not leaning to the side. Feet flat on ground. Shoulder abducted with forearm resting flat on table in a pronated position. Forearm is parallel to front of table. Elbow at 14-cm line. 1-lb weight placed at ulnar edge of wrist; distal end of the weight is aligned with ulnar styloid process.	Hand movement begins - slides 1-lb weight towards the 40-cm line	Ulnar styloid marker velocity surpasses 2% of peak velocity	Hand slides 1-lb weight across the 40-cm line	Ulnar styloid marker crosses the markers at 40-cm line and the ulnar styloid marker velocity returns to 2% of the peak velocity

Appendix 27: Therapy log

Tan Tock Seng HOSPITAL Rehabilitation Centre

Patient's Therapy Log

Patient ID : _____ Date : _____

Time post stroke: 1st / 2nd / 3rd / 4th / 5th / 6th month

Therapy activities for the arm	Time spent (minutes)	Frequency (number of times per day)	Remarks
(A) Stretching exercises			
(B) Range of motion exercises			
(C) Arm training			
(1) Hand bicycle			
(2) Pulley			
(3) Strengthening exercises (weights, exercise equipment)			
(4) Active exercise/Active-assisted exercise by therapist/carer			
(D) Electrical stimulation			
(E) Other treatment			
(1) Acupuncture			
(2) Acupressure			
(3) Traditional massage			
(4) Others (specify) _____			

Day Rehabilitation Centre: _____ times per week

_____ minutes on arm training

Inpatient therapy / Outpatient therapy / Home-based therapy:

_____ times per week

_____ minutes on arm training

Average therapy time spent on arm training per day: _____

Appendix 28: Ethics approval notice for Phase 1A study from the Faculty of Health Sciences, University of Southampton (Ethics number 7547)

From: **Ergo** ergo@soton.ac.uk
Subject: Your Ethics Submission (Ethics ID:7547) has been reviewed and approved
Date: 26 September, 2013 7:39 pm
To: Wee S.K. skw1g12@soton.ac.uk

Submission Number: 7547
Submission Name: Relationship between trunk control and recovery of upper extremity function in subacute and chronic stroke patients: Phase 1 study
This is email is to let you know your submission was approved by the Ethics Committee.

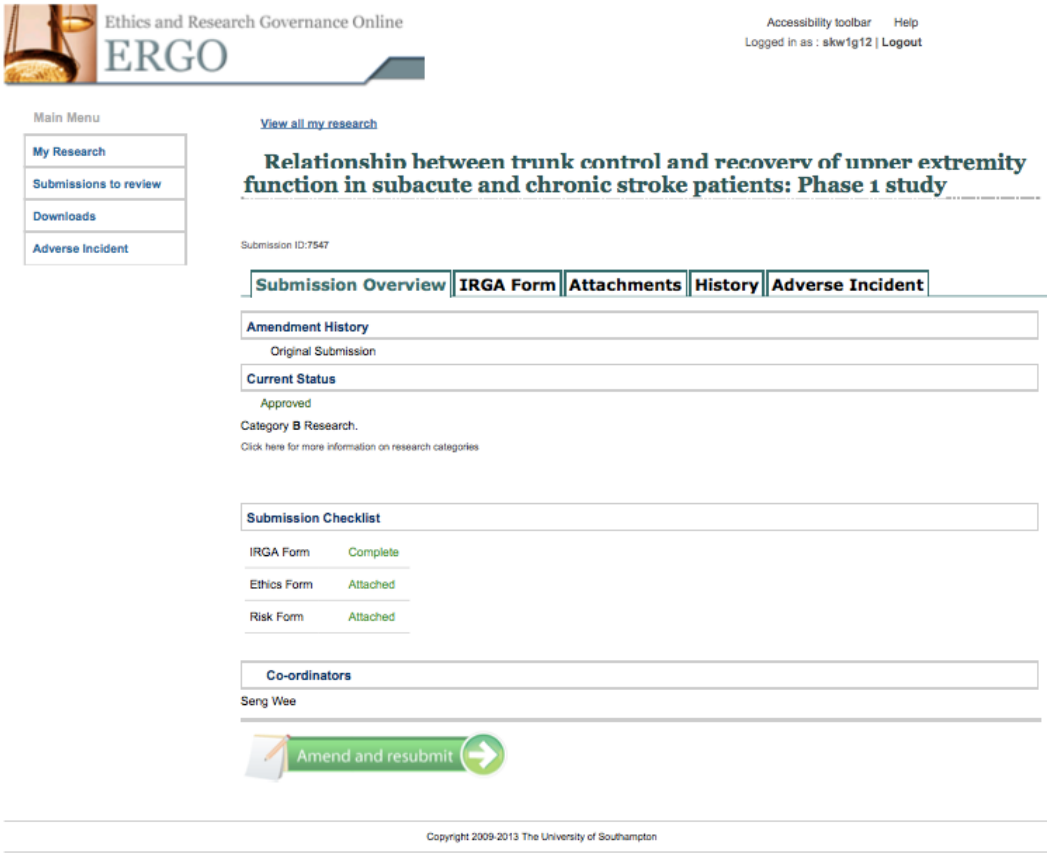
You can begin your research unless you are still awaiting specific Health and Safety approval (e.g. for a Genetic or Biological Materials Risk Assessment)

Comments
1.Good, clear amendments - well done

Click here to view your submission<http://www.ergo.soton.ac.uk>

ERGO : Ethics and Research Governance Online
http://www.ergo.soton.ac.uk

DO NOT REPLY TO THIS EMAIL



Appendix 29: Ethics approval notice for Phase 1B and Phase 2 studies from the Faculty of Health Sciences, University of Southampton (Ethics number 10647)

From: Ergo ergo@soton.ac.uk
Subject: Your Ethics Amendment (Ethics ID:10647) has been reviewed and approved
Date: 13 June 2014 12:25 am
To: Wee S.K. skw1g12@soton.ac.uk

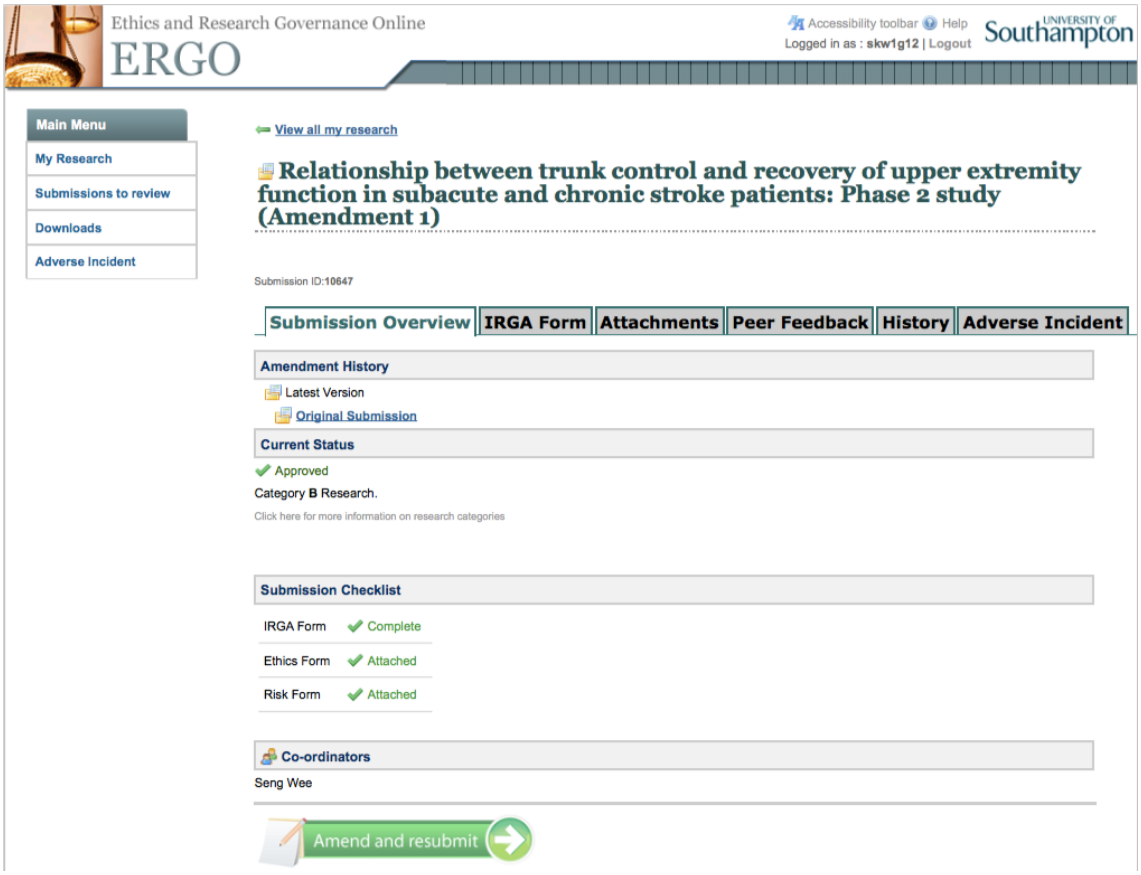
Submission Number 10647:
This email is to confirm that the amendment request to your ethics form (Relationship between trunk control and recovery of upper extremity function in subacute and chronic stroke patients: Phase 2 study (Amendment 1))has been approved by the Ethics Committee.

You can begin your research unless you are still awaiting specific Health and Safety approval (e.g. for a Genetic or Biological Materials Risk Assessment)

Comments
1.Thank you for your request for amendment, and for the clarity with which you have highlighted the changes requested. I am happy to approve this amendment, providing you observe the lone-working policy of the Faculty. Good luck with the study.

Click here to view your submission<http://www.ergo.soton.ac.uk>

ERGO : Ethics and Research Governance Online
http://www.ergo.soton.ac.uk



Appendix 30: Ethics approval letter for Phase 1B and Phase 2 studies from the Institutional Review Board of National Healthcare Group of Singapore (Ethics number 2014/00229)

National Healthcare Group

Adding years of healthy life

3 Fusionopolis Link
#03-08 Nexus@one-north
Singapore 138543
Tel: 6496 6600 Fax:6486 6870
www.nhg.com.sg
RCB No. 200002150H

NHG DSRB Ref: 2014/00229

08 May 2014

Mr Seng Kwee Wee
Department of Rehabilitation Medicine
Tan Tock Seng Hospital

Dear Mr Wee

NHG DOMAIN SPECIFIC REVIEW BOARD (DSRB) APPROVAL

STUDY TITLE: Relationship between trunk control and recovery of upper extremity function in subacute stroke patients

We are pleased to inform you that the NHG Domain Specific Review Board has approved the application as titled above to be conducted in **Tan Tock Seng Hospital**.

The approval period is from **08 May 2014** to **07 May 2015**. The NHG DSRB reference number for this study is **2014/00229**. Please use this reference number for all future correspondence.

The documents reviewed are:

a) NHG DSRB Application Form: **Version No. 1**
b) Research protocol: **Version 1 dated 23/04/2014**
c) Informed Consent Form: **Version 1 dated 08/05/2014**
d) Poster: **Version 1 dated 23/04/2014**
e) Study Schedule: **Version 1 dated 28/10/2013**

The NHG DSRB acknowledges the receipt of the following documents:

f) Informed Consent Form Version 1 with Short Consent Form (Chinese): **Version dated 08/05/2014**
g) Informed Consent Form Version 1 with Short Consent Form (Malay): **Version dated 08/05/2014**
h) Informed Consent Form Version 1 with Short Consent Form (Tamil): **Version dated 08/05/2014**

Continued approval is conditional upon your compliance with the following requirements:
1. Only the approved Informed Consent Form should be used. It must be signed by each subject prior to initiation of any protocol procedures. In addition, each subject should be given a copy of the signed consent form.

2. No deviation from or changes to the study should be implemented without documented approval from the NHG DSRB, except where necessary to eliminate apparent immediate hazard(s) to the study subjects.

3. Any deviation from or changes to the study to eliminate an immediate hazard should be promptly reported to the NHG DSRB within seven calendar days.

4. Please note that for studies requiring Clinical Trial Certificate, apart from the approval from NHG DSRB, no deviation from, or changes of the Research Protocol and Informed Consent Form should be implemented without documented approval from the Health Sciences Authority unless otherwise advised by the Health Sciences Authority.

5. Please submit the following to the NHG DSRB:

a. All Unanticipated Problems Involving Risk To Subjects Or Others (UPIRTSOs) must be reported to the NHG DSRB. All problems involving local deaths must be reported immediately within 24 hours after first knowledge by the Investigator, regardless of the causality and expectedness of the death. All other problems must be reported as soon as possible but not later than seven calendar days after first knowledge by the Investigator.

b. Report(s) on any new information that may adversely affect the safety of the subject or the conduct of the study.

c. NHG DSRB Study Status Report Form – this is to be submitted 4 to 6 weeks prior to expiry of the approval period. The study cannot continue beyond **07 May 2015** until approval is renewed by the NHG DSRB.

d. Study completion – this is to be submitted using the NHG DSRB Study Status Report Form within 4 to 6 weeks of study completion.

6. Established since May 2006, the NHG Research Quality Management (RQM) Program seeks to promote the responsible conduct of research in a research culture with high ethical standards, identify potential systemic weaknesses and make recommendations for continual improvement. Hence, this research study may be randomly selected for a review by the Research Quality Management (RQM) team. For more information, please visit www.research.nhg.com.sg.

Yours Sincerely

A/Prof Low Yin Peng
Chairman
NHG Domain Specific Review Board D