EFFECTS OF MIND-BODY EXERCISE ON DUAL-TASKING PERFORMANCE AND CARDIOVASCULAR FUNCTIONS IN CHRONIC STROKE SURVIVORS

CHAN WING NGA

PhD

The Hong Kong Polytechnic University

2018

The Hong Kong Polytechnic University

Department of Rehabilitation Sciences

Effects of Mind-body Exercise on Dual-tasking Performance and Cardiovascular Functions in Chronic Stroke Survivors

Chan Wing Nga

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

November 2017

CERTIFICATE OF ORIGINALITY

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

Chan Wing Nga

November 2017

In memory of my best friend

Ms. Mable Shum Wai Yan (1982 – 2016)

ABSTRACT

Regaining functional ability and preventing cardiovascular complications are two of the primary objectives in stroke rehabilitation. Turning and stepping down are common daily activities, but they often cause falls in stroke survivors. These activities demand a high level of physical skill and additional cognitive tasks may be challenging. Few studies emphasize these dual-tasking activities, and consensus on rehabilitation exercises has yet to be reached. Further, strokes have detrimental effects on arterial compliance and cardiac autonomic regulation, leading to various cardiovascular pathologies.

Tai Chi is a mind-body exercise and is dual-tasking in nature. It has been shown to improve dual-tasking ability and cardiovascular function in older community-dwelling adults. However, the effects on stroke survivors are still unknown. This study is therefore designed to:

1) Investigate how stroke survivors respond to dual-tasking, and

2) Examine the effects of Tai Chi training on dual-tasking ability and cardiovascular function among stroke survivors.

There were two phases in this study: a cross-sectional study and a randomized controlled trial (RCT) to achieve the first and second objectives, respectively. In the first phase, stroke survivors were tested under two dual-tasking situations: turning-while-walking and stepping down combined with an auditory Stroop test respectively. The performance when dual-tasking was compared with both the single-tasking

performance and the performance of controls. In the second phase, stroke survivors were randomized into either Tai Chi, conventional exercise or control groups. The two dual-tasking conditions employed in the first phase, together with arterial compliance, blood pressure, and heart rate variability were assessed before, immediately after, and one month after the intervention.

In the cross-sectional study, stroke survivors showed a decreased composite score in the auditory Stroop test when performing turning-while-walking (n=59; dual-tasking: 71.5±24.2, single-tasking: 83.5±22.8) or stepping down (n=26; dual-tasking: 76.4±31.2, single-tasking: 90.0±25.6). However, physical task performances when both single-tasking and dual-tasking were similar. Moreover, stroke survivors performed less well than the controls in all measures. These findings may be explained by the hypothesis that stroke survivors had insufficient resources during dual-tasking and they employed a posture-first strategy to preserve control of balance.

In the RCT phase, the composite score improved in both dual-tasking conditions after Tai Chi training [turning-while-walking (n=47): pre-assessment: 73.1±27.6, post-assessment: 89.9±23.4, follow-up: 91.7±26.9; stepping down (n=23): pre-assessment: 64.6±22.7, post-assessment: 91.9±19.2, follow-up: 94.4±20.6]. The score of the Tai Chi group was higher than that of the conventional exercise group (55.7±11.1) in the follow-up period when dual-tasking with a stepping down test. Subjects in the Tai Chi group completed the dual-tasking turning-while-walking faster in the follow-up (14.9±4.9 sec) than in the pre-assessment (17.7±6.9 sec). For the cardiovascular function (n=56), significant improvement in small arterial compliance (pre-assessment: 3.7±2.0 ml/mmHg*100, post-assessment: 4.2±2.2 ml/mmHg*100) and systolic blood

pressure (pre-assessment: 129.2±17.3 mmHg, post-assessment: 125.0±18.6 mmHg), but not heart rate variability, was observed in subjects who practiced Tai Chi.

The results showed that Tai Chi enhanced dual-tasking ability, and is possibly more effective than conventional exercise for the stepping down task. The observed improvements might imply that the effect of Tai Chi training transfers to other dual-tasking activities. Further, Tai Chi improved arterial compliance and blood pressure but not cardiac autonomic regulation. Further studies with a larger sample and exploring the underlying mechanisms of mind-body exercise are needed.

PUBLICATIONS ARISING FROM THE THESIS

Manuscripts

1. Chan, W. N., & Tsang, W. W. The performance of stroke survivors in turning-while-walking while carrying out a concurrent cognitive task compared with controls. Submitted to *PLoS ONE*. Under second review.
2. Chan, W. N., & Tsang, W. W. Compromised cognition while stepping down among stroke survivors. Submitted to *PLoS ONE*. Under second review.
3. Chan, W. N., & Tsang, W. W. Effect of Tai Chi training on dual-tasking performance among stroke survivors: A randomized controlled trial. Submitted to *Clinical Rehabilitation.* Under second review.
4. Chan, W. N., & Tsang, W. W. (2017). Effect of Tai Chi training on dual-tasking performance that involves stepping down among stroke survivors. *Evidence-based Complementary and Alternative Medicine. In press*.
5. Chan, W. N., & Tsang, W. W. Short-term Tai Chi training may benefit arterial compliance but not heart rate variability among stroke survivors: A randomized controlled trial. Submitted to *BMC Complementary and Alternative Medicine.* Under second review.

Conference presentation

Chan, W. N., Xiao, E. J., & Tsang, W. W. (2016, October). *Effects of Tai Chi practice on dual-tasking performance in turning-while-walking with and without a cognitive task*. Paper presented at the 10th Singapore International Physiotherapy Congress, Singapore.

Chan, W. N., Xiao, E. J., & Tsang, W. W. (2016, October). *Comparing dual-tasking performance, with turning-while-walking as physical task, between healthy older adults and chronic stroke survivors.* Paper presented at the 10th Singapore International Physiotherapy Congress, Singapore.

Chan, W. N., Xiao, E. J., & Tsang, W. W. (2016, November). Comparing performance of stepping down with and without a concurrent cognitive task in controls and chronic stroke survivors. Paper presented in the 10th Pan-Pacific Conference on Rehabilitation, Shanghai, China. **Silver Award of oral presentation.**

ACKNOWLEDGMENTS

This thesis could not have been completed without the help and support of the following people.

I owe my deepest gratitude to my chief supervisor, Dr. William Tsang Wai Nam, Associate Head of the Department of Rehabilitation Sciences, The Hong Kong Polytechnic University. Being his undergraduate student and his research assistant before I pursued my Ph.D. studies, his passion for both research and Tai Chi inspired my research study. His invaluable advice and kind encouragement helped me to overcome the difficulties encountered during the process. He is not only a supervisor but also a mentor and a friend of mine.

There are also a lot of people I would like to express my appreciations:

- Mr. John Chung Yan Leung, chief physiotherapist, Rehabilitation Centre, St. Teresa's Hospital, for his great support in this project. I also thank my colleagues for their encouragement during my study.
- All the participants of this study. Thank you for respecting me as a Tai Chi instructor and loving me as if I was your daughter or granddaughter.
- Mr. Siu Sik Cheung and Mr. Man Cheung for their technical support and Mr. Edward Xiao for conducting the assessments.
- Tai Chi Master Wong Lin Ying for her expertise in the martial art.
- Mr. Patrick Kwong, Mr. Alfred Wong Hong Lok, Mr. Leung King Hon, Ms. Eva Fung Pui Lin, and Mrs. Yip-Ma Bik Yin for subjects recruitment.

I would like to express my gratefulness to Mrs. Kwong Chan Man Chong and Dr. Kevin Kwong Shek Chuen. Without them, I would not be who I am today. My heartfelt thanks also go to Mr. Victor Ngai Man Chan, who was the kindest physiotherapist. I will always remember him. Further, I would like to thank my friends, especially Rose, Maggie, Daisy, Kathy, Macy, and Edith for their abundant encouragement. Last but not least, my immense gratitude to my parents, my brother Kenneth, my aunt Sindy, and my boyfriend Tony. Thank you for your selfless support.

I could not have done it without you all.

PREFACE

Chapter 1 is the Introduction, providing background information to this study. Chapter 2 lists the objectives and hypotheses. Chapter 3 comprises five papers which are either in press (Chapter 3.4) or under 1st and 2nd review (Chapter 3.1, 3.2, 3.3, and 3.5). The full authorship and titles are listed in the section *Publications arising from the thesis (Manuscripts)* (p.vi). These paper and manuscripts have been reformatted to provide consistency throughout the thesis. Chapter 4 summarizes the results and provides general discussion of the studies. Chapter 5 is the Conclusion section. All references are listed at the end of the thesis in the References section.

TABLE OF CONTENTS

STATEMENT OF ORIGINALITY………………………………………………….. i

DEDICATION……………………………………………………………………… ii

ABSTRACT…………………………………………………………………….... iii

PUBLICATIONS ARISING FROM THE THESIS…………………….……….. vi

ACKNOWLEDGEMENTS……………………………………………………… viii

PREFACE……………………………………………………………………….... x

TABLE OF CONTENTS………………………………………………………... xi

LIST OF TABLES……………………………………………………………….. xix

LIST OF FIGURES……………………………………………………………… xx

CHAPTER 1 INTRODUCTION

1.1 Stroke……………………………………………………………………… 2

- 1.1.1 Definition and epidemiology…………………………………….. 2
- 1.1.2 Types of stroke………………………………………………….... 3
- 1.1.3 Recovery after stroke…………………………………………….. 5
- 1.1.4 Rehabilitation after stroke……………………………………….. 8
- 1.1.5 Functional ability………………………………………………… 8
  - 1.1.5.1 Turning-while-walking………………………………… 8
  - 1.1.5.2 Stepping down……………………………………….. 15
  - 1.1.5.3 Dual-tasking……………………………………………. 18
    - 1.1.5.3.1 Dual-tasking performance involving turning-while-walking………………………………. 23

1.1.5.3.2 Dual-tasking performance involving stepping down………………………………. 25
1.1.5.3.3 Effect of exercise on dual-tasking performance in stroke survivors……………. 26
1.1.6 Cardiovascular function………………………………………….. 30
1.1.6.1 Arterial stiffness……………………………………... 30
1.1.6.1.1 Arterial stiffness and stroke………………… 34
1.1.6.1.2 Effect of exercise on arterial stiffness……… 35
1.1.6.2 Cardiac autonomic regulation………………………….. 38
1.1.6.2.1 Cardiac autonomic regulation and stroke…... 39
1.1.6.2.2 Effect of exercise training on cardiac autonomic regulation……………………….. 40
1.2 Tai Chi…………………………………………………………….. 42
1.2.1 Features of Tai Chi………………………………………………. 42
1.2.1.1 Physical requirements………………………………….. 42
1.2.1.2 Cognitive involvement…………………………………. 44
1.2.1.3 Dual-tasking feature……………………………………. 45
1.2.1.4 Aerobic exercise with moderate intensity……………… 47
1.2.1.5 Mind-body exercise…………………………………….. 48
1.2.2 Effect of Tai Chi training among stroke survivors………………. 49
1.2.3 Dosage and principle of Tai Chi training………………………... 51

CHAPTER 2 OBJECTIVES AND HYPOTHESES

CHAPTER 3 THE MAIN STUDY

3.1 The performance of stroke survivors in turning-while-walking while carrying out a concurrent cognitive task compared with controls…… 66

3.1.1 Abstract……………………………………………………………... 67

3.1.2 Introduction…………………………………………………………. 68

3.1.3 Methods…………………………………………………………….. 71

3.1.3.1 Participants……………………………………………... 71

3.1.3.2 Assessment……………………………………………... 72

3.1.3.2.1 Single auditory Stroop test…………………. 72

3.1.3.2.2 Single turning-while-walking test………….. 73

3.1.3.2.3 Dual-tasking test……………………………. 74

3.1.3.3 Repeatability of the assessment………………………… 75

3.1.3.4 Statistical analysis……………………………………… 75

3.1.4 Results………………………………………………………………. 76

3.1.4.1 Participants……………………………………………... 76

3.1.4.2 Repeatability of the assessment………………………… 77

3.1.4.3 Comparing single-tasking and dual-tasking performance in stroke survivors……………………………………… 79

3.1.4.4 Comparing stroke survivors and controls………………. 79

3.1.5 Discussions………………………………………………………….. 81

3.1.6 Limitations…………………………………………………………... 84

3.1.7 Conclusions…………………………………………………………. 84

3.2 The performance of stroke survivors in stepping down while carrying out a concurrent cognitive task compared with controls……………… 86

3.2.1 Abstract…………………………………………………………... 87

3.2.2 Introduction………………………………………………………. 88

3.2.3 Methods…………………………………………………………... 90

3.2.3.1 Participants…………………………………………... 90

3.2.3.2 Assessment…………………………………………... 91

3.2.3.2.1 Single auditory Stroop test…………………. 91

3.2.3.2.2 Single stepping down test…………………... 92

3.2.3.2.3 Dual-tasking test……………………………. 94

3.2.3.3 Repeatability of the assessment………………………… 94

3.2.3.4 Statistical analysis……………………………………… 95

3.2.4 Results……………………………………………………………. 95

3.2.4.1 Participants…………………………………………... 95

3.2.4.2 Repeatability of the assessment………………………… 96

3.2.4.3 Comparing single-tasking and dual-tasking performance in stroke survivors……………………………………… 98

3.2.4.4 Comparing stroke survivors and controls………………. 98

3.2.5 Discussions……………………………………………………….. 100

3.2.6 Limitations……………………………………………………….. 102

3.2.7 Conclusions………………………………………………………. 103

3.3 The effect of Tai Chi training on the dual-tasking performance that involved turning-while-walking of stroke survivors: A randomized controlled trial……………………………………………………………… 105

3.3.1 Abstract……………………………………………………………... 106

3.3.2 Introduction………………………………………………………… 107

3.3.3 Methods…………………………………………………………….. 109

3.3.3.1 Participants…………………………………………….... 109

3.3.3.2 Intervention……………………………………………... 110

3.3.3.2.1 Tai Chi group……………………………….. 110

3.3.3.2.2 Conventional exercise group……………….. 111

3.3.3.2.3 Control group………………………………. 111

3.3.3.3 Assessment……………………………………………... 113

3.3.3.3.1 Single auditory Stroop test…………………. 113

3.3.3.3.2 Single turning-while-walking test………….. 114

3.3.3.3.3 Dual-tasking test……………………………. 114

3.3.3.4 Statistical analysis……………………………………… 115

3.3.4 Results……………………………………..…………………….. 116

3.3.5 Discussions………………………………………………………. 120

3.3.6 Limitations……………………………………………………….. 123

3.3.7 Conclusions……………………………………………………… 124

3.4 The effect of Tai Chi training on dual-tasking performance that

involves stepping down among stroke survivors……………………….. 125

3.4.1 Abstract………………………………………………………... 126

3.4.2 Introduction…………………………………………………… 127

3.4.3 Methods……………………………………………………….. 130

3.4.3.1 Participants…………………………………………... 130

3.4.3.2 Intervention………………………………………….. 130

3.4.3.2.1 Tai Chi group……………………………….. 131

3.4.3.2.2 Conventional exercise group……………….. 132

3.4.3.2.3 Control group………………………………. 132

3.4.3.3 Assessment…………………………………………... 132

3.4.3.3.1 Single auditory Stroop test…………………. 133

3.4.3.3.2 Single stepping down test…………………... 134

3.4.3.3.3 Dual-tasking test……………………………. 135

3.4.3.4 Statistical analysis…………………………………… 135

3.4.4 Results………………………………………………………… 136

3.4.5 Discussions……………………………………………………. 141

3.4.6 Limitations…………………………………………………….. 146

3.4.7 Conclusions…………………………………………………… 147

3.5 The effects of Tai Chi training on arterial compliance, blood pressure, and cardiac autonomic regulation among stroke survivors... 148

3.5.1 Abstract………………………………………………………... 149

3.5.2 Introduction…………………………………………………… 150

3.5.3 Methods………………………………………………………….. 152

  3.5.3.1 Participants…………………………………………... 152

  3.5.3.2 Intervention………………………………………….. 152

    3.5.3.2.1 Tai Chi group……………………………….. 153

    3.5.3.2.2 Conventional exercise group……………….. 154

    3.5.3.2.3 Control group………………………………. 154

  3.5.3.3 Assessment…………………………………………... 154

    3.5.3.3.1 Arterial compliance and blood pressure……. 155

    3.5.3.3.2 Cardiac autonomic regulation………………. 155

  3.5.3.4 Statistical analysis…………………………………… 156

3.5.4 Results…………………………………………………………… 157

  3.5.4.1 Arterial compliance and blood pressure………………... 159

  3.5.4.2 Cardiac autonomic regulation………………………….. 162

3.5.5 Discussions……………………………………………………. 164

3.5.6 Limitations…………………………………………………….. 167

3.5.7 Conclusions…………………………………………………… 167

CHAPTER 4 GENERAL DISCUSSION

4.1 Summary of the findings and discussion…………………………………. 169

4.2 Limitations…………………………………………………………… 177

4.3 Clinical relevance…………………………………………………. 178

4.4 Future research suggestions……………………………………………….. 179

CHAPTER 5 CONCLUSION

APPENDICES…………………………………………………………………... 183

I Information sheet and consent form………………………………………. 184

II Details of the 12-form Tai Chi…………………………………………….. 188

III Details of the conventional exercise………………………………………. 194

REFERENCES………………………………………………………………. 195

LIST OF TABLES

Table 1.1 Summary of the amount of Tai Chi training and corresponding results from previous studies………………………………………. 53

Table 3.1.1 Demographics of both the controls and stroke survivors………….. 76

Table 3.1.2 Repeatability of the assessment……………………………………. 78

Table 3.1.3 Results of single-tasking and dual-tasking performance in both controls and stroke survivors………………………………………. 80

Table 3.2.1 Demographics of both the controls and the stroke survivors……… 96

Table 3.2.2 Repeatability of the assessment……………………………………. 97

Table 3.2.3 Results of single-tasking and dual-tasking performance in both controls and stroke survivors………………………………………. 99

Table 3.3.1 Name and training specificity of the 12 Yang-style Tai Chi forms... 112

Table 3.3.2 Demographic and clinical characteristics of the subjects………….. 118

Table 3.3.3 Changes in single-tasking and dual-tasking performance (turning-while-walking)…………………………………………………... 119

Table 3.4.1 Demographic and clinical characteristics of the subjects………….. 138

Table 3.4.2 Changes in single-tasking and dual-tasking performance (stepping down)………………………………………………………………. 139

Table 3.5.1 Demographic and clinical characteristics of the subjects………….. 159

Table 3.5.2 Changes in arterial compliance and blood pressure……………….. 161

Table 3.4.3 Changes in heart rate variability…………………………………… 163

LIST OF FIGURES

Figure 3.2.1 The stepping down test setup…………………………………….. 93

Figure 3.3.1 CONSORT diagram……………………………………………… 117

Figure 3.4.1 CONSORT diagram……………………………………………… 137

Figure 3.5.1 CONSORT diagram……………………………………………… 158

CHAPTER 1

INTRODUCTION

1.1 Stroke

1.1.1 Definition and epidemiology

Stroke, or cerebrovascular accident, is defined as ‘an accident with 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’ (WHO MONICA Project, 1998).

Stroke is a common problem globally. There were 16 million first-time strokes and 62 million stroke survivors worldwide (Strong et al., 2007). Due to advances in the acute medical management of stroke in recent decades, the death rate after the accident is decreasing (Macdonald, 2014). However, the prevalence of stroke is still high. In mainland China, the prevalence of stroke in urban areas ranged from 295.3 to 388.6 cases per 100,000 population, while that in rural regions was 193.6 cases per 100,000 populations (Sun et al., 2013).

Most stroke survivors suffer from long term-disability. Even with proper rehabilitation, 50% of the survivors encounter some degree of hemiparesis, 30% are unable to walk without assistance, and 26% are dependent on assistance for daily activities. In addition, 46% of them experience some cognitive deficits (Go et al., 2013; Kelly-Hayes et al., 2003). The high prevalence of stroke and the residual impairment increases the cost of stroke care. The average cost of stroke rehabilitation in the first year after discharge is USD $7,318 and the estimated mean lifetime cost of ischemic stroke is USD $140,048 in the United States (Go et al., 2013).

1.1.2 Types of stroke

There are two main kinds of stroke: ischemic stroke and hemorrhagic stroke. The hemorrhagic case can be further divided into intracerebral hemorrhage and subarachnoid hemorrhage. Ischemia is the most common type of stroke, accounting for 87% of all strokes, while 10% and 3% of the stroke are intracerebral hemorrhage and subarachnoid hemorrhage, respectively (Go et al., 2013).

Ischemic stroke

Brain ischemia is defined as a reduction in blood flow and oxygen supply to the brain that results in dysfunction (Verheyden & Ashburn, 2012; Wieloch & Nikolich, 2006). It can be classified further into four subtypes (Dorrance & Fink, 2015):

(1) Large-artery atherothrombotic disease, which results in large areas of ischemic injury and accounts for around 50% of all ischemic strokes.
(2) Lacunar stroke, which is caused by the occlusion of small intracranial arteries and affects smaller regions of the brain. Approximately 25% of ischemic strokes are of this type.
(3) Cerebral artery occlusion by cardiac emboli causes 20% of ischemic strokes.
(4) Hemodynamic stroke, which is caused by cerebral hypoperfusion without any clot or emboli, makes up the remainder of ischemic strokes.

When there is an infarct at the arteries that supply a specific brain region, the brain tissues in that area may die. The penumbra, which is the tissues surrounding the infarct, may also be injured but able to recover (Verheyden & Ashburn, 2012). The death or damage of the brain tissues results in a loss of corresponding functions (Verheyden & Ashburn, 2012; Zeiler & Krakauer, 2013). The dysfunction may also occur in the non-ischemic peri-infarct region and remote brain areas that are connected to the infarcted zone, such as the contralesional hemisphere. The condition of a focal lesion in the brain that leads to dysfunction of the brain tissues away from the insult is called diaschisis (Albert & Kesselring, 2012; Pekna et al., 2012; Wieloch & Nikolich, 2006).

Intracerebral hemorrhage

Intracerebral hemorrhage occurs when there is a rupture of any blood vessel within the brain result in bleeding. Leading causes of intracerebral hemorrhage include amyloid angiopathy, brain tumors, aneurysms, and arteriovenous malformations (Manno, 2012; Xi et al., 2006).

Only around 20% of patients with an intracerebral hemorrhage regain independence at six months after the insult (Manno, 2012). The resulting neurological deficits can be attributed to hematoma expansion and brain edema. The edema is caused by both the hematoma and the disrupted blood brain barrier, followed by an increase in intracranial pressure and resulting necrosis of brain tissues (Manno, 2012; Xi et al., 2006). The degree of brain edema after intracerebral hemorrhage has been related to the patients' outcome (Xi et al., 2006). Another potential factor leading to brain damage after hemorrhage is the decreased blood flow to the brain, resulting in ischemia (Xi et al., 2006).

Subarachnoid hemorrhage

Subarachnoid hemorrhage occurs when there is a rupture of an aneurysm and blood flows into the subarachnoid space, the brain parenchyma and the ventricles (Stern et al., 2006).

Most patients with this kind of stroke suffer from permanent neurological deficits. The deficits are the result of the acute brain injury caused by the hemorrhage and delayed cerebral ischemia, which develops in around one-third of the patients. Immediately after the rupture, the hemorrhage may damage the brain physically and cause transient ischemia as a result of increased intracranial pressure, microcirculatory constriction, and micro-thrombosis. The hemorrhage may also trigger activation of the sympathetic nervous system, leading to systemic complications such as pulmonary edema, lung injury, and cardiac dysfunction. Delayed cerebral ischemia may also develop after the acute phase of the stroke. The ischemia can be attributed to various causes, including angiographic vasospasm. Most of the vasospasm resolves spontaneously. However, some of its complications, such as arterial fibrosis and endothelial thickening, may persist, resulting in increased arterial stiffness (Macdonald, 2014).

1.1.3 Recovery after stroke

Recovery from a stroke can be spontaneous or enhanced by rehabilitative training. It has been suggested that functional recovery after a stroke involves three phases (Pekna et al., 2012; Wieloch & Nikolich, 2006):

1) Diaschisis reversal, cell genesis activation, and repair of injured tissues.
2) Remodeling of the properties of neuronal pathways.
3) Establishment and consolidation of new neuronal pathways by neuroplasticity.

All these phases occur during the spontaneous recovery period, while the second and the third phases can be enhanced by motor training (Pekna et al., 2012).

Spontaneous recovery

There is a sensitive period after a stroke when spontaneous recovery occurs even without training or treatment. The sensitive period lasts for around six months after a stroke in human, with recovery being most prominent in the first three months (Caleo, 2015; Wieloch & Nikolich, 2006; Zeiler & Krakauer, 2013).

During the sensitive period, the injured brain cells and the region around them recover spontaneously. It is further hypothesized that different areas of the brain can take over the functions of the damaged areas, which is called vicariation (Albert & Kesselring, 2012). As some motor functions recover within a few days after a stroke, this recovery may be a result of the unmasking or activation of some silent pathways or synapses (Wieloch & Nikolich, 2006). Previous animal studies have shown that after stroke is induced in the primary motor cortex, the premotor areas take over some of the functions of the disrupted neuronal tissues (Caleo, 2015). Axonal growing and dendritic sprouting in the cortical regions in both the ipsilesional and contralesional hemispheres are also demonstrated in animal models (Albert & Kesselring, 2012; Wieloch & Nikolich, 2006).

Training induced recovery

Although spontaneous recovery occurs after a stroke, such recovery only gives limited restoration of function (Caleo, 2015). External interventions, especially those involving motor learning and development of new motor skills, can stabilize and strengthen, or even further recruit newly developed neuronal networks and pathways established during spontaneous recovery (Albert & Kesselring, 2012; Caleo, 2015; Krakauer, 2006; Pekna et al., 2012; Wieloch & Nikolich, 2006). This reorganization of the brain structure and neuronal function is referred as neuroplasticity, or neural plasticity (Albert & Kesselring, 2012; Caleo, 2015; Pekna et al., 2012). In addition to the damaged areas, neuroplasticity can occur in different brain regions, even extending to areas remote from the damage (Wieloch & Nikolich, 2006; Zeiler & Krakauer, 2013). The more severe the damage, the longer the distance over which change can take place (Wieloch & Nikolich, 2006).

Recovery after the sensitive period

It was believed that recovery after the sensitive period post-stroke is limited. On the contrary, the “plateau” effect may only be due to neuromuscular adaptation to the exercises employed (Page et al., 2004). Substantial motor improvement can occur even in the chronic stage of stroke (Wieloch & Nikolich, 2006), especially with variable training dosage or novel task-specific rehabilitation exercise (Krakauer, 2006; Page et al., 2004). These kinds of training are regarded as problem-solving instead of the replay of a memorized movement, allowing motor function to be enhanced even at the chronic stage of a stroke (Krakauer, 2006; Page et al., 2004).

1.1.4 Rehabilitation after stroke

Rehabilitation after a stroke is aimed mainly at restoring daily function and preventing cardiovascular complications (Hankey, 2014; Verheyden & Ashburn, 2012). One of the commonly employed rehabilitation techniques is physical exercise. It is well-established that physical exercise helps to restore functional ability. Further, although controlling cardiovascular risk factors is mainly achieved by pharmacological means, physical exercise still plays an important role (Hankey, 2014). Therefore, previous studies focused on the effects of different types of exercise training on functional ability and cardiovascular function in stroke survivors.

The following sections will introduce functional ability and cardiovascular function after a stroke. The corresponding effects of exercise training will also be discussed.

1.1.5 Functional ability

One of the major objectives in stroke rehabilitation is to regain function. There are different types of functional activities, but walking, turning, and stepping down are among the most common ones that lead to falls (Hyndman et al., 2002; National Safety Council, 2016; Startzell et al., 2000). Gait training is one of the main focuses of rehabilitation in both clinical practice and research. In contrast, turning-while-walking and stepping down attract relatively little attention. This section will therefore discuss these two activities.

1.1.5.1 Turning-while-walking

Turning is common in daily life, when navigating around furniture, changing directions while walking, or avoiding others in a crowded area (Cumming & Klineberg, 1994). We turn even more frequently in an environment with tighter constraints (Sedgman et al., 1994). Turning was found to be the second most common activity leading to a fall among stroke survivors (Hyndman et al., 2002) and could result in serious injury. For instance, a fractured hip is 7.9 times more likely when falling during turning than when walking in a straight line (Cumming & Klineberg, 1994). In addition, turning performance, reflected by the time and number of steps to turn 180 degrees, has been related to functional ability among chronic stroke survivors (Lam & Luttmann, 2009).

Types of turning strategy

There are different strategies for turning, specifically, pivoting turn, multiple steps turn, and mixed steps and pivoting turn (Thigpen et al., 2000).

Pivoting turn

Pivoting turns are characterized by spinning the body over the stance leg toward the new direction (Hase & Stein, 1999), resulting in a fast and highly efficient movement (Hollands et al., 2010a). A prior study investigating turning behavior in people of different age groups showed that the pivoting turn was employed by all young subjects and around half of the older adults without turning difficulties. This turning strategy was observed in few older subjects with turning difficulties (Thigpen et al., 2000). However, it can be dangerous, as a fall may occur if the physical function is not high enough to support the fast movement, or they turned without anticipating the action (Yamada et al., 2012).

Multiple steps turn

Multiple steps turn is a turn accomplished by a series of steps or weight shifts with only minimal hip and trunk rotation and without any pivoting. The multiple steps turn is a strategy which simplifies the complex, large and fast pivoting turn into simpler, smaller and slower movements to compensate for degraded physical ability (Thigpen et al., 2000). A study showed that 42% of older subjects with turning difficulties, but only 7% of those without such problem, employed this strategy to make a 180-degree turn (Thigpen et al., 2000). Another study also showed that older people with a history of falling tended to turn with multiple steps (Dite & Temple, 2002).

Mixed steps and pivots turn

The mixed type of turn consists of pivoting movements but is completed with multiple steps. In turning, the body rotates to a certain degree, but not completely, over the weight bearing leg. The other leg may either remain off the floor or pivot with the weight bearing leg. There may be some steps without any pivoting during the movement. This turning strategy may enhance safety while maximizing the efficiency of the action. A previous study showed that 36% of the older subjects without turning difficulties and 53% of those with them performed a 180-degree turn using this strategy (Thigpen et al., 2000).

Involvement of cognitive function

It has been suggested that turning is not an automatic movement but involves cognitive function (Hollands et al., 2014; Manaf et al., 2015). Both feedforward and feedback mechanisms are required. The feedforward mechanism allows an individual to anticipate and plan for the movement before the turn occurs (Hase & Stein, 1999; Yamada et al., 2012). This mechanism is critical in the pivoting turn (Shumway-Cook & Woollacott, 2007). On the other hand, the feedback system is necessary to integrate information from various sensory systems and make appropriate adjustments during the turn. It plays a crucial role in all types of turning, especially the multiple step turn and the mixed steps and pivots turn (Shumway-Cook & Woollacott, 2007; Thigpen et al., 2000). Inability to plan or to adjust movements during the turn may result in loss of balance or even a fall (Hollands et al., 2013).

Turning-while-walking in stroke survivors

Turning performance is declined with aging (Thigpen et al., 2000). Having a stroke may further exaggerate such deterioration.

Turning duration and number of steps to turn

Previous studies have shown that stroke survivors take longer to turn and use more steps than non-stroke controls (Dite & Temple, 2002; Lam & Luttmann, 2009). Stroke survivors with a history of falling also need more time to complete a turn than healthy subjects during timed Up-and-Go tests (Hollands et al., 2010a). A longer turning duration and a higher number of steps to turn have been related to a history of falling in chronic stroke survivors (Dite & Temple, 2002).

Center of mass displacement

A recent study showed that the displacement of the center of mass during turning in the mediolateral direction was significantly less and slower in stroke survivors than in healthy controls. This behavior may reflect a decreased ability to translate the body in the turning direction and consequently less efficient movement (Bonnyaud et al., 2015b).

Reorientation sequence of body segments

Previous studies have shown that reorientation of body segments during a turn is affected by different factors, including the amplitude of the turning angle, the cueing time of the turning direction, the side of turning, and the physical ability of the stroke survivor ((Hollands et al., 2010a, 2010b; Lamontagne & Fung, 2009; Orendurff et al., 2006).

With a small turning amplitude (45-degree), Hollands and colleagues (2010b) demonstrated that the reorientation sequence of body segments was similar between stroke survivors and healthy controls. Both groups initiated the reorientation before the turning point with a rostrocaudal sequence: the gaze shifted toward the turning direction, consecutively followed by the head, the trunk and pelvis, and finally the legs. The early reorientation of gaze and head enables an individual to gather visual information and applies feedforward mechanism before the turn (Lam & Luttmann, 2009; Yamada et al., 2012).

On the other hand, the reorientation characteristics varied with larger turning amplitudes (90-degree and 180-degree). When the subjects were informed of the turning direction before the start of the test, the reorientation sequence of the body segments was preserved. However, if the direction was only known just before the turn, the sequence was disrupted in the stroke survivors (Hollands et al., 2010a; Lamontagne & Fung, 2009). The reorientation sequence may also vary with the physical functioning level of the stroke survivors and the side of the turn. When turning towards the less affected side, stroke survivors with a higher level of physical function showed a top-down but more synchronized sequence. However, the sequence was disrupted when subjects turned to the affected side. By contrast, those with lower physical function turned to the less affected side in a caudorostral manner: the turn was initiated by the pelvis, followed by the thorax, and finally the head and gaze. This disrupted sequence was not observed when they turned to the affected side, but synchronized movement was still detected (Lamontagne & Fung, 2009). These results imply that both the physical ability of the stroke survivor and the side of turning play a role in the reorientation behavior among stroke survivors.

The effect of turning side among stroke survivors

Unlike straight-line walking, turning is facilitated by asymmetrical movements of the two legs (Hollands et al., 2010b; Orendurff et al., 2006). The inner leg should bear more weight to provide extra time for the outer leg to swing through the arc of the turn. This increased weight bearing also promotes a shift of the center of mass toward the turning side to facilitate an efficient movement (Orendurff et al., 2006). Therefore, stroke survivors with hemiparesis may turn differently to the affected side than the less affected side.

When turning to the affected side, the decreased weight bearing of the affected leg may reduce the time of its single support phase. The less affected leg (the outer leg), therefore, is not able to swing through the arc of the turn. As a result, more steps and time are needed to complete the movement, especially when the turning amplitude is large (Lamontagne & Fung, 2009). A prior study showed that the single support phase of the affected leg and the swing phase of the less affected leg explained 56% of the variance in turning time (Bonnyaud et al., 2015b). Additionally, gait asymmetry has also been found to be positively associated with the time required to turn 180-degree toward the affected side ($r^2 = 0.62$) (Lam & Luttmann, 2009).

The disadvantages of hemiparesis on turning to the affected side may not be observed among stroke survivors with rotational bias, where the body is rotated to the affected side when standing due to physical impairment. Stroke survivors with a lower level of physical function and a rotational bias toward the affected side turned with a preserved reorientation sequence toward the affected side. This sequence was, however, completely disrupted when turning to the less affected side (Lamontagne & Fung, 2009). The rotational bias facilitates turning to the affected side by initiating body segments early. Further, a lesser degree of body rotation is needed to achieve the required turning amplitude when such a bias is present. Thus, those subjects were able to turn to the affected side in a shorter time and with a preserved reorientation sequence of body segments (Hollands et al., 2010b).

To summarize the discussion above, stroke survivors need longer and take more steps to turn than their non-stroke counterparts. They also demonstrate a lower mediolateral displacement of the center of mass when turning. In addition, stroke survivors reorient their body segments differently from the controls. The level of variation depends on the turning amplitude, the cueing time of the turning direction, the side of turning, and the physical ability of the stroke survivors.

1.1.5.2 Stepping down

The ability to negotiate stairs is important for the independence of community-dwelling stroke survivors (Alzahrani et al., 2009). Falling on stairs, especially when descending, may result in severe harm such as head injury (Jacobs, 2016; Startzell et al., 2000). It is also one of the leading causes of fall-related accidental deaths (National Safety Council, 2016). Falls occur more frequently when descending stairs than when ascending (Startzell et al., 2000). Nearly 60% of falls occur on the first or last two steps of the stairs (Telonio et al., 2014).

Stairs negotiation is perceived as one of the most challenging daily activities for stroke survivors (Tsuji et al., 1995). Compared with walking on level ground, stairs demand greater neuromuscular control, especially in older adults or those with disabilities (Jacobs, 2016; Novak & Brouwer, 2012). When stepping down, there is a forward and downward momentum along the sagittal plane (Lee & Chou, 2007). Stability in the frontal plane is also disturbed by the weight shifting between the two legs (Novak & Brouwer, 2013). Lower limb muscles must be strong enough and sufficiently well-coordinated to achieve the following goals (Perry & Burnfield, 2010):

1) To stabilize the lower limb joints during the stance phase: that is, supporting the hip joint to decrease body sway, the knee joint to prevent it from collapsing and the ankle joint to take the body weight.

2) To lower the body in a controlled manner.
3) To clear the foot from the edge of the step, preventing tripping and falling.
4) To place the foot properly.
5) To absorb the shock generated when stepping down.

Apart from neuromuscular control, the negotiation of stairs also involves cognitive functions to evaluate the stairs' configuration and integrate sensory information from various sensory systems (Jacobs, 2016; Ojha et al., 2009; Startzell et al., 2000).

Stepping down in healthy older adults

Previous studies have investigated the effect of aging on stepping down behavior and the corresponding compensatory strategies. Compared with healthy young subjects, older adults showed lower knee and ankle torque in the stance leg when stepping down (Lark et al., 2003). The lower torque may diminish the ability of these joints to support the body weight leading to an increase in body sway. Weakness at the hip abductor of the stance leg, which stabilizes the trunk over the lower limb, may also exaggerate shifting of the center of mass in the frontal plane (Reid et al., 2011).

In contrast to the increased sway of the center of mass, previous studies have shown a lower center of pressure displacement and velocity among older subjects than those who are younger (Kim, 2009; Reid et al., 2011). The large shift of the center of mass but minimal center of pressure displacement results in a significant divergence between the center of mass and the center of pressure, implying a more unstable position and thus increased risk of falling (Hsue & Su, 2014).

It has been reported that the moments required at the ankle joint and the knee joint are between 1.5 and 2.0 Nm/kg body weight when descending stairs. However, the maximum isometric strength of older people for knee flexion and ankle plantar flexion are only 1.6 and 2.0 N/kg body weight, respectively (Startzell et al., 2000). The moments at the joints are just enough to step down but may not be sufficient to overcome any external disturbance during the movement.

Because of the effect of aging on stepping down performance, healthy older adults have developed different strategies to maintain balance, such as reduced walking speed (Hsue & Su, 2014) and lengthening the double-support time (Hsue & Su, 2014; Lark et al., 2003).

Stepping down among stroke survivors

The biomechanical alterations to stepping down seen among healthy older adults can also be observed in stroke survivors, but the changes are even more evident. The moment of the lower limb muscles, particularly the hip abductors and ankle invertors, are lower in stroke survivors than non-stroke controls (Novak & Brouwer, 2013). This diminished moment may result in increased lateral sway and risk of falling sideways.

When stepping down, the range of dorsiflexion of the trailing leg must be large enough to allow a controlled lowering. However, stiffening of the affected ankle is common among stroke survivors. As a result, the hip and knee may have to take a more extended posture to compensate for the reduced range of dorsiflexion (Novak & Brouwer, 2013). However, the extensors of the affected leg may not be strong enough to both stabilize the joints and lower the body to the next step at the same time, potentially increasing the risk of falling (Lark et al., 2003).

As discussed above, both aging and stroke affect the behavior of stepping down. The high demand for neuromuscular control makes it difficult for older adults and stroke survivors to descend stairs. If there is an external disturbance during the movement, neither may be able to maintain balance, resulting in a fall. Indeed, being distracted has been reported as one of the most common causes of falls when negotiating stairs (Templer, 1992).

1.1.5.3 Dual-tasking

The simultaneous performance of two different tasks is called dual-tasking. Dual-tasking is common in daily life, for example talking while walking or crossing the road according to a traffic light signal. Previous studies have shown a relationship between dual-tasking performance and falls in older adults (Muir-Hunter & Wittwer, 2016; Springer et al., 2006) and stroke survivors (Baetens et al., 2013). It has also been related to balancing ability (Manaf et al., 2014a) and gait performance (Plummer-D'Amato & Altmann, 2012) among people with stroke.

Interaction between cognitive and physical tasks under dual-tasking condition

In dual-tasking conditions, there may be an interaction between the two tasks. Therefore, the performance of either or both tasks may be altered (Al-Yahya et al., 2011; Woollacott & Shumway-Cook, 2002). Different factors have been proposed to explain the interaction between the two tasks when dual-tasking: competition for attentional resources, prioritization of tasks, posture-first strategies, and habitual responses.

Competition for attentional resources

The theory of competition for attentional resources explains the impaired task performance under dual-tasking conditions. There are two main assumptions in this theory (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012):

1) Every physical activity requires attentional resources for cognitive processing.
2) There is a limitation of attentional resources available to perform any task.

Based on these two assumptions, various factors have been suggested to have an effect on the interaction between cognitive and physical tasks under dual-tasking conditions. These factors may also combine to worsen the performance further (Woollacott & Shumway-Cook, 2002).

The first is that the attentional resources required to conduct a physical task vary according to the level of difficulty of the task. If the task is a simple one, such as static standing, fewer attentional resources are needed. By contrast, more attentional resources are required for a complex task, such as turning or negotiating stairs. Additionally, the interaction effect is believed to be even stronger if both the cognitive and physical tasks share similar neural processes, for instance, when an executive function is involved in both tasks (Woollacott & Shumway-Cook, 2002). Moreover, the ability of an individual to perform the specific task may also affect the resources needed. For example, walking a straight line is considered automatic in healthy young adults, and thus minimal attentional resources are required. However, this activity could be difficult for stroke survivors who have lower limb weakness and balance problems, so there is a greater demand for resources (Baetens et al., 2012).

The second factor that affects the dual-tasking performance is the availability of attentional resources (Woollacott & Shumway-Cook, 2002). Attentional resources are reduced by aging or brain injury. If the available resources are insufficient for an individual to conduct two tasks simultaneously, deterioration in the performance of either or both tasks may result (Lacour et al., 2008; Plummer et al., 2013; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012). In such situation, the ability to allocate resources properly between tasks may also affect dual-tasking performance. How the resources are allocated can be explained by task prioritization.

Prioritization of task

Prioritization of task is the process of deciding how to allocate limited attentional resources between the two tasks when dual-tasking (Lacour et al., 2008; Yogev-Seligmann et al., 2012). There are different types of task prioritization:

Posture-first strategy

Posture-first strategy, or balance-first strategy, means that the physical task is being prioritized over the cognitive task to maintain balance and minimize the risk of falling when dual-tasking (Yogev-Seligmann et al., 2012). Different factors have been suggested affecting the judgment of employing this strategy: the complexity of the physical task and the individual's ability to estimate the risk and carry out the physical task (Yogev-Seligmann et al., 2012).

The posture-first strategy is commonly seen in older adults, especially those who are very frail or have impaired balance (Lacour et al., 2008). For example, older adults tend to slow down or even stop walking to talk. Another condition where this strategy is adopted is that when the physical task is complicated and threatens loss of balance (Plummer et al., 2013; Shumway-Cook & Woollacott, 2007), or when the physical task is new to the individual (Kizony et al., 2010). The posture-first strategy is considered to be a safety measure when the individual perceives that he or she is not capable of performing both tasks simultaneously.

Goal directed response and habitual response

When reacting to an external stimulus, there are two types of response: the goal-directed response and the habitual response. A goal-directed response is an action that is determined by the predicted and desired outcome, while a habitual response refers to the natural reaction to the stimuli (Chersi et al., 2013). A goal-directed response is involved when an individual learns a new skill. With repeated training, a habitual response is established and become dominant, especially under a stressful situation requiring a quick reaction. However, when there is an unexpected condition, the response shifts from the habitual one to the goal-directed one in order to achieve the desired outcome (Redgrave et al., 2010).

Animal studies have revealed that goal-directed and habitual responses are regulated by the dorsomedial striatum and the dorsolateral striatum, respectively (Redgrave et al., 2010). With learning and repeated practice, connections between the striatum and the prefrontal cortex, the sensory cortex or the motor cortex are strengthened. On the other hand, damage to the corresponding brain region may result in an inability to shift between the two response systems (Chersi et al., 2013).

Dual-tasking performance among stroke survivors

Several factors contributing to the aging effect on dual-tasking performance have been suggested (Woollacott & Shumway-Cook, 2002):

1) Increased demand for attentional resources to carry out the individual physical and cognitive tasks.
2) Decreased availability of attentional resources to dual-tasking.
3) Inability to shift attentional resources between the two tasks.
4) Combinations of these factors.

Dual-tasking performance may deteriorate further after a stroke. Numerous studies have investigated dual-tasking performance in stroke survivors. Most involved a gait-related task. In general, those studies showed interference either to the physical task (Baetens et al., 2013; Bowen et al., 2001), or to both tasks (Patel & Bhatt, 2014; Plummer-D'Amato et al., 2008; Pohl et al., 2011).

Interactions between the cognitive task and physical task may depend on the level of difficulty of the tasks. When subjects with stroke were asked to talk and walk concurrently on an oval track at a preferred speed, the physical performance deteriorated, but performance of the cognitive task was preserved. By contrast, when the subjects were asked to walk at their fastest speed, the accuracy of the cognitive task reduced, but the walking performance was maintained (Dennis et al., 2009; Plummer-D'Amato et al., 2008, 2010). The results may imply that under conditions that challenge their balance, stroke survivors may prioritize the physical task over the cognitive task. Such prioritization was also seen in the study by Smulders and colleagues (2012), where stroke survivors performed an obstacle avoidance task with a concurrent auditory Stroop test. The cognitive task performance was poorer when compared with single-tasking, while the gait pattern and the rate of successful obstacle avoidance were similar between the two tasking conditions. Therefore, it can be postulated that stroke survivors applied the posture-first strategy to prevent trips and falls when crossing the obstacles.

In general, previous studies have shown that the dual-tasking effect was greater in stroke survivors than in the healthy controls. In a study by Dennis and colleagues (2009) that involved straight line walking, stroke survivors demonstrated decreased performance when dual-tasking, but no change was found in non-stroke controls. Another study showed a reduction in performance for both the cognitive task and the physical task performance when the subjects with stroke were asked to walk and talk at the same time, while only physical performance was compromised in the age-matched controls (Pohl et al., 2011). According to the model of competition for attentional resources (Woollacott & Shumway-Cook, 2002), the greater effect of dual-tasking on stroke survivors can be explained by several factors: increased demand for attentional resources to carry out the individual tasks, a smaller amount of resources available, reduced ability to allocate the resources properly between the two tasks, or the combination of these factors (Lacour et al., 2008; Woollacott and Shumway-Cook, 2002).

1.1.5.3.1 Dual-tasking performance involving turning-while-walking

Only a few studies have investigated dual-tasking performance involving turning-while-walking in stroke survivors (Hollands et al., 2014; Manaf et al., 2014a, 2014b, 2017). Hollands and colleagues (2014) examined dual-tasking performance with 90-degree turns and serial 3s subtraction. The results showed a significant decrease in walking speed, a higher variability in turning time, and a longer single support phase when dual-tasking compared with single-tasking. Another study group also found that the physical task was performed less efficiently when dual-tasking (2014a, 2014b, 2017). The subjects performed timed Up-and-Go tests with a concurrent serial subtraction. The results showed longer completion times (Manaf et al., 2014a, 2014b), delayed initiation of turning, and a tendency to disruption of the reorientation sequence (Manaf et al., 2017) under dual-tasking conditions by comparison with the single-tasking.

Although the results of these studies consistently showed a deterioration in the physical task performance, they cannot truly reflect the interaction between the cognitive task and the physical task. All these studies focused on physical task performance. They either did not compare cognitive task performance between single-tasking and dual-tasking (Hollands et al., 2014) or did not conduct statistical analyses for the cognitive task (Manaf et al., 2014a, 2014b, 2017). Moreover, the subjects were instructed to prioritize the cognitive task over the physical task in most of these studies (Manaf et al., 2014a, 2014b, 2017). Therefore, the natural response of stroke subjects to dual-tasking that involves turning-while-walking is still not understood.

Another limitation of these studies is the nature of the cognitive task. All the studies employed serial 3s subtraction. The test is considered to involve internal interference, which means that the subject should initiate the response by continuous subtraction, instead of by reacting to an external stimulus (Al-Yahya et al., 2011). However, in a real life situation, disturbance can be triggered either internally by the individual or externally by the environment. How stroke survivors react to external disturbance while turning-while-walking has not yet been considered.

1.1.5.3.2 Dual-tasking performance involving stepping down

There has been no study of stroke survivors examining dual-tasking performance with stepping down. However, previous studies demonstrated compromised performance in both healthy younger and older people when dual-tasking. Previous studies showed increased body sway amplitude among healthy young subjects when stepping down with a concurrent cognitive task (Je et al., 2011; Qu & Hu, 2014). They also descend stairs more slowly when dual-tasking (Madehkhaksar & Egges, 2016). The deterioration in performance when dual-tasking with stepping down is even greater in healthy older adults. Tsang and colleagues (2013) showed that both healthy older and younger subjects swayed more when stepping down when dual-tasking than when single-tasking. However, only the older subjects demonstrated decreased accuracy in the auditory Stroop test, which was the cognitive task (Tsang et al., 2013). Similarly, another study detected a higher dual-task cost, which is defined as the percentage change in performance because of another concurrent task and is calculated by (McCulloch et al., 2009):

$$\frac{(\text{Dual-tasking performance} - \text{Single-tasking performance})}{\text{Single-tasking performance}}$$

among older adults than in younger counterparts (Telonio et al., 2014).

As discussed in the previous section, negotiation of stairs is related to the independence level of stroke survivors (Alzahrani et al., 2009). Being distracted is one of the commonest causes of falls on stairs, which can result in severe injuries (Jacobs, 2016; Startzell et al., 2000), or even death (National Safety Council, 2016). Further, falls are commoner when descending stairs than when ascending stairs. Therefore, stroke survivors' ability to dual-task when stepping down is worth studying.

1.1.5.3.3 Effect of exercise on dual-tasking performance in stroke survivors

Although the attention given to dual-tasking has increased in recent decades, there is still no intervention that promises to enhance dual-tasking performance among healthy older adults (Agmon et al., 2014; Gobbo et al., 2014). There are even fewer related interventions targeted at stroke survivors, and the results are only preliminary.

Single-tasking exercise training

The number of studies that have investigated the effect of single-task exercise training on dual-tasking performance among people with stroke is limited. An early study on this topic was a case series. Ten subjects with stroke received conventional exercise training for between one and nine months. Their dual-tasking ability was assessed with walking as the physical task and word generation and digit span as the cognitive tasks. After the training period, only one subject showed improvement in both tasks when dual-tasking. Six demonstrated enhanced physical task performance and another two improved in the cognitive task when dual-tasking (Cockburn et al., 2003). However, other larger scale studies failed to find any significant effect of a 3-month single-tasking rehabilitation exercise on dual-tasking performance involving static standing (De Haart et al., 2004; Roerdink et al., 2006, 2009).

Dual-tasking training

A recent case series studied the effect of dual-tasking training on dual-tasking performance in stroke survivors (Plummer et al., 2014). Seven subjects participated in 12 sessions of training, a walking exercise performed with various cognitive tasks. The training effect was evaluated by a dual-tasking test, which also involved walking but with different cognitive tasks than those used in training. After the intervention period, five participants showed decreased dual-task cost to gait speed. Preliminary results from this study seem to support the beneficial effect of dual-task training on dual-tasking performance in some stroke survivors. However, the effect cannot be confirmed as no control group was included and the sample size was small. Further, the mean length of time since the subjects' stroke was only 8.5 ± 3.5 months, so that spontaneous recovery may have occurred during the intervention period.

Effectiveness of exercise training on dual-tasking ability

According to the theory of competition for attentional resources in dual-tasking, enhancing single-tasking performance can reduce the resources demanded by that task and improve dual-tasking ability (Al-Yahya et al., 2011; Woollacott & Shumway-Cook, 2002). However, this effect was not observed in previous studies (Agmon et al., 2014; De Haart et al., 2004; Gobbo et al., 2014; Roerdink et al., 2006, 2009). A possible explanation is the method of learning used in training. When learning a new skill, either an explicit or an implicit method is involved. In explicit learning, the participant intends to acquire a new skill so attention, memory, and reasoning are all engaged. By contrast, in implicit learning the individual is not motivated to learn a skill but only to follow a movement, thus reducing the cognitive demand. It has been suggested that explicit learning enhances dual-tasking performance more effectively than implicit learning (Strobach et al., 2014). Hence, the effectiveness of an exercise at improving dual-tasking ability may depend on whether explicit or implicit learning was involved. In addition, dual-task training that requires changes in the allocation of attentional resources between the two tasks is more effective than those without such variation (Strobach et al., 2014). Instructions to shift resources between the two tasks may be essential to improve dual-tasking ability.

It is also worth addressing how a particular type of dual-task training transfers to other combinations of dual-tasking. There are many dual-tasking combinations in daily life. It would be more helpful if the effect of particular dual-task training is transferred to other dual-tasking activities. Several factors have been proposed to enhance the transfer effect of dual-task training. The first factor is involvement of the executive function (Lussier et al., 2017; Strobach et al., 2014). Executive function includes shifting attention, inhibition, monitoring goal-directed behavior and controlling complex activities (Royall et al., 2002), which are explicit in nature and are all-important to dual-tasking (Strobach et al., 2014). Involving executive function in training may therefore enhance the general dual-tasking ability and thus the transfer effect. Another factor that may increase the transfer effect of dual-task training is changing the skill learned, or the allocation of attentional resources between the two tasks (Lussier et al., 2017). Though the exact mechanisms are not clear, it is speculated that the alteration enhances attentional control when dual-tasking. Such variation may also improve the executive function, thus promoting the transfer effect (Lussier et al., 2017).

Summaries of functional ability

Regaining functional ability is one of the main objectives of stroke rehabilitation. Amongst regular daily activities, walking, turning, and stepping down are common causes of falling. Previous studies found altered behavior when turning-while-walking and stepping down among stroke survivors. On the other hand, there is growing attention to dual-tasking performance, which is common in daily life, among stroke survivors. The interaction between the cognitive task and the physical task in dual-tasking can be explained by competition for attentional resources, prioritization of tasks, posture-first strategy, goal-directed responses, and habitual response. Based on these theories and the suggestion that cognitive processing is essential in both turning-while-walking and stepping down, it is expected that a decrease in dual-tasking performance involving these activities will be observed in stroke survivors. However, while numerous studies have been conducted on dual-tasking ability in the population, most of them focused on walking. Only a few related to turning-while-walking, and none of them involved stepping down. Because of the study design, those related to turning-while-walking were not able to reflect the natural response of stroke survivors to such dual-tasking challenges. Therefore, further studies examining dual-tasking performance that employ turning-while-walking or stepping down as the physical task are required. Further, there is a need to explore exercises to improve dual-tasking performance in the stroke survivors.

1.1.6 Cardiovascular function

Apart from improving functional ability, another important aim of stroke rehabilitation is to reduce the risk of cardiovascular diseases. There are various measurements that reflect cardiovascular health. Blood pressure is the most widely recognized, but other parameters, including arterial stiffness and cardiac autonomic regulation, are becoming more common in both research and clinical settings. These assessments have also been found to predict cardiovascular disease independently of classic risk factors such as age, blood pressure, prior cardiovascular disease, and smoking (Cavalcante et al., 2011; Mäkikallio et al., 2004; Sakuragi & Abahayaratna, 2010; Umpierre & Stein, 2007).

1.1.6.1 Arterial stiffness

In normal situations, an artery can vary its properties in response to changes in pulsatile pressure and blood flow (Avolio et al., 2011; Nichols et al., 2011). This minimizes the effect of pressure fluctuations on the central circulation and maintains the blood supply to different organs (Hamilton et al., 2007; Tanaka et al., 2000; Umpierre & Stein, 2007). However, this ability is decreased by aging or chronic diseases such as hypertension, diabetes mellitus, or hyperlipidemia (Prisant et al., 2002). Arterial stiffness refers to loss of an artery's capacity to alter its properties in response to stimuli (Hamilton et al., 2007).

Arterial stiffness can be quantified by arterial compliance (Hamilton et al., 2007), which is the ability of the artery to distend and change its volume according to change in pressure. It is defined as:

$$\frac{\Delta V}{\Delta P}$$

where ΔV is the change in volume, while ΔP is the change in pressure (Nichols et al., 2011). There are different methods of measuring arterial compliance (Hamilton et al., 2007):

1) Systemic stiffness, which refers to the entire circulation.
2) Regional or segmental stiffness, which describes the properties of a segment of the arterial tree.
3) Local stiffness, which only concerns a small section of a blood vessel.

Arterial compliance is an independent predictor of mortality both from all causes and various cardiovascular diseases (Cavalcante et al., 2011; Sakuragi & Abahayaratna, 2010; Umpierre & Stein, 2007). Its predictive value is also suggested to be higher than that of conventional risk factors, such as age and blood pressure (Acampa et al., 2014). This high predictive value can probably be explained by the finding that alterations in the arterial structure and function precede any observable change in blood pressure. Thirty percent of normotensive subjects were found to have a reduced systemic arterial compliance (Pibarot & Dumesnil, 2012). Further, arterial stiffness is associated with elevated cardiovascular risk (Tang et al., 2014), systolic hypertension (Cameron & Dart, 1994), hyperlipidemia (Baltgaile, 2012), and diabetes mellitus (Baltgaile, 2012; Cavalcante et al., 2011).

Different factors have been proposed to cause arterial stiffening: structural changes, functional changes, and autonomic dysregulation.

Structure changes

Long-term arterial distention, as in aging, stresses the arterial wall repeatedly and results in a fracture of elastin fibers. The ability of the artery to bear the load caused by the pulsatile pressure may then be reduced, leading to a decline in arterial compliance (Hamilton et al., 2007; Nichols et al., 2011; O'Rourke & Hashimoto, 2008). Additionally, the long-term stress acting on the vessel wall causes inflammation, promoting the production of collagen fibers and disturbing the synthesis of elastin, further reducing the distensibility of the arteries (Laurent et al., 2006; Shirwany & Zou, 2010). Because of the high proportion of elastin fibers in large proximal arteries, the structural changes leading to arterial stiffness are more prominent in those regions than in small distal ones (Nichols et al., 2011; O'Rourke & Hashimoto, 2008; Sakuragi & Abhayaratna, 2010).

Functional changes

Functional changes of the artery occur mainly in the endothelial cells and the smooth muscle cells.

Endothelial cells are distributed across the intima of the artery and are exposed to the stress caused by blood flow (Baltgaile, 2012; Nichols et al., 2011). This stress produces endothelin-1, which is a powerful vasoconstrictor (Nichols et al., 2011). In addition, an optimal shear force acting on the endothelium has been found to promote the production of nitric oxide (Nichols et al., 2011), which modifies the process of collagen cross-links formation (Avolio et al., 2011). However, long-term stress acting on the intima may damage the endothelium, affect its functions and consequently increase arterial stiffness (Clarkson et al., 1999; Shirwany & Zou, 2010).

Smooth muscle cells also contribute to arterial compliance by maintaining the correct tension in the arterial wall in response to mechanical stimuli. The cells are stretched circumferentially when there is a sudden change in blood pressure (Nichols et al., 2011). In the long run, such abrupt stretches may alter the phenotype of the smooth muscle cells, leading to mineralization and calcification of the tunica media, resulting in increased arterial stiffness (Avolio et al., 2011).

Autonomic dysregulation

Previous studies have investigated the relationship between arterial stiffness and autonomic regulation. A prior study found that compliance of the radial artery reduced immediately after the activation of the sympathetic nervous system (Boutouyrie et al., 1994). Further, the sympathetic nervous system works with the endothelium to modulate vasomotor tone and regulate distensibility of the arteries (Boutouyrie et al., 1994; Laurent et al., 2006). Therefore, sympathetic dysregulation, which is common among older people (De Meersman & Stein, 2007; Sörös & Hachinski, 2012) and stroke survivors (Francica et al., 2015; Xiong et al., 2013), may contribute to the altered arterial compliance. Moreover, reduced vagal anti-inflammatory signaling has been suggested to contribute to the formation of atherosclerotic plaque, which then develops into arterial stiffening (Micieli & Cavallini, 2008).

1.1.6.1.1 Arterial stiffness and stroke

The relationship between arterial stiffness and stroke is reciprocal: increased arterial stiffness contributes to stroke incidence; a stroke may increase arterial stiffness.

The suggested mechanism by which increased arterial stiffness leads to a stroke is as follows: The cushioning effect is impaired in a stiff artery, which increases both pressure and flow pulsatility. The small arteries of the brain, which have low vascular resistance, may not be able to withstand the elevated pulsatile force, resulting in a rupture and a hemorrhage (Kim et al., 2016; Van Sloten et al., 2015). Additionally, increased stiffness of the carotid artery may also reflect the development of rupture-prone atherosclerotic plaques. When the plaques fracture from the arterial wall, an ischemic stroke may result (Van Sloten et al., 2015).

On the other hand, the exact mechanism of increased arterial stiffness after a stroke is still not clear. Proposed explanations include high blood pressure, endothelial dysfunction, and immune-inflammatory activation induced by the stroke (Tuttolomondo et al., 2010). Further, increased arterial stiffness is a risk factor for stroke (Mattace-Raso et al., 2006) and has been associated with stroke incidence (Kim et al., 2016; Van Sloten et al., 2015). It is not unexpected that stroke survivors are found to have a higher arterial stiffness. Nevertheless, the predictive value of arterial stiffness for cardiovascular disease also applies to stroke survivors (Calvet et al., 2014; Kim et al., 2014). In addition, it has been suggested that arterial compliance predicts the functional outcome (Gąsecki et al., 2012a, 2012b) and stroke recurrence (Tsivgoulis et al., 2006, 2012).

1.1.6.1.2 Effect of exercise on arterial stiffness

Although cardiovascular risk factors are mainly managed by pharmacological means, physical activity also plays a role in its management. Exercise has been found to prevent secondary stroke and reduce cardiovascular risk factors (Hankey, 2014). Also, prior studies show that exercise training improves arterial stiffness among healthy older adults (Tanaka et al., 2000). However, variations in the type and intensity of exercise may have different effects on arterial compliance.

Aerobic exercise training has been shown to enhance arterial compliance among healthy subjects in different age groups (Tanaka et al., 2000). A prospective study found increased arterial compliance after one year of progressive and vigorous aerobic exercise training among middle- and older-aged men who had a sedentary lifestyle. The compliance was even comparable to age-matched subjects who were trained with long-term endurance exercise (Tanaka et al., 2000). Furthermore, arterial compliance can be altered acutely after aerobic exercise (Nickel et al., 2011). A significant increase in small arterial compliance was found immediately after a moderately intense cycling exercise among healthy young subjects. However, these changes vanished within 24 hours of the exercise. Also, no significant change in large arterial compliance was observed during the assessment period (Nickel et al., 2011).

By contrast, resistance training at high and moderate intensity has been shown to be deleterious to arterial compliance (Cavalcante et al., 2011; Collier et al., 2008). However, this adverse effect was not observed with low-intensity resistance exercises (Umpierre & Stein, 2007) or when the resistance was gradually increased (Collier et al., 2008). Moreover, by adding an aerobic exercise into the resistance training, the unfavorable effect on arterial compliance was diminished (Yang et al., 2011).

Proposed mechanisms for the effect of exercise on arterial stiffness

How aerobic exercise training benefits arterial stiffness is not yet completely understood. A few mechanisms have been proposed, including promoted arterial function, altered arterial structure, and enhanced autonomic regulation on the artery.

The first and most commonly accepted mechanism is enhanced endothelial function and bioavailability of nitric oxide. During aerobic exercise, the increased arterial pressure and pulsatile force raise the shear stress acting on the arteries. The function of the endothelium is then stimulated, increasing the release and synthesis of nitric oxide and thus improving arterial compliance (Cameron & Dart, 1994; Clarkson et al., 1999; DeSouza et al., 2000; O'Rourke & Hashimoto, 2008; Sakuragi & Abhayaratna, 2010; Seals et al., 2008).

Another potential mechanism is structural change in the arterial wall. As shown in animal models, collagen fibers in the arterial wall are stretched after aerobic exercise training. The stretch transforms the cross-links of the fibers and thus increases the distensibility of the artery. However, it is believed that the elastin-collagen composition of the arterial wall, particularly in the large elastic arteries, takes years to be modified. Any change in arterial compliance after short-term treatment is unlikely to be attributable to structural change (Cameron & Dart, 1994; Seals et al., 2008; Tanaka et al., 2000).

The third proposed explanation is that aerobic exercise training reduces sympathetic vasoconstriction tone and enhances vagal modulation (De Meersman & Stein, 2007; Mueller, 2007; Micieli & Cavallini, 2008), which may also affect arterial compliance as discussed above (p.33).

Effect of exercise on arterial stiffness among stroke survivors

Research into this topic only started in recent years, with few studies available. Two prospective studies reveal a significant decrease in arterial stiffness after combined aerobic and resistance exercise training (Lee et al., 2015; Takatori et al., 2012). By contrast, another randomized controlled trial showed that both low-intensity and high-intensity aerobic exercise trainings were ineffective in improving arterial compliance (Tang et al., 2014). The discrepancy between the study results could be due to the measurements employed. In both studies that showed that exercise training was beneficial, regional arterial stiffness (carotid-femoral pulse wave velocity, cardio-ankle vascular index, and ankle-brachial pressure index) was examined as the outcome measure. The other study that showed no change tested local arterial stiffness (brachial pulse pressure), which may not have the sensitivity to detect systematic modifications in the arterial system after aerobic exercise training.

Currently available studies on the effect of exercise training on arterial compliance in stroke survivors are limited. As promoting cardiovascular health is one of the main objectives of stroke rehabilitation, further exploration of exercises that improve arterial compliance in this population is warranted.

1.1.6.2 Cardiac autonomic regulation

Cardiac autonomic regulation refers to the control of heart rate by modulating the balance between two branches of the autonomic system: the parasympathetic nervous system and the sympathetic nervous system. For healthy people, both systems are active in the resting condition, but the parasympathetic one is dominant. The relative balance between the two systems varies with changes in the internal and external environment (Shaffer et al., 2014).

With advancing age, there is an increase in sympathetic tone, but a decrease of parasympathetic tone (De Meersman & Stein, 2007; Sörös & Hachinski, 2012). This autonomic imbalance may lead to cardiovascular complications, myocardial injury, and arrhythmias (Figueroa et al., 2012; Sörös & Hachinski, 2012). The elevated sympathetic nervous system has been associated with various cardiovascular diseases, including heart failure and hypertension (Mueller, 2007). Similarly, reduced parasympathetic tone has been found to contribute to the development of atherosclerotic plaque, which may further increase arterial stiffness and the risk of stroke (Micieli & Cavallini, 2008).

The exact mechanisms of the effect of aging on cardiac autonomic regulation are not well understood, but several factors have been proposed. The over-activation of the sympathetic nervous system can be explained by the deterioration of baroreflex sensitivity (Hotta & Uchida, 2010; Moodithaya & Avadhany, 2012). Such deterioration degrades the capacity of blood vessels to change their properties in response to internal or external stimulation, which is believed to be caused by reduced arterial compliance (Njemanze et al., 2016; Wichi et al., 2009). Another proposed reason is the decreased ability of neurons to uptake noradrenaline, resulting in an increased discharge rate of the sympathetic nerves (Wichi et al., 2009).

It has been suggested that lower parasympathetic nervous activity is related to vagal nerve dysfunction (Wichi et al., 2009), including a decreased number of nerve fibers (Moodithaya & Avadhany, 2012) and reduced maximum conduction velocity in the nerve (Hotta & Uchida, 2010). This dysfunction may then lead to an altered neural discharge of the vagal nerve to the sinoatrial node of the heart (Moodithaya & Avadhany, 2012).

1.1.6.2.1 Cardiac autonomic regulation and stroke

Cardiac autonomic dysregulation, which is reflected by elevated sympathetic activity and reduced parasympathetic activity, may increase cardiovascular morbidity and mortality among stroke survivors (Dorrance & Fink, 2015; Micieli & Cavallini, 2008; Xiong et al., 2013). It has also been correlated with the level of neurological deficit and impairment after a stroke (Francica et al., 2015). Dysregulation happens at the acute stage of a stroke, but can also be observed in the chronic stage (Dorrance & Fink, 2015; Francica et al., 2015; Sörös & Hachinski, 2012).

Two main reasons have been proposed for cardiac autonomic dysregulation after a stroke. The first is that the stroke damages the brain regions that are responsible for cardiac autonomic regulation, such as the insular cortex (McLaren et al., 2005; Xiong et al., 2013). A further factor is that patients with stroke may not be able to engage in an adequate amount of exercise due to physical impairment, which may increase cardiac sympathetic tone and decrease parasympathetic drive (Francica et al., 2015).

1.1.6.2.2 Effect of exercise training on cardiac autonomic regulation

Previous studies have demonstrated the beneficial effect of long-term exercise training on resting cardiac autonomic regulation in healthy older adults (Chang et al., 2008; De Meersman & Stein, 2007; Micieli & Cavallini, 2008; Mueller, 2007). Such improvements protect an individual from sudden cardiac death (Chang et al., 2008). The exact mechanisms of the effect remain speculative (Jin et al., 2013). Deep breathing during aerobic exercise has been suggested to enhance parasympathetic regulation (Cole et al., 2016). Animal models suggest that physical activity may induce neuroplasticity in the region that is responsible for cardiac autonomic regulation (Mueller, 2007). Further investigation is desirable to determine if the effect of exercise can be extended to stroke survivors.

<u>Summaries on cardiovascular function</u>

Arterial stiffness has been found to predict cardiovascular risks. There is a reduction in arterial compliance with aging, which can account for the structural changes, functional changes, and autonomic dysregulation of the arteries. Decreased arterial compliance is a risk factor for stroke, while compliance has also been found decreased after a stroke. Previous studies have demonstrated the favorable effect of aerobic exercise on arterial compliance in healthy older adults. However, it is not clear that this effect is also present in stroke survivors.

Cardiac autonomic dysregulation is another predictor of cardiovascular risks among both healthy older adults and stroke survivors. The activity of the sympathetic nervous system increases, while that of the parasympathetic one decreases with aging or the occurrence of a stroke. Although studies have supported the advantageous effect of exercise on cardiac autonomic regulation among healthy older individuals, no study has been conducted on people with stroke.

Both arterial compliance and cardiac autonomic regulation are predictors of cardiovascular risk among stroke survivors. Moreover, exercise training has been found to benefit both functions in healthy older people. A natural question is whether the effect of exercise on these functions also applies to stroke survivors.

Summary of stroke

The aims of stroke rehabilitation are to regain physical function and prevent cardiovascular complications. Walking, turning, and negotiation of stairs are common daily activities that can lead to a fall in stroke survivors. It has been suggested that cognition is involved when performing these activities. An additional cognitive task during the movement, which is considered to be dual-tasking, may be challenging for this population. Previous studies have focused on dual-tasking performance involving straight line walking in stroke survivors. However, dual-tasking abilities while turning or stepping down are not well understood. In addition, enhancement of dual-tasking ability is still a neglected area.

Apart from regaining function, it is also important to prevent cardiovascular complications in stroke survivors. Arterial compliance and cardiac autonomic regulation are expected to predict cardiovascular morbidity and mortality. Although aerobic exercise has been shown to benefit both functions in healthy older adults, it is not clear that the effects extend to stroke survivors.

Regarding the objectives of stroke rehabilitation and the fact that there is a lack of effective training, it is critical to explore an exercise regime that can achieve the dual aims of improving function and cardiovascular health among the stroke survivors.

1.2 Tai Chi

Tai Chi is a Chinese traditional martial art, which has been practiced for many years. In recent decades, Tai Chi has been adopted as both an exercise that promotes healthy aging and a mean of rehabilitation for patients with different diseases. There are different styles of Tai Chi, including Chen (陳) style, Yang (楊) style, Sun (孫) style, Wu (吳) style and Wu (武) style. The Yang style is among the most commonly employed in health related scientific research. Further, there are different numbers of forms, such as 24-form, 48-form, or 108-form Tai Chi. The greater the number of forms practiced, the higher the level of demand for motor skill, attention, and memory is required (Man et al., 2010). Despite the variations in style and number of forms, the principles are similar.

1.2.1 Features of Tai Chi

The following sections will discuss the beneficial effect of Tai Chi on different functions, which can probably be explained by its physical requirements, cognitive involvement, dual-tasking nature, aerobic characteristic, and mind-body relationship.

1.2.1.1 Physical requirements

The movement of Tai Chi is slow. The Tai Chi gait has a lower average speed (0.09 m/s) and a longer gait cycle (11.9 sec) than the walking gait (speed = 0.84 m/s;

gait cycle = 1.3 sec) (Wu et al., 2004). When practicing Tai Chi, body weight is shifted continuously between the two legs in a semi-squat posture. These characteristics may explain the higher levels of lower limb muscles activation and co-contraction during the Tai Chi gait (Tseng et al., 2007; Wu et al., 2004). Indeed, previous studies have demonstrated a significant improvement in lower limb muscle strength and endurance after long-term Tai Chi practice in community-dwelling older adults (Audette et al., 2006; Lu et al., 2013a; Mao et al., 2006).

Precise positioning of the limbs is also emphasized in Tai Chi (Wolf et al., 1996). A prior study found only minimal intra-subject and inter-subject variations in the movement of the ankle joint and hip joint during Tai Chi practice (Wu et al., 2004). This similar movement may explain the higher proprioceptive sense of the lower limb joints among older Tai Chi practitioners than in age-matched controls (Tsang & Hui-Chan, 2003, 2008; Xu et al., 2004).

The center of pressure is shifted continuously with large amplitude in different directions during Tai Chi practice (Gatts & Woollacott, 2007; Hackney & Wolf, 2014; Jiménez-Martin & Hernández-Neira, 2014; Leung & Tsang, 2008; Mao et al., 2006). To maintain balance during such large amplitude of movements, Tai Chi practitioners stand upright (Gatts & Woollacott, 2006; Hart et al., 2004) and keep the center of mass within the base of support (Wu et al., 2004) throughout practice. Additionally, a prior study showed that after Tai Chi training, older adults were able to walk with a greater divergence between the center of mass and the center of pressure, reflecting a less stable posture. It may also imply that practitioners have an increased tolerance of unsteadiness during walking (Hsue & Su, 2014).

1.2.1.2 Cognitive involvement

Previous studies have demonstrated the advantageous effect of Tai Chi on different domains of the cognitive functioning, such as global cognition (Lam et al., 2009, 2012) and executive function, including attention and working memory (Kasai et al., 2010; Miller & Taylor-Piliae, 2014; Nguyen & Kruse, 2012; Taylor-Piliae et al., 2010; Wayne et al. 2014). The precise mechanisms for the effect of Tai Chi training on cognitive functioning are still unknown but have been suggested to be associated with the effect of physical exercise and the characteristics of Tai Chi. Tai Chi is an aerobic exercise of moderate intensity (Lan et al., 1996). Exercise of this intensity has been suggested to promote angiogenesis (Lista & Sorrentino, 2010; Voss et al., 2010) and increase blood flow in the brain (Colcombe et al., 2003). Also, aerobic exercise training promotes neuronal growth and repair and neuroplasticity (Colcombe et al., 2006; Voss et al., 2010). The aerobic nature of Tai Chi may therefore explain the improvement of cognitive function after the training (Miller & Taylor-Piliae, 2014; Wayne et al., 2014).

The process of learning and practicing Tai Chi may also explain the enhancement of cognitive function. Acquiring Tai Chi movements is a process of skill-based motor learning (Walsh et al., 2015; Wayne et al., 2014). Learning a new skill promotes synaptic connectivity, hence enhancing cognitive function (Lista & Sorrentino, 2010). Also, when practicing Tai Chi, an individual must maintain a high level of attention to ensure the correct sequence of movements and precise limb positioning (Taylor-Piliae et al., 2010). As the whole Tai Chi movement cycle lasts for between a few minutes to more than ten minutes and is usually repeated several times during the practice, sustained attention may therefore be enhanced by long-term practice (Man et al., 2010; Wayne et al., 2014). Moreover, memorizing all the Tai Chi forms and their sequence may promote memory function (Man et al., 2010; Miller & Taylor-Pillae et al., 2014; Taylor-Piliae et al., 2010). Working memory may also be enhanced, as an individual should perform the current movement and plan for the subsequent one simultaneously (Man et al., 2010; Taylor-Piliae et al., 2010; Wayne et al., 2014).

1.2.1.3 Dual-tasking feature

Tai Chi is considered to be a dual-tasking exercise as it involves both physical and cognitive processing. The Tai Chi practitioner must maintain balance and perform different physical movements while memorizing and planning the subsequent Tai Chi form. Previous studies have shown a beneficial effect of Tai Chi training on dual-tasking performance in healthy older adults. Lu and colleagues (2013b) compared dual-tasking performance between Tai Chi practitioners and non-practitioners with an auditory Stroop test and a stepping down test. In dual-tasking conditions, the practitioners made fewer errors in the cognitive task and swayed less in the physical task by comparison with non-practitioners (Lu et al., 2013b). A similar effect was also observed in community-dwelling older adults after 16 weeks of Tai Chi training (Lu et al., 2016). Another study found a faster gait speed and a lower gait variation in healthy older adults when dual-tasking after six months of Tai Chi training (Wayne et al., 2015). A faster gait speed than controls when dual-tasking was also observed in healthy older subjects who were trained with 12 weeks of Tai Chi exercise (Manor et al., 2014).

The exact mechanisms of why dual-tasking performance is improved after Tai Chi training are not yet understood. However, according to the theory of competition for attentional resources (Woollacott & Shumway-Cook, 2002), it can be explained by enhanced cognitive and physical functions, increased attentional resources, and a better ability to allocate the resources after Tai Chi training. As discussed above, studies have demonstrated the beneficial effects of Tai Chi training on both physical (1.2.1.1, pp.42–43) and cognitive (1.2.1.2, pp.44–45) functioning. The improved functions may imply that fewer attentional resources are required to carry out the individual tasks, thus provides extra resources to conduct both tasks simultaneously. The other possible mechanisms are an increased availability of attentional resources and an enhanced ability to allocate resources when dual-tasking. A previous cross-sectional study showed that Tai Chi practitioners had a thicker cerebral cortex at the middle frontal sulcus, right insula region, right precentral gyrus, left medial occipitotemporal sulcus, and left lingual sulcus (Wei et al., 2013). Another event-related potential study found that older Tai Chi practitioners had higher P3 amplitudes than older subjects with a sedentary lifestyle in a task-switching test. The amplitudes of the practitioners were comparable to those of younger subjects (Fong et al., 2014). It is suggested that a higher P3 amplitude is related to a better ability to allocate attentional resources to different tasks (Polich & Heine, 1996). Nevertheless, the mechanisms of how Tai Chi improves dual-tasking performance warrant further investigation.

In contrast with the results that support the training effect of Tai Chi on dual-tasking, a study by Hall and colleagues (2009) demonstrated no significant improvement in dual-tasking performance after 12 weeks of Tai Chi training with healthy older adults. The authors attributed the insignificant results to the instruction method being employed in the study; the instructor provided continuous visual and verbal cues during the practice. The frequent prompts may have discouraged the subjects from actively memorizing and planning the sequence and movement, hence minimizing the dual-tasking feature of Tai Chi.

1.2.1.4 Aerobic exercise with moderate intensity

Although the movement of Tai Chi is slow, it has been shown to be an aerobic exercise with moderate intensity (Lan et al., 1996). A possible reason for such intensity is the prolonged lower limb muscle co-contraction, which increases the metabolic demand (Zorzi et al., 2015). Indeed, a recent meta-analysis supported the beneficial effects of Tai Chi training among healthy adults on blood pressure, heart rate, stroke volume, and cardiac output, which is attributable to its aerobic nature (Zheng et al., 2015).

The aerobic nature of Tai Chi may also explain its effect on arterial compliance. A randomized controlled trial showed a significantly higher compliance in both large and small arteries among healthy older women after 16 weeks of Tai Chi training (Lu et al., 2013a). Similar improvements were also found in those with rheumatoid arthritis (Shin et al., 2015). The effect of Tai Chi training on arterial compliance may depend on the method of assessment used. A prior study found a significant improvement in systemic vascular compliance but not brachial artery compliance after five months of Tai Chi training in community-dwelling older adults (Huang et al., 2011). Further, those studies that showed significant improvement also measured the systemic arterial compliance (Lu et al., 2013a) and regional compliance (brachial-ankle) (Shin et al., 2015). As Tai Chi is a whole body exercise, measurements that cover a larger area of the arterial tree may be more sensitive to changes resulting from training than local ones.

Other than the direct measurement of arterial compliance, factors crucial to arterial compliance, including endothelial function (Shin et al., 2015) and the amount of blood nitric oxide (Pan et al., 2015) were enhanced, while serum endothelin-1 level was reduced (Lu & Kuo, 2013), after Tai Chi training.

1.2.1.5 Mind-body exercise

Tai Chi is a mind-body exercise. It is not only a physical movement but also involves the mind; the mind should be relaxed but concentrated during the practice (Chang et al., 2008; Hart et al., 2004; Miller & Taylor-Piliae, 2014). The slow and deep abdominal breathing is synchronized with the fluid movement of Tai Chi. It is believed that this breathing pattern helps practitioners to attain a relaxed and concentrated state of mind (Hart et al., 2004; Tseng et al., 2007; Zorzi et al., 2015).

The relaxed state of mind (Curiati et al., 2005; Fong et al., 2015; Lazar et al., 2000), the slow breathing pattern (Figueroa et al., 2012; Lu & Kuo, 2003, 2014), and the aerobic nature (Chang et al., 2008; De Meersman & Stein, 2007; Micieli & Cavallini, 2008; Mueller, 2007) have all been suggested to contribute to the improvement in cardiac autonomic regulation after Tai Chi training. Previous studies demonstrated a shifting of cardiac autonomic balance immediately after Tai Chi exercise towards the parasympathetic nervous system by enhancing its activity and reducing the sympathetic one (Chang et al., 2008; Lu & Kuo, 2003, 2006, 2014; Motivala et al., 2006; Väänänen et al., 2002). However, results of studies of the long-term effect of Tai Chi training were controversial. A cross-sectional study showed that the parasympathetic nervous system was more active at rest and during isometric contraction stressors among Tai Chi practitioners as compared with non-practitioners (Figueroa et al., 2012). Also, a randomized controlled trial demonstrated that after 12 weeks of Tai Chi training, healthy older women had a higher parasympathetic but a lower sympathetic activity at rest (Audette et al., 2006). Conversely, another two clinical trials showed no significant change in autonomic regulation in the resting condition among patients with coronary heart disease (Chang et al., 2008; Sato et al., 2010).

Different target populations enrolled in these studies may explain the discrepancy between the results. It has also been proposed that reflex activities of the autonomic nervous system can be observed immediately after exercise. In contrast, a longer time and more frequent stimulation are required to show a significant change in the tonic activities of the autonomic nervous system (Chang et al., 2008). Although the two studies that showed no significant improvement in the autonomic regulation employed an intervention period of more than nine months, the in-class training took place only once a week. The low training frequency may explain the lack of significant change in the cardiac autonomic regulation following Tai Chi training.

1.2.2 Effect of Tai Chi training among stroke survivors

Previous studies have supported the training effect of Tai Chi among stroke survivors. In the study by Au-Yeung and colleagues (2009), stroke survivors performed the Limits of Stability Test with a shorter reaction time and greater maximum excursion of the center of gravity after 12 weeks of Tai Chi training. Also, the visual ratio and vestibular ratio in the Sensory Organization Test improved. The benefit of Tai Chi training can also be observed among hospitalized stroke survivors. Subjects who had practiced Tai Chi for 12 weeks showed less bodily sway when standing. Functional reach, gait speed, and timed Up-and-Go test performance also improved (Kim et al., 2015). Another randomized controlled trial found that stroke survivors had greater lower limb muscle strength and higher aerobic endurance after 12 weeks of Tai Chi training. More importantly, there were two-third fewer falls among subjects in the Tai Chi group than those in either the exercise group or the control group (Taylor-Piliae et al., 2014). Although previous studies into the effect of Tai Chi training on stroke survivors showed satisfactory results, there has been no research into its effect on dual-tasking performance, arterial compliance, and cardiac autonomic regulation among stroke survivors.

The beneficial effects of Tai Chi training to stroke survivors can be attributed to its characteristics. Keeping a proper posture when practicing Tai Chi may help to tackle the problem of postural asymmetry in stroke survivors. Additionally, this asymmetry may be improved by increasing the weight bearing on the affected side, as weight shifts constantly between the legs during Tai Chi training (Kim et al., 2015; Taylor-Piliae & Coull, 2012).

Due to physical and cognitive impairment, special care should be given to stroke survivors during Tai Chi practice. For instance, the class size should be small so that the instructor can provide close supervision to the participants. In addition, standby physical assistance, such as a chair, walking aid or manual support, should be available.

Moreover, there should be adequate rest periods whenever needed. Various strategies, including encouragement, personalized feedback, and good communication, may also help to improve adherence to the intervention (Taylor-Piliae & Coull, 2012).

1.2.3 Dosage and principle of Tai Chi training

Although there is evidence supporting the training effect of Tai Chi, no consensus has been reached on the training dosage. On the other hand, factors other than dosage may affect the outcome of training. It has been suggested that older adults should exercise for at least 30 minutes on most days of the week to maintain cardiovascular health, with a longer training period to promote additional effects (Pescatello et al., 2014). A summary of the training dosage and the corresponding results from previous studies on the effect of Tai Chi training are presented in Table 1.1. Results of previous studies demonstrated that a total of 12 hours of Tai Chi training (1 hour/session, 2/week) was sufficient to improve dual-tasking ability in healthy older adults (Manor et al., 2014) or decrease arterial stiffness in women with rheumatoid arthritis (Shin et al., 2015). By contrast, there was no change in dual-tasking performance in older adults after a total of 36 hours of Tai Chi training in the study by Hall and colleagues (2009). Further, no significant change was found in brachial arterial compliance after 60 hours of Tai Chi training over 20 weeks (Huang et al., 2011) or in cardiac autonomic regulation after 54 hours of training over 36 weeks (Chang et al., 2008). The results suggest that the training dosage may not be the only factor that determining the training effect of Tai Chi. Different factors such as the outcome measurements employed, target population, instruction method and the focus of training may also play a role. For example, the location of measurement may explain the discrepancies in the effect of Tai Chi training on arterial stiffness, as discussed in the section of Arterial Stiffness (Section 1.1.6.1.2, p.34–35). The inconsistent results for heart rate variability may also be attributed to the different populations studied, i.e. healthy older adults (Audette et al., 2006) vs patients with heart disease (Chang et al., 2008; Sato et al., 2010).

Table 1.1 Summary of the amount of Tai Chi training and corresponding results from previous studies

(a) Training effect of Tai Chi on dual-tasking ability among older adults

Study	Subjects	Tai Chi style	Frequency (/week)	Time (hours)	Duration (weeks)	Total training (hours)	Results
Hall et al., 2009	Tai Chi (n = 8) Control (health education) (n = 7) (Mean age of both groups = 72.2 ± 7.7)	24-form Yang style	2	1.5	12	36	**SOT with auditory Stroop test:** • No significant change with Tai Chi **Obstacle crossing with 3-choice reaction time task:** • No significant change with Tai Chi
Lu et al., 2013b	Tai Chi (n = 15, age = 72.8 ± 6.7) Control (recreational activities) (n = 16, age = 67.3 ± 6.6)	12-form Yang style	3	1.5	16	72	**Stepping down with a auditory Stroop test:** • Fewer errors on the auditory Stroop test with Tai Chi • Lower CoP sway path and sway area with Tai Chi • Less CoP sway area with Tai Chi than control
Manor et al., 2014	Tai Chi (n = 29, age = 87 ± 5) Control (health education) (n = 28, age = 86 ± 6)	Yang style	2	1	12	12	**Walking with serial subtraction:** • Increased speed with Tai Chi • Higher speed with Tai Chi than control

Wayne et al., 2015	Tai Chi (n = 31, age = 63.9 ± 8.0) Control (n = 29, age = 64.5 ± 7.4)	24	2 (1st month) 3 (after 1 month)	1	36	40	**Walking with serial subtraction:** • Improved gait speed and decreased stride time variability with Tai Chi • No significant difference between Tai Chi and control

(b) Training effect of Tai Chi on cardiovascular function among older adults

Study	Subjects	Tai Chi style	Frequency (/week)	Time (hours)	Duration (weeks)	Total training (hours)	Results
Audette et al., 2006	Tai Chi (n = 11, age = 71.5 ± 4.6) Brisk walking (n = 8, age = 71.3 ± 4.4) Control (n = 8, age = 73.5 ± 5.7)	10-form Yang style	3	1	12	36	**Resting heart rate variability:** • Increased normalized high frequency and decreased normalized low frequency with Tai Chi • No between group comparison conducted
Chang et al., 2008	*Patients with coronary artery disease* Tai Chi (n = 22, age = 58.2 ± 11.3) Controls (n = 39, age = 66.3 ± 9.5)	108-form Yang style	1	1.5	36	54	**Resting heart rate variability:** • No significant change in time and frequency domains with Tai Chi • No significant difference between Tai Chi and controls

Huang et al., 2011	Tai Chi (n = 83, age = 62.3 ± 9.0)	24-form Yang style	3	1	20	60	**Systemic vascular compliance:** • Increased after training **Brachial artery compliance:** • No significant change after training
Lu et al., 2016	Tai Chi (n = 15, age = 72.8 ± 6.7) Control (recreational activities) (n = 16, age = 67.3 ± 6.6)	12-form Yang style	3	1.5	16	72	**Compliance of large and small arteries** • Improved with Tai Chi • Similar between Tai Chi and control
Lu & Kuo, 2013	Tai Chi (n = 22, age = 56*) Controls (n = 20, age = 52*)	Yang style	7	1	12	84	**Serum level of endothelin-1** • Decreased with Tai Chi • Lower with Tai Chi than control
Pan et al., 2015	*Patients with hypertension* Tai Chi (n = 24, age = 56.4 ± 4.0) Control (n = 16, age = 56.9 ± 4.0)	24-form Yang style	6	1	12	72	**Level of plasma nitric oxide** • Increased with Tai Chi • Higher with Tai Chi than control
Sato et al., 2010	*Patients with coronary heart disease* Tai Chi (n = 10, age = 68 ± 5) Control (n = 10, age = 68 ± 4)	8-form Yang style	1	1	52	52	**Resting heart rate variability** • No significant change with Tai Chi • No significant difference between Tai Chi and control

Shin et al., 2015	*Women with rheumatoid arthritis* Tai Chi (n = 29, age = 64.0 ± 5.4) Control (n = 27, age = 62.7 ± 5.9)	Tai Chi for arthritis	1	1	12	12	**Brachial-ankle pulse wave velocity** • Improved with Tai Chi • Slower with Tai Chi than control

(c) Training effect of Tai Chi among stroke survivors

Study	**Subjects**	**Tai Chi style**	**Frequency (/week)**	**Time (hours)**	**Duration (weeks)**	**Total training (hours)**	**Results**
Au-Yeung et al., 2009	Tai Chi (n = 59, age = 61.7 ± 10.5) Control (n = 55, age = 65.9 ± 10.7)	12-form Sun style	1	1	12	12	**Limits of Stability** • Decreased reaction time to forward, backward, and less affected side with Tai Chi • Faster reaction time to less affected side with Tai Chi than control • Increased maximum excursion to all directions with Tai Chi • Greater maximum excursion to all directions with Tai Chi than control **Sensory Organization Test** • Improved visual ratio and vestibular ration with Tai

							Chi • Higher vestibular ratio with Tai Chi than control **TUGT** • No significant change with Tai Chi • No significant different between Tai Chi and control
Hart et al., 2004	Tai Chi (n = 9, age = 61.4*) Control (Physiotherapy) (n = 9, age = 57.3 ± 6.8)	Not reported	2	1	12	24	**Romberg's test, standing on the less affected leg, Emory Fractional Ambulation Profile, BBS, TUGT** • No significant change with Tai Chi • No significant difference between Tai Chi and control
Kim et al., 2015	Tai Chi (n = 11, age = 53.5 ± 11.5) Physical exercise (n = 11, age = 55.2 ± 10.2)	10-form	2	1	6	12	**Static standing (eyes opened and eyes closed):** • Decreased sway with Tai Chi • Less sway with Tai Chi than physical exercise **Functional reach:** • Increased distance with Tai Chi • Longer distance with Tai Chi than physical exercise **10-m walking test:**

							• Decreased time with Tai Chi • Faster with Tai Chi than physical exercise **TUGT:** • Decreased time with Tai Chi • Faster with Tai Chi than physical exercise
Taylor-Piliae et al., 2014	Tai Chi (n = 53, age = 71.5 ± 10.3) Exercise control (n = 44, age = 69.6 ± 9.4) Control (usual care) (n = 48, age = 68.2 ± 10.3)	24-form Yang style	12	3	1	36	**Number of falls** • 2/3 fewer falls with Tai Chi than exercise and control **2-minute step test** • Improved with Tai Chi • Better with Tai Chi than control • No significant difference between Tai Chi and control **SPPB** • No significant change with Tai Chi • No significant difference among the three groups

Notes: BBS: Berg Balance Scale; CoP: center of pressure; SPPB: Short Physical Performance Battery; TUGT: timed up-and-go test
* Standard deviations not reported

Training specificity may also account for inconsistent results in previous studies into the effects of Tai Chi training. Regarding dual-tasking ability, significant improvement was observed in two previous studies (Lu et al., 2013b; Wayne et al., 2015), but not in the one by Hall and her team (2009). Although it is possible that the study by Hall and colleagues employed a lower training dosage leading to an insignificant result, the authors also argued that the instruction method might play a role (detailed discussion in Section 1.2.1.3, p.45–47). Indeed, as discussed in the section of the effect of exercise training on dual-tasking (Section 1.1.5.3.3, p.26–29), factors such as the involvement of explicit learning, executive function, the variation of skill, and shifting of the attentional resources may affect the effectiveness of an exercise on dual-tasking ability and its transfer effect. Further, older people tend to learn through implicit methods, for example, by following the movement of the instructor only while exercising (Caljouw et al., 2016), which may explain the results of the study by Hall and colleagues (2009).

Factors mentioned above that may enhance the transfer effect of an exercise should be emphasized when practicing Tai Chi in order to maximize its effect on dual-tasking ability. For example, practitioners should be encouraged to memorize and plan for the Tai Chi forms rather than just following the movement of an instructor, so as to promote explicit learning. There could also be variations of movement when practicing Tai Chi, such as gradually increasing the level of difficulty by eliminating physical support or separating the upper limb and lower limb movements during training. These strategies may also help those who have physical or cognitive impairment to acquire the Tai Chi movement. Moreover, participants may shift their attention between the physical movement and the cognition required to plan the motion according to the complexity of the Tai Chi form or the capacity of the individual. For instance, in the form Kick with Heel, which involves single leg standing and knee extension of the other leg, attentional resources should be allocated to the physical task to keep balance. In a form that demands less for balance, such as Wave Hands in Clouds, resources may be shifted to coordinate the movement of the two hands. On the other hand, those forms with both complex movement and challenging balance requirements, such as Brush Knee and Twist Step, attentional resources should be divided equally or shifted continuously between the two tasks. These strategies may enhance explicit learning, varying the movement and altering the allocation of attentional resources when practicing Tai Chi, thus hopefully improving dual-tasking ability and maximizing the transfer effect. Further, these features also distinguish Tai Chi from conventional exercise, which is single-tasking in nature and does not require explicit learning and shifting of attention, though variations in training are still possible.

Nevertheless, although a higher training dosage and longer training period may be more efficient in achieving the beneficial effect of Tai Chi, factors such as the target population, assessment method, and training specificity should also be considered. Further, the amount of training should be feasible taking into account the disabilities and needs of the target population.

Summary of Tai Chi

Previous studies have supported the beneficial effects of Tai Chi on physical ability, cognitive function, dual-tasking performance, cardiovascular function, and cardiac autonomic regulation. Various features of Tai Chi may explain its beneficial effects. Research has also demonstrated the training effect of Tai Chi among stroke survivors. However, none of them were concerned with dual-tasking performance, arterial compliance and cardiac autonomic regulation. In addition, special care and training specificity have to be designed and arranged when instructing the stroke population in Tai Chi.

In this Introduction section, the needs of stroke survivors and the features of Tai Chi as a rehabilitative exercise have been discussed. It is highly possible that the characteristics of Tai Chi practice match the aims of stroke rehabilitation. Therefore, the effect of Tai Chi training on dual-tasking performance and cardiovascular function among stroke survivors is worth studying.

CHAPTER 2

OBJECTIVES AND HYPOTHESES

Objectives

The objectives of this study were:

1) To examine the dual-tasking performance of stroke survivors in two situations:
    a. Turning-while-walking with a concurrent cognitive task.
    b. Stepping down with a concurrent cognitive task.
2) To investigate the effect of Tai Chi training in stroke survivors on:
    a. Dual-tasking performance involving turning-while-walking.
    b. Dual-tasking performance involving stepping down.
    c. Cardiovascular function as measured by blood pressure, arterial stiffness, and cardiac autonomic regulation.

Hypotheses

Physical and cognitive impairment is common among stroke survivors. It has been suggested that cognitive function is needed in both turning-while-walking and stepping down activities. Based on the theory of competition for attentional resources during dual-tasking, the hypotheses addressed by the first objective were:

I. There would be a decrement in the performance of both the cognitive task and the physical task when stroke survivors performed dual-tasking.
II. The performance of the stroke survivors in dual-tasking would be inferior to that of the non-stroke controls.

Tai Chi has been shown to benefit both dual-tasking ability and cardiovascular function in healthy older adults. Therefore, the hypotheses of the second objective of this study were:

I. Both single-tasking and dual-tasking performance would be enhanced in stroke survivors after Tai Chi training.
II. Cardiovascular function in stroke survivors, as measured by blood pressure, arterial stiffness and cardiac autonomic regulation, would improve after Tai Chi training.
III. The beneficial effects of Tai Chi training would be greater than those of conventional exercise.

There were two phases to this study. The first was a cross-sectional study to achieve the first objective. The second was a randomized controlled trial to accomplish the second objective.

CHAPTER 3

THE MAIN STUDY

CHAPTER 3.1

THE PERFORMANCE OF STROKE SURVIVORS IN TURNING-WHILE-WALKING WHILE CARRYING OUT A CONCURRENT COGNITIVE TASK COMPARED WITH CONTROLS

Submitted:

Chan, W. N., & Tsang, W. W. The performance of stroke survivors in turning-while-walking while carrying out a concurrent cognitive task compared with controls. Submitted to *PLoS ONE*. Under second review.

3.1.1 Abstract

Background

Turning-while-walking is one of the commonest causes of falls in stroke survivors. It involves cognitive processing and may be challenging when performed concurrently with a cognitive task. Previous studies of dual-tasking involving turning-while-walking in stroke survivors show that the performance of physical tasks is compromised. However, the design of those studies did not address the response of stroke survivors under dual-tasking condition without specifying the task-preference and its effect on the performance of the cognitive task.

Objective

First, to compare the performance of single-tasking and dual-tasking that involved turning-while-walking in stroke survivors.

Second, to compare the performance of stroke survivors with non-stroke controls.

Methods

Fifty-nine stroke survivors and 45 controls were assessed with an auditory Stroop test, a turning-while-walking test, and a combination of the two single tasks. The outcome of the cognitive task was measured by a composite score, which was calculated by dividing the accuracy by the reaction time. The physical task was evaluated by measuring the turning duration, number of steps to turn, and time to complete the turning-while-walking test. Two-way mixed ANOVA was employed for statistical analysis.

Results

Stroke survivors showed a significantly lower composite score on the auditory Stroop test when dual-tasking than in single-tasking. Their performance in the turning-while-walking task was similar under both single-tasking and dual-tasking conditions. Additionally, stroke survivors demonstrated a significantly poorer cognitive task performance than the controls both when single-tasking and dual-tasking. They took longer to turn, with more steps, and needed more time to complete the turning-while-walking task in both tasking conditions.

Conclusions

The results show that stroke survivors with high mobility function compromise the performance of the auditory Stroop test while preserving simultaneous turning-while-walking performance. They also demonstrated poorer performance in both single-tasking and dual-tasking as compared with controls.

Keywords

Turning-while-walking; dual-tasking; stroke

3.1.2 Introduction

Turning-while-walking is a common daily activity (Cumming & Klineberg, 1994; Sedgman et al., 1994). It has been suggested that turning is not automatic but requires cognitive processing to provide feedback control (Hollands et al. 2014; Manaf et al., 2015). Information from various sensory systems, including the visual system, vestibular system and somatosensory system, are integrated throughout the movement, and the body adjusts accordingly (Shumway-Cook & Woollacott, 2007; Thigpen et al., 2000). In turning-while-walking, failing to adjust the movement from the already coordinated straight line walking may result in loss of balance or even a fall (Hollands et al., 2013). Indeed, turning is among the activities most frequently reported to cause a fall in older people with stroke (Hyndman et al., 2002). Falling during a turn is 7.9 times more likely to result in a hip fracture in stroke survivors than walking in a straight line (Cumming & Klineberg, 1994). Previous studies have shown that a stroke affects the performance of turning-while-walking. Stroke survivors took a longer time to turn and needed more steps than their age-matched counterparts (Dite & Temple, 2002; Lam & Luttmann, 2009). In addition, they turned more slowly with less displacement of the center of mass in the mediolateral direction (Bonnyaud et al., 2015a). The reorientation sequence of body segments was also disrupted (Hollands et al., 2010a; Lamontagne & Fung, 2009).

Performing two tasks simultaneously, such as responding to an external distraction while walking, is common in everyday life. This dual-tasking ability has been shown to relate to both falls (Baetens et al., 2013) and functional ability (Manaf et al., 2014a; Plummer-D’Amato & Altmann, 2012; Plummer-D’Amato et al., 2010). Based on the theory of competition for attentional resources, dual-tasking performance is suggested to be affected by several factors: 1) fewer attentional resources are available to perform two tasks concurrently, 2) inability to allocate resources between the two tasks properly, 3) increased resources requirement to carry out the individual tasks, and 4) a combination of these factors (Lacour et al., 2008; Woollacott &

Shumway-Cook, 2002; Yogev-Seligmann et al., 2012). If any of these factors are present, the performance of either or both tasks will be downgraded.

Many studies have been conducted to investigate dual-tasking ability in stroke survivors (Baetens et al., 2013; Bowen et al., 2001; Patel & Bhatt, 2014; Plummer et al., 2013; Plummer-D'Amato et al., 2010; Smulders et al., 2012) but the number investigating turning-while-walking is limited. The available studies consistently showed that an additional cognitive task has a detrimental effect on the turning-while-walking performance (Hollands et al., 2014; Manaf et al., 2014a, 2014b, 2017). However, there are questions that those studies could not answer. First, in some of the studies subjects were asked to prioritize the cognitive task over the physical task (Manaf et al., 2014a, 2014b, 2017). Therefore, it is not clear which task the subjects would naturally prioritize without this instruction. Further, the level of performance of the cognitive task under dual-tasking conditions was not given by the available studies. They either did not compare changes in cognitive task performance from single-tasking to dual-tasking (Hollands et al., 2014) or did not consider the performance in the statistical analyses (Manaf et al., 2014a, 2014b, 2017). Therefore, it is not clear whether the subjects also compromised the cognitive task under dual-tasking conditions. Moreover, the cognitive task (serial subtraction) employed in these studies uses internal interference. The response of stroke survivors to a dual-tasking condition involving an external disturbance, which is common in daily life, is yet to be determined.

Therefore, this study was conducted to investigate the natural response of stroke survivors to a dual-tasking challenge involving turning-while-walking as the physical task. This study had two aims:

1) To compare single-tasking performance with dual-tasking performance in stroke survivors. We hypothesized that the performance of both tasks would be degraded when dual-tasking.
2) To compare the performance of stroke survivors with non-stroke controls. We postulated that stroke survivors would have a lower dual-tasking ability than the controls due to a decreased ability to conduct the individual tasks, as reflected by the single-tasking performance.

3.1.3 Methods

3.1.3.1 Participants

Community-dwelling stroke survivors were recruited from local mutual self-help groups and local hospitals. The control subjects were recruited in the community. Eligible subjects were aged 50 or above, able to walk unaided for at least 15 meters indoor without physical assistance, and able to follow instructions. An additional criterion for subjects in the stroke survivor group was it having been at least six months since the onset of stroke. Subjects with any of the following conditions were excluded: a severe visual or hearing problem, a score of less than 18 on the Mini-Mental State Examination (MMSE) (Cantonese version) (Lam et al., 2008), any neurological disease (other than stroke in the stroke survivor group) or any musculoskeletal trauma or medical operation within the previous six months. This study was approved by the Ethics Committee of the Hong Kong Polytechnic University. The aims and procedures were explained to all participants before they gave their informed consent.

3.1.3.2 Assessment

Demographic data including gender, age, height, weight, and mobility function [the timed Up-and-Go test (TUGT) and the Breg Balance Scale (BBS)] were obtained before the assessment. For the stroke subjects, chronicity, side, number and type of stroke were collected. All of the subjects were assessed with a single cognitive task (auditory Stroop test), a single physical task (turning-while-walking test), and a combination of the two single tasks. Detailed procedures were explained and familiarization trials were given to all the subjects before the assessment. The sequence of testing the three conditions was randomized to minimize any learning effect.

3.1.3.2.1 Single auditory Stroop test

The auditory Stroop test was designed to assess the executive function, including working memory, selective attention, and ability to inhibit automatic responses (Royall et al., 2002; Rozenblatt, 2011). In this test, two pre-recorded words, “high” and “low,” were pronounced in two different pitches, high and low, to form four combinations. The subjects were instructed to ignore the meaning of the word and respond to its pitch as quickly and as accurately as possible. A two-button switch, with each button representing the high and low pitch respectively, was given to the subject to react to the auditory Stroop test. Stroke subjects held the switch with the less affected hand, while controls held it with the dominant hand (defined as the hand used for writing). Each combination of word and pitch was tested three times for each subject in a randomized sequence.

The reaction times and accuracy of the responses were recorded using custom-made software (LabVIEW version 8.6, National Instruments Corp., Austin, TX, USA). The reaction time was defined as the period from the start of the sound to the button press. The average reaction time of the 12 trials was calculated. The accuracy was calculated by dividing the number of correct responses by the total number of trials. A composite score as defined as (Springer et al., 2006):

$$\text{Composite score} = \frac{\text{Accuracy}}{\text{Averaged reaction time (s)}}$$

was employed to represent the cognitive task performance.

3.1.3.2.2 Single turning-while-walking test

In the single turning-while-walking test, the subjects were asked to walk a 5-meter straight line, make a 180-degree turn, and then return to the starting position as quickly and safely as possible (Chan et al., 2016a). A force platform (Model OR6-5-1000, Advanced Mechanical Technologies Inc., Newton, MA, USA) was installed in the walking surface five meters from the starting position. As the force platform was used to trigger the auditory Stroop test in the dual-tasking condition, no sound was produced in this single-tasking test. The subjects should press any button on the switch used in the auditory Stroop test while turning to make the data comparable with those from the dual-tasking tests. A research assistant walked closely behind the subject during the assessment to ensure safety. The subjects were allowed to use any walking aids or wear their ankle foot orthoses as preferred.

A gyroscopic sensor system for gait analysis (Mobility Lab iWalk, OPAL sensors, APDM Inc., Portland, OR, USA) was used to record the turning performance. Sensors on the trunk and the lumbar region detected the moment when turning started and ended. Any step with more than 50% of its phase within the turning period was counted as a step within the turn (Salarian et al., 2010; APDM, 2014). The test was repeated three times. Averages of the turning duration, number of steps to turn, and duration of the turning-while-walking test were employed for data analysis.

The subjects with stroke were asked to turn towards the affected side, as falls are more common when turning to this side (Hyndman et al., 2002). Control subjects were tested turning to both sides. However, there was no significant difference in performance between the two turning sides ($p > 0.05$). Thus, data from controls of all trials were combined for statistical analysis.

3.1.3.2.3 Dual-tasking test

In the dual-tasking test, subjects were required to perform the turning-while-walking test concurrently with the auditory Stroop test. The setting was the same as that of the single turning-while-walking test. The force platform installed in the walking surface triggered one of the four combinations of the sound of the auditory Stroop test when the subject stepped on it. Each of the four combinations was assessed once in a randomized sequence. The subjects were told that both tasks were equally important and no priority of the task was instructed. The parameters used in the single tasks were adopted in the dual-tasking condition. Any assistive devices used in the single-tasking test were used again.

3.1.3.3 Repeatability of the assessment

Repeatability of the three tasking conditions was assessed. Thirteen stroke and nine control subjects were included. They were asked to take the assessments twice within two weeks. Subjects who had any change in medical, physical or cognitive condition or regular exercise habits within the test-retest period were excluded. The testing sequence in the retest session was identical to that of the first session.

3.1.3.4 Statistical analysis

Commercial software, Statistical Package for the Social Sciences (SPSS, version 23, IBM Corp., Armonk, NY, USA), was used for data analysis. Repeatability of the tests was assessed with an intraclass correlation coefficient (ICC), model ICC (3,*k*), with '*k*' as the number of trials in the tests being assessed. The difference in demographic characteristics between the stroke survivors and controls were assessed with independent t-tests. The sex distribution between the two groups was compared with a chi-squared test. Two-way mixed analysis of variance (ANOVA) was employed to investigate the task effect (single-tasking and dual-tasking), the group effect (stroke survivors and controls), and the interaction effect (task x group). If results were significant, further data analyses were conducted using the paired t-test for significant task effect and the independent t-test for significant group effect. Bonferroni adjustments were applied for all follow-up analyses. The statistical significance level was set at 0.05.

3.1.4 Results

3.1.4.1 Participants

Forty-five controls and 59 stroke survivors participated in this study. The demographic data are shown in Table 3.1.1. Gender, body height, MMSE score, TUGT, and BBS score were significantly different between the two groups.

Table 3.1.1 Demographics of both the controls and stroke survivors

		Control (n = 45)	**Stroke (n = 59)**	***p*-value**
Age (years)		61.3 ± 4.8	62.4 ± 6.8	0.337
Gender (male : female)		9 : 36	29 : 30	0.004*
Height (cm)		158.1 ± 6.7	162.0 ± 8.5	0.016*
Weight (kg)		61.1 ± 10.1	61.8 ± 11.4	0.712
MMSE score		29.4 ± 1.1	27.9 ± 2.2	< 0.001*
BBS score		55.9 ± 0.3	48.1 ± 6.8	<0.001*
TUGT (sec)		6.3 ± 1.0	18.0 ± 8.9	< 0.001*
Education (years)		10.1 ± 3.5	9.5 ± 4.1	0.525
Chronicity (years)		/	5.4 ± 4.8	/
Affected side	Right	/	25	/
	Left		34	
Number of strokes	1	/	49	/
	2		8	
	3		2	
Type of stroke	Ischemic	/	40	/
	Hemorrhage		17	
	Both		2	

Values are in mean ± standard deviation; MMSE = Mini-Mental Status Examination (Cantonese version); BBS: Berg Balance Scale; TUGT: Timed Up-and-go Test
* denotes a significant difference between stroke survivors and controls ($p < 0.05$)

3.1.4.2 Repeatability of the assessment

Table 3.1.2 shows the results of the repeatability tests. The single auditory Stroop test, single turning-while-walking test, and the physical task of the dual-tasking showed an excellent repeatability, with all ICC values equal to or larger than 0.90. The auditory Stroop test under dual-tasking condition demonstrated a good repeatability, with an ICC (3, 4) value of 0.85.

Table 3.1.2 Repeatability of the assessment

		Time 1	Time 2	ICC (3,*k*)	95% CI Lower	95% CI Upper
Single-tasking						
Auditory Stroop test	Composite score	94.6 ± 26.5	99.5 ± 31.7	0.90	0.70	0.96
Turning-while-walking	Turning duration (sec)	3.7 ± 1.5	3.4 ± 1.7	0.94	0.86	0.98
	Number of steps to turn	7.3 ± 1.7	7.1 ± 1.7	0.91	0.79	0.97
	Completion time (sec)	13.7 ± 6.8	12.2 ± 6.6	0.97	0.93	0.99
Dual-tasking						
Auditory Stroop test	Composite score	78.0 ± 27.0	89.1 ± 31.0	0.85	0.63	0.94
Turning-while-walking	Turning duration (sec)	3.6 ± 1.7	3.3 ± 1.8	0.97	0.92	0.99
	Number of steps to turn	7.4 ± 2.0	7.0 ± 1.8	0.97	0.92	0.99
	Completion time (sec)	13.2 ± 6.5	12.2 ± 6.6	0.97	0.92	0.99

Values are in mean ± standard deviation

3.1.4.3 Comparing single-tasking and dual-tasking performance in stroke survivors

There was a significant difference between single-tasking and dual-tasking performance on the composite score of the auditory Stroop test [$F(1,90) = 23.577$, $p < 0.001$]. Follow-up analysis showed that stroke survivors had a lower composite score in the dual-tasking than in the single-tasking ($p = 0.001$) (Table 4.1.3).

In contrast with the cognitive task performance, no significant difference was found in the turning-while-walking performance between the single-tasking and dual-tasking conditions among the stroke survivors ($p > 0.05$).

3.1.4.4 Comparing stroke survivors and controls

There were significant differences between the two groups in all the parameters of both the cognitive and physical tasks. In the auditory Stroop test, stroke survivors showed a significantly lower composite score than the controls in both single-tasking and dual-tasking conditions (all p-values < 0.001). For the turning-while-walking performance under dual-tasking condition, stroke survivors took a longer turning time and more steps to turn than the controls (both p-values < 0.001). Subjects with stroke also needed more time to complete the turning-while-walking test ($p < 0.001$). Similar differences between the two groups were also observed in the single-tasking condition (All p-values < 0.001) (Table 3.1.3).

Table 3.1.3 Results of single-tasking and dual-tasking performance in both controls and stroke survivors

		Controls (n = 45)		**Stroke (n = 59)**		***F*-value (*p*-value)**		
		Single-tasking	**Dual-tasking**	**Single-tasking**	**Dual-tasking**	**Between-task difference**	**Between-group difference**	**Interaction effect**
Auditory Stroop test	Composite score	107.0 ± 23.4	93.9 ± 24.9	83.5 ± 22.8	71.5 ± 24.2	23.58 (< 0.000)[a]	29.15 (< 0.001)[b, c]	0.05 (0.831)
Turning-while-walking	Turning duration (sec)	2.4 ± 0.4	2.4 ± 0.5	5.2 ± 2.4	5.4 ± 2.4	1.70 (0.196)	63.90 (< 0.001)[b, c]	0.77 (0.381)
	Number of steps to turn	6.1 ± 0.7	6.2 ± 0.6	9.1 ± 2.2	9.1 ± 2.4	1.27 (0.263)	63.90 (< 0.001)[b, c]	0.11 (0.746)
	Completion time (sec)	8.0 ± 1.7	8.0 ± 1.6	21.2 ± 13.0	21.3 ± 12.4	0.03 (0.857)	48.83 (< 0.001)[b, c]	0.00 (0.995)

Values are in mean ± standard deviation

[a] Significant difference between single-tasking and dual-tasking in controls and stroke survivors ($p = 0.001$)

[b] Significant difference between controls and stroke survivors in single-tasking ($p < 0.001$)

[c] Significant difference between controls and stroke survivors in dual-tasking ($p < 0.001$)

3.1.5 Discussions

This study examined how stroke survivors performed in dual-tasking that involved an auditory Stroop test and a turning-while-walking test. The results show that when dual-tasking, stroke survivors performed poorer in the cognitive task but with similar turning-while-walking performance. Further, stroke survivors demonstrated a lower composite score on the auditory Stroop test by comparison with the controls. They also took longer to turn with more steps and needed more time to complete the turning-while-walking test.

In this study, stroke survivors responded to dual-tasking with degraded performance in the auditory Stroop test but with similar performance of the physical task. According to the theory of competition for attentional resources in dual-tasking (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012), the results may imply that, at least in these conditions, stroke survivors may not have sufficient resources to perform both tasks concurrently. However, the hypothesis of interference between the cognitive and physical task when dual-tasking was only partly supported. This unexpected result can be explained by a posture-first strategy (Lacour et al., 2008; Yogev-Seligmann et al., 2012). When dual-tasking, if the physical task is too complex that it may place a postural threat on an individual, or if the individual is not capable of performing the task due to physical impairment, attentional resources are drawn from the cognitive task to the postural task to maintain balance (Plummer et al., 2013; Shumway-Cook & Woollacott, 2007). This strategy would be a safety measure to prevent a fall and is commonly seen in older adults, people with impaired balance (Lacour et al., 2008) or when the physical task is challenging

(Smulders et al., 2012; Tsang et al., 2013). The results of this study may imply that stroke survivors prioritize the physical task over the cognitive task to maintain balance during turning.

The result that stroke survivors prioritized the physical task over the cognitive one was inconsistent with previous studies that showed a compromised turning-while-walking performance when dual-tasking (Hollands et al., 2014; Manaf et al., 2014a, 2014b, 2017). A possible explanation for this discrepancy is the instruction given on task prioritization. In the studies by Manaf's research team, subjects were instructed to prioritize the cognitive task over the physical task (Manaf et al., 2014a, 2014b, 2017). Conversely, subjects in our study were told that both tasks were equally important and the task priority was not specified. It has been proposed that directing the priority of tasks may affect an individual's response to a dual-tasking challenge (Jansen et al., 2016). In the absence of a specific instruction about the priority of tasks as in this study, stroke survivors were able to naturally react to the dual-tasking challenge. In addition, the nature of the cognitive task may affect the results of dual-tasking. In daily life, disturbances to physical movement could be triggered internally by an individual or externally by the environment. The cognitive task used in previous studies (Hollands et al., 2014; Manaf et al., 2014a, 2014b, 2017), serial subtraction, involves an internal interfering factor (Al-Yahya et al., 2011) so that subjects initiate the cognitive challenge without being prompted. By contrast, the auditory Stroop test requires the subject to react to an external event. The results of this study imply that the nature of the cognitive task plays a role in the interaction between the cognitive task and the physical task. However, further studies are needed to investigate the effect of instruction on task prioritization and the nature of the cognitive task on dual-tasking performance in stroke survivors.

The second hypothesis that the dual-tasking performance of the stroke survivors would be worse than that of the controls was supported by this study. According to the theory of competition for attentional resources when dual-tasking, the increased demand for resources to conduct the individual tasks has a detrimental effect on dual-tasking performance (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012). In this study, the lower level of single-tasking performance of both the cognitive task and physical task found in stroke survivors may therefore contribute to the decreased dual-tasking ability, at least in such tasks combination. However, the exact mechanism that explains the poorer dual-tasking performance revealed in stroke survivors requires further investigation.

Stroke survivors in this study turned with a longer duration and a higher number of steps than the controls. This difference can be attributed to various factors such as gait asymmetry and lower limb weakness, which is common in stroke survivors. In a 180-degree turn, the inner leg acts as the axis of the turn and accepts the entire body weight. The outer leg then swings for a longer time and travels a longer distance than in straight line walking (Hollands et al., 2010b). However, if the ability of the inner leg to bear the body weight diminished, the single leg stance time would then decrease. The time and distance for the outer leg to travel would therefore be reduced. As a result, a longer time and a greater number of steps should be made to complete the turn. This may explain the difference in turning performance between stroke survivors and controls found in this study. Furthermore, the mean turning duration for stroke survivors in this study was more than 3.18 sec, suggesting that they exhibited some difficulty while turning (Thigpen et al., 2000).

3.1.6 Limitations

One of the limitations of this study was that subjects with a stroke were relatively mobile; they were able to walk and turn unaided indoors. Besides, the mean MMSE score was 27.9 out of 30. Hence, the results of this study only apply to stroke survivors with relatively high global cognitive functioning and physical function. Further research including stroke survivors with lower cognitive and physical functions is needed to improve the generalization of the study results. Another limitation was the uneven distribution of gender between the two groups. In addition, the stroke survivors were significantly taller than the controls. Statistical analyses were conducted again by adding the gender and body height as covariates. The results remained similar with the covariates added. It is therefore reasonable to assume that gender and height difference do not affect the findings of this study.

3.1.7 Conclusions

Results from this study suggest that stroke survivors compromise cognitive task performance to perform the turning-while-walking task when dual-tasking. The behavior can be explained by the theory of competition for attentional resources and the posture-first strategy. These results differ from those of previous studies. Variation in the instruction of task prioritization and the nature of the cognitive task may explain the discrepancy. However, further studies must be carried out to examine this hypothesis. Additionally, stroke survivors had a lower composite score on the auditory Stroop test when both single-tasking and dual-tasking as compared with controls. They also turned with a longer duration and more steps and took a longer time to complete the turning-while-walking test under both tasking conditions. The degraded single-tasking ability after a stroke may contribute to the poorer dual-tasking performance, but further investigation is needed to find out the exact mechanism of such phenomenon. Furthermore, results of this study may suggest a need of rehabiltation exercise to improve dual-tasking performance that concerns turning-while-walking in this population.

CHAPTER 3.2

THE PERFORMANCE OF STROKE SURVIVORS IN STEPPING DOWN WHILE CARRYING OUT A CONCURRENT COGNITIVE TASK COMPARED WITH CONTROLS

Submitted:

Chan, W. N., & Tsang, W. W. Compromised cognition while stepping down among stroke survivors. Submitted to *PLoS ONE*. Under second review.

3.2.1 Abstract

Background

Descending stairs is an indicator of independence among community-dwelling stroke survivors, but is demanding in terms of both neuromuscular control and cognitive functioning. Previous studies have shown compromised performance when stepping down with a concurrent cognitive task among healthy older adults. This study examined how stroke survivors respond to such dual-tasking.

Objective

To investigate the dual-tasking performance of stroke survivors asked to perform an auditory Stroop test while stepping down.

Methods

Twenty-six stroke survivors and 34 controls were asked to perform an auditory Stroop test while stepping off a 19-cm high platform, and the results were compared with those when each task was performed alone. The auditory Stroop test was evaluated with a composite score. Stepping down performance was quantified in terms of the subjects' sway amplitudes in the anteroposterior and mediolateral directions after landing and the sway velocity of their center of pressure. Two-way mixed ANOVA was employed to investigate the significance of the differences between the single-tasking and dual-tasking conditions, and between the stroke survivors and the controls.

Results

The stroke survivors demonstrated significantly lower composite scores on the auditory Stroop test when dual-tasking (76.4 ± 31.2) compared with that when single-tasking (90.0 ± 25.6). However, no significant difference in stepping down performance was observed between the two tasking conditions. The stroke survivors had, however, significantly lower composite scores on the auditory Stroop test and higher sway amplitudes and velocities after stepping down than the controls.

Conclusions

The results suggest a motor-related cognitive interference in dual-tasking that involves stepping down among the stroke survivors. It can be explained by competition for attentional resources between the cognitive and physical tasks, adopting a posture-first strategy, and the increased attentional demands of the individual tasks.

Keywords

Dual-tasking; stepping down; stroke; center of pressure; body sway; auditory Stroop test

3.2.2 Introduction

The term dual-tasking describes performing two different tasks simultaneously. Dual-tasking ability depends on various factors, including the level of difficulty of the tasks, an individual’s ability to perform each of them, and the availability and allocation of attentional resources to perform them simultaneously (Al-Yahya et al., 2011;

Woollacott & Shumway-Cook, 2002). Residual cognitive and physical impairment are common in stroke survivors even after proper rehabilitation (Kelly-Hayes et al., 2003). It should not be surprising, therefore, that dual-tasking can be impaired after a stroke. But the detrimental effect on an additional cognitive task may be more significant when the physical task is more challenging, such as avoiding obstacles (Smulders et al., 2012).

Negotiating stairs, which is common in daily life, is considered to be one of the most challenging activities for community-dwelling stroke survivors (Tsuji et al., 1995). It is also an important indicator of independence among that population (Alzahrani et al., 2009). The perceived difficulty of negotiating stairs relates to the greater demands on the neuromuscular system compared with walking on level ground (Jacobs, 2016; Novak & Brouwer, 2012, 2013; Startzell et al., 2000). In addition, there is attentional involvement needed to evaluate the stairs' configurations and to integrate sensory information from the visual and somatosensory systems (Jabos, 2016; Ojha et al., 2009; Startzell et al., 2000). The attentional involvement has been reflected in dual-tasking studies, which have documented compromised performance (Lu et al., 2013b; Telonio et al., 2014; Tsang et al., 2013). Even healthy older adults respond in an auditory Stroop test with longer reaction time and a higher error rate when stepping down, although they are able to maintain normal body sway (Lu et al., 2013b; Tsang et al., 2013). Another study showed increased minimal foot clearance when the healthy subjects descended stairs while dealing with a concurrent cognitive task (Telonio et al., 2014). Indeed, being distracted is one of the most common causes of falls on stairs (Templer, 1992). Such falls, especially when descending, can result in severe injury (Jacobs, 2016; Startzell et al., 2000), or even death (National Safety Council, 2016).

Previous studies have shown the detrimental effect of stroke on dual-tasking performance, especially when dynamic balance is involved. There has, however, been no study specifically addressing how stroke survivors respond to descending stairs while dealing with an additional cognitive task. This study was therefore designed to investigate dual-tasking performance that involved stepping down among stroke survivors. As prior studies have demonstrated both cognitive impairment and less agile descending of stairs after a stroke, concurrent cognitive and physical task performance would be expected to be poorer than in single-tasking. This study also compared the performance of such tasks between stroke survivors and healthy controls. We postulated that stroke survivors would have a lower dual-tasking ability than the controls.

3.2.3 Methods

3.2.3.1 Participants

Community-dwelling stroke survivors were recruited from local self-help groups and local hospitals. Healthy older subjects were recruited in the community. The study's inclusion criteria were an age of 50 or above, able to step down without any physical assistance and able to follow instructions. An additional inclusion criterion for the stroke survivors was a period of at least six months since the stroke. The exclusion criteria were severe hearing or visual impairment, a score of less than 18 on the Cantonese version of the Mini-Mental Status Examination (MMSE) (Lam et al., 2008), any neurological disease (other than stroke in the stroke survivor group), or any musculoskeletal injury or major surgery in the previous six months. This study was approved by the Ethics Committee of the Hong Kong Polytechnic University. Informed consent was obtained from each participant after the aims and procedures of the study had been explained.

3.2.3.2 Assessment

Age, height and body weight data were collected from each subject and their cognitive ability was assessed with the MMSE. Each of them also had their balance rated using the timed Up-and-Go test (TUGT) and the Berg Balance Scale (BBS). Information related to stroke, such as chronicity and side, number, and type were obtained from the stroke survivors.

The study’s cognitive task was an auditory Stroop test, the physical task was stepping down, and dual-tasking involved performing them simultaneously. The three conditions were assessed in a randomized order. Before data collection, each subject was allowed demonstration and familiarization trials.

3.2.3.2.1 Single auditory Stroop test

In the auditory Stroop test employed as the cognitive task to assess executive functioning (Royall et al., 2002; Rozenblatt, 2011), two recorded Cantonese words signifying ‘high’ and ‘low’ were played with high and low pitches, resulting in four combinations. The subjects responded by pressing one of two buttons representing the high and low pitch respectively on a switch. The stroke survivors held the switch in their less-affected hand, while the control subjects held it in their dominant hand (defined as the hand used for writing). The subjects were instructed to ignore the word’s meaning and respond only to the pitch of the sound as accurately and as quickly as possible. Each combination of the word and pitch was repeated three times for each subject in a randomized sequence.

Each subject's composite score was defined as (Springer et al., 2006):

$$\text{Composite score} = \frac{\text{Accuracy}}{\text{Averaged reaction time (s)}}$$

where accuracy was calculated by dividing the number of correct answers by the total number of trials. Reaction time was the time between the word being played and the subject's pressing either button. The averaged of the 12 trials was used to calculate the composite score. The data were recorded using a customized LabVIEW program (version 8.6, National Instruments Corp., Austin, TX, USA).

3.2.3.2.2 Single stepping down test

Stepping down off a step was the physical task. A force platform (Model OR6-5-1000, Advanced Mechanical Technologies Inc., Newton, MA, USA) was placed in front of a 19cm high block. Each subject stepped down in bare feet from the block onto the force platform. The movement was led by the affected leg for the stroke survivors or the non-dominant leg (the stance leg when kicking a ball) for the controls, followed by the other leg. They were instructed to keep their posture as stable as possible after stepping onto the force platform. They should press any button used in the auditory Stroop test while stepping down to make the data more comparable with that during the dual-tasking. A visual fixation was positioned two meters away from the center of the force platform at the subject's eye-level after stepping down to standardize visual attention. A trained assessor stood next to the subject during the assessment to ensure safety. The setting is illustrated in Figure 3.2.1.

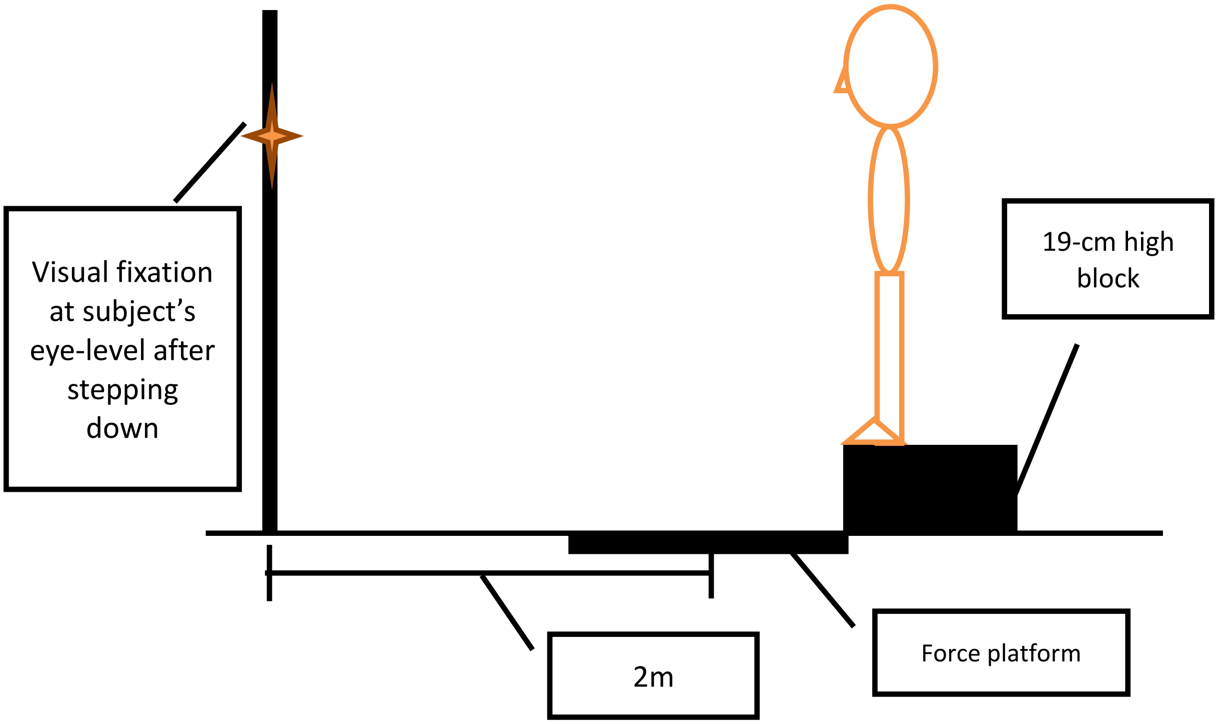


Figure 3.2.1 The stepping down test setup

The center of pressure (CoP) was tracked for five seconds after the trailing leg was lifted from the block. Data reduction was carried out with a customized MATLAB program (Version 8.3, The Math Works, Inc., Natick, MA, USA). The raw data from the force platform were resampled at rates from 1000Hz to 125Hz and filtered with a second-order Butterworth low-pass filter with a cutoff frequency of 10Hz. The CoP sway amplitudes in the anteroposterior (CoP-AP) and mediolateral (CoP-ML) directions were outcome measures of the stepping down test. They were normalized using the subject's height. Another result was the average velocity of the CoP's movement (V-CoP). It was calculated by dividing the normalized total pathway of the CoP movement by five seconds. The task was repeated three times with the averages being used in the statistical analysis.

3.2.3.2.3 Dual-tasking test

The dual-tasking combined the auditory Stroop test with the stepping down. The setting was as same as that shown in Figure 3.2.1. The subjects were instructed to step down and lead with the affected leg or the non-dominant leg as before. The same LabVIEW program as in the single-tasking situation triggered the auditory Stroop test, but when the subject stepped onto the force plate. Each combination of the auditory Stroop test was assessed once in a randomized sequence, resulting in four trials. The subjects were told that both tasks were of equal importance and no task priority was mentioned. The outcome measures were those used in the single-tasking conditions.

3.2.3.3 Repeatability of the assessment

The repeatability of the individual task and the dual-tasking test was examined using seven stroke survivors and nine control subjects. All of the assessments were performed twice by the same assessor within two weeks. The sequence of the three assessments and the sound combination of the auditory Stroop test were the same in both testing sessions. Subjects were excluded if there was any change in their regular physical activities or in their medical, physical, or cognitive condition during the two-week period.

The ICC (3, *k*) intra-class correlation coefficient, with '*k*' as the number of trials, was used to quantify the tests' repeatability.

3.2.3.4 Statistical analysis

Data analysis was conducted using the Statistical Package for the Social Sciences (SPSS, version 23, IBM Corp., Armonk, NY, USA). The significance of the differences in demographic data between the stroke survivors and controls was tested using independent t-tests for the continuous data and chi-squared tests for the categorical data. Two-way mixed analysis of variance (ANOVA) (group x task) was conducted to determine the significance of any group effect or task effect. If a significant group effect was found, follow-up analyses were done with independent t-tests between the two groups in single-tasking and dual-tasking separately. If a significant task effect was revealed, further analyses were made with paired t-tests to compare the single-tasking and dual-tasking performance among the stroke survivors and the controls separately. Bonferroni adjustments were applied for every follow-up analysis. The level of significance was set at 0.05.

3.2.4 Results

3.2.4.1 Participants

Twenty-six stroke survivors and 34 control subjects participated in this study. Their demographic data are presented in Table 3.2.1. There were significant between-group differences in gender distribution, height, and MMSE, TUGT time, and BBS scores ($p < 0.05$).

Table 3.2.1 Demographics of both the controls and the stroke survivors

		Controls (n = 34)	**Stroke (n = 26)**	***p*-value**
Age (years)		61.8 ± 4.8	63.2 ± 6.6	0.336
Gender (male : female)		7 : 27	13 : 13	0.017*
Height (cm)		158.0 ± 7.1	162.2 ± 7.1	0.027*
Weight (kg)		60.5 ± 10.2	60.7 ± 11.4	0.947
MMSE score		29.2 ± 1.2	28.0 ± 2.3	0.015*
BBS score		55.9 ± 0.2	53.0 ± 2.5	< 0.001*
TUGT (sec)		6.3 ± 1.1	12.2 ± 4.3	< 0.001*
Education (years)		9.6 ± 3.7	9.7 ± 4.0	0.977
Chronicity (years)		/	5.2 ± 4.7	/
Affected side	Right	/	12	/
	Left		14	
Number of strokes	1	/	23	/
	2		3	
Types of stroke	Ischemic	/	19	/
	Hemorrhage		6	
	Both		1	

Values are in mean ± standard deviation; MMSE = Mini-Mental Status Examination (Cantonese version); BBS: Berg Balance Scale; TUGT: Timed Up-and-go Test
* denotes a significant difference between control group and stroke survivor group ($p < 0.05$)

3.2.4.2 Repeatability of the assessment

Table 3.2.2 shows the repeatability of the assessment. The composite auditory Stroop test scores in the single-tasking and dual-tasking conditions yielded ICC values of over 0.80, representing good reliability. The results also showed good repeatability of the stepping down task under both single-tasking and dual-tasking conditions.

Table 3.2.2 Repeatability of the assessment

		Time 1	Time 2	ICC (3,*k*)	95% CI Lower	95% CI Upper
Single-tasking						
Auditory Stroop test	Composite score	102.4 ± 26.6	105.9 ± 35.4	0.88	0.57	0.97
Stepping down	CoP-AP	31.6 ± 11.0	35.1 ± 13.5	0.82	0.46	0.94
	CoP-ML	42.8 ± 27.2	46.3 ± 26.5	0.69	0.11	0.89
	VCoP	153.8 ± 61.9	157.8 ± 61.7	0.68	0.07	0.89
Dual-tasking						
Auditory Stroop test	Composite score	90.5 ± 37.2	100.1 ± 42.8	0.82	0.48	0.94
Stepping down	CoP-AP	33.4 ± 14.3	37.5 ± 9.3	0.66	0.04	0.88
	CoP-ML	46.2 ± 32.2	41.7 ± 18.3	0.72	0.17	0.91
	VCoP	169.2 ± 85.5	167.9 ± 58.8	0.89	0.70	0.96

Values are in mean ± standard deviation; CoP-AP = anteroposterior sway amplitude of the center of pressure normalized with the subject's height; CoP-ML = mediolateral sway amplitude similarly normalized; VCoP = average sway velocity of the center of pressure normalized with the subject's height

3.2.4.3 Comparing single-tasking and dual-tasking performance in stroke survivors

Significant task effect was found in the composite scores on the auditory Stroop test [F (1,58) = 8.90, $p < 0.001$]. There were significantly lower composite scores in dual-tasking than in single-tasking for the stroke survivors ($p = 0.010$). By contrast, there were no significant difference between the single-tasking and dual-tasking on CoP-AL, CoP-ML or VCoP when stepping down (Table 3.2.3).

3.2.4.4 Comparing stroke survivors and controls

Two-way mixed ANOVA showed a significant group effect [F (1,58) = 12.24, $p = 0.018$] in the composite scores on the auditory Stroop test (Table 3.2.3). Follow-up analysis showed a similar average composite score on the auditory Stroop test between the controls and the stroke survivors in the dual-tasking condition ($p = 0.055$). However, control subjects had a higher composite score than the stroke survivors in the single-tasking condition ($p = 0.020$).

Significant group effects were revealed in the CoP-AP [F (1, 58) = 9.04, $p = 0.004$], CoP-ML [F (1, 58) = 27.84, $p < 0.001$], and VCoP [F (1, 58) = 30.63, $p < 0.001$] results (Table 3.2.3). Follow-up analysis illustrated that the stroke survivors had, on average, larger CoP-AP and CoP-ML sway amplitudes than the controls in both single-tasking (CoP-AP: $p = 0.007$; CoP-ML: $p < 0.001$) and dual-tasking (CoP-AP: $p = 0.006$; CoP-ML: $p < 0.001$). The average VCoPs were also significantly higher among the stroke survivors than among the controls in both single-tasking and dual-tasking (both p-values < 0.001).

Table 3.2.3 Results of single-tasking and dual-tasking performance in both controls and stroke survivors

		Controls (n = 34)		Stroke (n = 26)		*F*-value (*p*-value)		
		Single-tasking	**Dual-tasking**	**Single-tasking**	**Dual-tasking**	**Between-task difference**	**Between-group difference**	**Interaction effect**
Auditory Stroop test	Composite score	104.6 ± 21.7	91.9 ± 29.8	90.0 ± 25.6	76.4 ± 31.2	8.90 (< 0.001)[a]	12.24 (0.018)[b, c]	0.02 (0.898)
Stepping down	CoP-AP	30.9 ± 8.0	29.3 ± 7.1	39.9 ± 16.6	38.3 ± 16.7	1.98 (0.164)	9.04 (0.004)[b, c]	0.01 (0.941)
	CoP-ML	29.2 ± 10.8	27.7 ± 12.1	62.0 ± 36.8	64.0 ± 36.9	0.03 (0.857)	27.84 (< 0.001)[b, c]	1.34 (0.252)
	VCoP	38.1 ± 11.8	36.1 ± 9.9	63.1 ± 30.2	65.8 ± 28.1	0.03 (0.872)	30.63 (< 0.001)[b, c]	1.13 (0.293)

Values are in mean ± standard deviation; CoP-AP = normalized center of pressure sway in the anteroposterior direction; CoP-ML = normalized center of pressure sway in the mediolateral direction; VCoP = average center of pressure sway velocity

[a] Significant difference between single-tasking and dual-tasking in controls and stroke survivors ($p = 0.001$)

[b] Significant difference between controls and stroke survivors in single-tasking ($p < 0.001$)

[c] Significant difference between controls and stroke survivors in dual-tasking ($p < 0.001$)

3.2.5 Discussions

This study investigated the performance of dual-tasking among stroke survivors with stepping down as the physical task. This has been the first published study of dual-tasking with such a population. The results demonstrate degraded auditory Stroop test performance when dual-tasking, but similar CoP sway. So the expectation that both cognitive task and physical task performance would be compromised under dual-tasking conditions was only partially supported.

One reason for the stroke survivors' compromised dual-tasking performance could be competition for limited attentional resources. Among many stroke survivors, the resources may be insufficient for an individual to perform both cognitive and physical tasks simultaneously. If so, the performance of either or both tasks is compromised (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012). The auditory Stroop test employed in this study examined executive functioning by challenging working memory, the ability to focus on relevant information, and inhibition of automatic responses (Royall et al., 2002; Rozenblatt, 2011). Stepping down also requires executive functioning to plan the movement and integrate different sensory information for a safe descent (Jacobs, 2016; Ojha et al., 2009; Startzell et al., 2000). The involvement of executive functioning in both tasks may have led to competition for attentional resources, and hence, degraded dual-tasking performance.

Performance in both the cognitive and the physical task was expected to be compromised in dual-tasking among the stroke survivors, but in fact, only their composite scores on the auditory Stroop test were poorer. Their stepping down performance was similar in the two conditions. These results can probably be explained by the task prioritization strategy they used (Lacour et al., 2008; Yogev-Seligmann et al., 2012). Choosing which task to prioritize is based on various factors, such as the perceived threat of losing one’s balance or the relative confidence in one’s cognitive and physical abilities. When there is an increased postural threat, more attentional resources would be allocated to maintain balance to prevent falling. This approach is termed a posture-first strategy, and it is commonly seen in older or frail individuals (Lacour et al., 2008). Indeed, both the stroke and the control subjects in this study showed a significant decrement in their cognitive task performance, but similar performance in the physical task when dual-tasking. That suggests that they were employing a posture-first strategy. The results echo those of a prior study which found that negotiating stairs is perceived as one of the most difficult tasks encountered by community-dwelling stroke survivors (Tsuji et al., 1995). The results are also in line with those studies showing motor-related cognitive-interference among healthy older adults while stepping down (Lu et al., 2013b; Tsang et al., 2013) or walking and avoiding obstacles (Smulders et al., 2012) with a concurrent cognitive challenge.

The compromised dual-tasking performance of the stroke survivors might also be explained by the increased attentional demand when performing the individual cognitive and physical tasks. In a prior study in our laboratory, healthy older adults showed significantly greater CoP sway than healthy young subjects when stepping down. Beyond that, when stepping down with a concurrent auditory Stroop test, the older subjects displayed a significant decrement in cognitive task performance, while the younger subjects performed similarly under single- and dual-tasking conditions (Lu et al., 2013b). Those results suggest an aging effect on dual-tasking ability, at least when the physical task involved is stepping down. In this current study, the CoP sway amplitudes and velocity, which indicate a person's ability to perform a controlled descent and to recover from any resulting balance perturbation (Lee & Chou, 2007), were both greater among the stroke survivors, on average, than among the healthy controls. Apart from the effect of aging, such differences suggest that a stroke generally degrades the ability to step down, as might be expected. The impairment may then lead to paying more attention in stepping down, thus compromising dual-tasking performance. The reduced ability to step down in both the single-tasking and dual-tasking conditions among the stroke survivors needs further attention and might perhaps respond to additional rehabilitation.

The difference between the controls and stroke survivors in the composite score on the auditory Stroop test when dual-tasking did not reach the statistical significance level of 0.05. However, the score of the controls (91.9 ± 29.8) was 15.5 higher than that of the stroke survivors (76.4 ± 31.2). Further, the *p*-value was approaching to significance ($p = 0.055$). Therefore, the possibility of a higher cognitive task performance when dual-tasking in controls than the stroke survivors cannot be excluded.

3.2.6 Limitations

One of the limitations of this study is that the subjects had relatively good cognitive and physical functioning. All of the subjects had MMSE scores higher than 24 and their mean BBS score was 53.0 (of a possible 56). All of them were also able to step down from a block 19cm high without any physical assistance. Therefore, the results of this study may not apply to less able stroke survivors. Another limitation is that the stepping down involved only one step. Previous studies have shown that the attentional demands differ across different phases of stair descent (Miyasike-deSilva & McIlroy, 2016; Telonio et al., 2014), so the effect on dual-tasking would be expected to differ as well. Studies of dual-tasking performance with multiple steps among stroke survivors are needed. In addition, there was a significant difference in gender distribution between the two groups, so further statistical analyses were carried out involving independent t-tests comparing the male and female subjects. The results showed no significant difference in any of the outcomes between the two gender groups, so it can be assumed that gender played only a minor role in this study.

3.2.7 Conclusions

This has been the first study of the dual-tasking performance of stroke survivors that involved stepping down as the physical task. The results show a decrement in performance on the auditory Stroop test but no obvious effect of dual-tasking on the body sway of subjects with stroke. This can be explained by supposing that they adopt a posture-first strategy – they find stepping down challenging so they compromised on cognitive task performance to maintain their balance while dual-tasking. The stroke subjects also swayed more and faster than their control counterparts when dual-tasking. Dual-tasking while descending stairs can be risky, yet it is common in daily life. These results may suggest a need for rehabilitation exercises that enhance dual-tasking performance among stroke survivors, with stepping down as one of the physical activities to be addressed. Further studies of stroke survivors with weaker cognitive and physical abilities are warranted. How stroke survivors respond to dual-tasking that involves descending multiple steps is also worth studying.

CHAPTER 3.3

THE EFFECT OF TAI CHI TRAINING ON THE DUAL-TASKING PERFORMANCE THAT INVOLVED TURNING-WHILE-WALKING OF STROKE SURVIVORS: A RANDOMIZED CONTROLLED TRIAL

Submitted:

Chan, W. N., & Tsang, W. W. Effect of Tai Chi training on dual-tasking performance among stroke survivors: A randomized controlled trial. Submitted to *Clinical Rehabilitation.* Under review.

3.3.1 Abstract

Background

Stroke has detrimental effects on turning and dual-tasking, where both activities have been related to falling. No intervention has been found to improve the dual-tasking ability that involves turning-while-walking in stroke survivors. Tai Chi is an exercise that has a feature of dual-tasking. Previous studies have supported the effect of Tai Chi training on dual-tasking ability among healthy older adults. However, its effect on stroke survivors was not well understood.

Objective

To investigate the effect of Tai Chi training on dual-tasking performance among stroke survivors.

Methods

This study was an assessor-blinded, randomized controlled trial. Patients with stroke randomized into a Tai Chi group (n = 15), a conventional exercise group (n = 17), or a control group (n = 15). Subjects in the Tai Chi group and the conventional exercise group were trained with the corresponding exercises for 12 weeks (1 hour/session, 2/week). No training was given to the controls. An auditory Stroop test, a turning-while-walking test, and a dual-tasking condition that combined the two tests were conducted at baseline, after the intervention, and one month later.

Results

Within-group comparisons showed significant improvements in dual-tasking performance after Tai Chi training and further significant improvement during the follow-up period (composite score on the auditory Stroop test: pre-assessment: 73.1 ± 27.6, post-assessment: 89.9 ± 23.4, follow-up assessment: 91.7 ± 26.9; completion time of the turning-while-walking test: pre-assessment: 17.7 ± 6.9 sec, post-assessment: 15.6 ± 5.2 sec, follow-up assessment: 14.9 ± 4.9 sec). There was, however, no significant difference in the outcome measures among the three groups after the intervention and at the 1-month follow-up assessment.

Conclusions

The results of this study do not support any superior effect of Tai Chi training on dual-tasking performance compared with conventional exercise among stroke survivors. Tai Chi training does, however, improve dual-tasking performance that involves turning-while-walking in such a population.

Keywords

Tai Chi; stroke; dual-tasking; turning-while-walking; auditory Stroop test

3.3.2 Introduction

There have been studies showing the detrimental effect of a stroke on the ability to turn while walking (Bonnyaud et al., 2015a, 2015b; Dite & Temple, 2002; Hollands et al., 2010a; Lam & Luttmann, 2009; Lamontagne & Fung, 2009) and on dual-tasking (Baetens et al., 2013; Bowen et al., 2001; Patel & Bhatt, 2014; Plummer et al., 2013;

Plummer-D’Amato et al., 2008, 2010; Pohl et al., 2011; Smulders et al., 2012). Turning has been reported as one of the activities that most frequently lead to falling among stroke survivors (Hyndman et al., 2002), and the falling can result in serious injuries, such as hip fracture (Cumming & Klineberg, 1994). It has been suggested that turning not being an automatic movement, cognitive processing is involved (Hollands et al., 2014; Manaf et al., 2015). Indeed, previous studies have shown a decrement in turning performance when an additional cognitive task is being performed simultaneously (Hollands et al., 2014; Manaf et al., 2014a, 2014b, 2017).

Tai Chi is a traditional martial art that has been employed as an exercise to promote healthy aging and rehabilitation in different populations. There is much evidence supporting the beneficial effects of Tai Chi training for healthy older adults (Chen et al., 2012; Leung et al., 2011; Lu et al., 2013a, 2013b; Tsang & Hui-Chan, 2004; Wayne et al., 2014) and for stroke survivors (Au-Yeung et al., 2009; Kim et al., 2015; Taylor-Piliae et al., 2014). Tai Chi emphasizes maintaining proper posture, shifting weight between the legs with a changing base of support, turning in different directions, and maintaining awareness of the body’s movements and position. In addition, a practitioner needs to memorize an elaborate sequence of Tai Chi forms and learn to plan their next movement while maintaining good balance. Such cognitive involvement adds a dual-tasking feature to Tai Chi practice.

Although previous studies have demonstrated impaired dual-tasking ability among stroke survivors, few studies have investigated the effect of exercise in improving dual-tasking performance, and has specifically addressed turning-while-walking as the physical task. Given that previous studies have supported an effect of Tai

Chi training on dual-tasking performance among community-dwelling healthy older adults (Lu et al., 2016; Wayne et al., 2015), the exercise may also benefit stroke survivors. This randomized controlled trial was, therefore, designed to explore the training effect of Tai Chi on stroke survivors' dual-tasking performance. The expectation was that dual-tasking performance would be enhanced in that population after Tai Chi training. The study also compared the training effect with that of the conventional exercise. Tai Chi was expected to be a better exercise than conventional exercise in enhancing dual-tasking ability.

3.3.3 Methods

3.3.3.1 Participants

This study was an assessor-blinded randomized controlled trial. It was registered at ClinicalTrials.gov (Registration number: NCT03252236) and approved by the Ethics Committee of the Hong Kong Polytechnic University (Reference number: HSEARS20131023003). The study was conducted from October 2014 to December 2016. Stroke survivors were recruited from stroke patient self-help groups and hospitals in Hong Kong. Community-dwelling stroke survivors aged 50 or over who had suffered a stroke at least six months previously, were able to walk five meters indoors without any physical support and were able to follow instructions in Cantonese were included. Those who had any neurological disease other than stroke, had received major surgery or musculoskeletal trauma during the previous six months, a score of less than 18 on the Mini-Mental Status Examination (Cantonese version) (Lam et al., 2008) or had severe hearing or visual impairments were excluded. Detailed information about the research was explained to each participant before they gave their written informed consent. The assessment was carried out at the Hong Kong Polytechnic University. The intervention was conducted either at the university or in one of the community centers.

3.3.3.2 Intervention

There were three intervention groups: a Tai Chi group, a conventional exercise group, and a control group. Eligible subjects were stratified according to their gender and age (50–59, 60–69, 70–79, ≥80 years old) and then allocated randomly into one of the three groups by drawing lots.

The interventions lasted 12 weeks. Subjects in the Tai Chi and conventional exercise groups participated in two one-hour training sessions each week, with a total of 24 sessions. Each session started with a 10-minute warm-up and ended with a 5-minute cool-down. The subjects were encouraged to practice the exercises outside of the training sessions for at least 30 minutes per week. Exercise logbooks were given to them for recording their self-practice progress.

3.3.3.2.1 Tai Chi group

The subjects in the Tai Chi group were trained in a modified Yang style Tai Chi. An experienced physiotherapist and a Tai Chi master with over 30 years of teaching experience together they selected twelve of the Yang forms which suit the abilities of community-dwelling stroke survivors. Another physiotherapist who is also an experienced Tai Chi practitioner conducted the training. The Tai Chi training focused on proper posture, weight shifting, and sequential movement of body segments when turning. It also emphasized memorizing, planning and performing the forms in a smooth sequence. Table 3.3.1 and Appendix II (pp. 188–193) list the names and training specificity of the 12-form Tai Chi. The group members were tested during the last training session to determine to what extent each of them could remember all of the movements and perform them in a correct sequence.

One or two new Tai Chi forms were introduced each week, along with reviewing the forms learned previously. Learning was promoted by limiting the class size to ten participants. When learning new movements that challenge balance, such as those involving large amplitude turning or single leg standing, the participants started by leaning against a wall with handheld support. The support reduced gradually as each participant's balance improved. The instructor also provided stand-by assistance until the participants could perform the movement safely. Rest periods were given whenever needed.

3.3.3.2.2 Conventional exercise group

Participants in the conventional exercise group walked and performed joint mobilization, stretching and strengthening exercises (Appendix III, p.194). All of the exercises, except for some involving the lower limbs and walking, were performed seated. The subjects were not required to memorize the exercises, but to simply follow the movements of the instructor, who also conducted the training in the Tai Chi group.

3.3.3.2.3 Control group

No training was provided to the subjects in this group, but they were allowed to continue their regular physical activities. After the completion of all of the assessments, the controls were offered Tai Chi training.

Table 3.3.1 Name and training specificity of the 12 Yang-style Tai Chi forms

	Name	Proper posture	Eccentric control	Turning	Forward stepping	Backward stepping	Sideways stepping	Single leg standing	Relaxation	Concentration
1	Commencing (起式)	v							v	v
2	White Crane Spreads Its Wings (白鶴亮翅)	v	v							v
3	Brush Knee And Twist Step (摟膝拗步)			v	v					v
4	Hand Strums The Lute (手揮琵琶)		v			v				v
5	Step Back And Whirl Arms (倒卷肱)					v				v
6	Work At Shuttles On Both Sides (左右穿梭)			v	v					v
7	Needle At The Sea Bottom (海底針)		v	v	v					v
8	Wave Hands In Clouds (雲手)			v			v			v
9	Golden Rooster Stands On One Leg (金雞獨立)	v						v		v
10	Kick With Heels (左右蹬腿)	v						v		v
11	Strike Ears With Both Fists (雙峰貫耳)	v							v	v
12	Closing (收式)	v							v	v

Note: Concentration includes memorizing, planning, and monitoring of the Tai Chi forms.

3.3.3.3 Assessment

Demographic data were collected from each subject along with information related to their stroke. The Mini-Mental Status Examination administered in the screening measured their cognitive functioning. The Berg Balance Scale was used to rate their skill in various functional movements commonly seen in daily activities, and Timed Up-and-Go test of functional mobility was also administered. All of the participants were asked to notify research personnel of any change in their physical or medical condition, medication or regular physical activity and to report any incidence of falls or injury within the study period.

An auditory Stroop test and a turning-while-walking test used as the cognitive and physical tasks, respectively. The dual-tasking involved turning-while-walking and concurrently performing an auditory Stroop test.

3.3.3.3.1 Single auditory Stroop test

In this test, there were four combinations of pre-recorded sound. The combinations were the Cantonese words for “high” and “low” spoken with either a high or low pitch. The subjects held a two-button switch, with each button representing one of the pitches. They were instructed to respond to the pitch and ignore the meaning of the words by pressing the corresponding button with their less affected thumb as quickly and as accurately as possible. Each combination was repeated three times in random order, resulting in 12 trials. Reaction time was defined as the period between the production of the sound and the subject’s pressing the button. Accuracy was calculated by dividing the number of correct responses by the total number of trials.

Both reaction time and accuracy were measured with custom-made software (LabVIEW version 8.6, National Instruments Corp., Austin, TX, USA). A composite score was computed as the outcome of the auditory Stroop test. It was computed as (Springer et al., 2006):

$$\text{Composite score} = \frac{\text{Accuracy}}{\text{Averaged reaction time (s)}}$$

3.3.3.3.2 Single turning-while-walking test

The subjects were asked to walk a straight line for five meters, make a 180-degree turn towards their affected side, and return to the starting position as quickly as possible. They were asked to press any button on the switch at any time while turning to minimize any effect of that action in the dual-tasking data analysis. A researcher walked close to the subject during the test to ensure safety. The task was repeated three times. The completion time of the turning-while-walking, turning duration, and number of steps taken during the turn were captured with a gyroscopic sensor system for gait analysis (Mobility Lab iWalk, OPAL sensors, APDM Inc., Portland, OR, USA). Averages over the three trials were used in the data analysis. Turn duration and the number of steps needed have been suggested to relate to functional ability (Lam & Luttmann, 2009) and history of falling (Dite & Temple, 2002) among stroke survivors.

3.3.3.3.3 Dual-tasking test

In the dual-tasking condition, the auditory Stroop test was triggered when the subject stepped on a force platform (Model OR6-5-1000, Advanced Mechanical Technologies Inc., Newton, MA, USA) placed five meters from the starting point of the walk. There were no task prioritization requirements. The subjects were asked to respond to the cognitive task as quickly and as accurately as possible while walking and turning as fast as possible. The test was repeated four times, with each combination of the auditory Stroop test performed once in a randomized order. The same outcome measures used in the single-tasking conditions were employed in the dual-tasking.

The repeatability of these assessments was found to be satisfactory in a previous study (Chan et al., 2016a). The three task conditions were assessed in a randomized sequence. There were rest periods whenever needed to minimize fatigue. All of the assessments were performed by a trained research assistant who was blinded to group allocation. The assessments were performed before (pre-assessment), after (post-assessment) and 1-month after (follow-up assessment) the intervention period. The test sequences were the same for each subject across all three assessment sessions.

3.3.3.4 Statistical analysis

Statistical analysis was conducted with the Statistical Package for the Social Sciences (SPSS, version 23, IBM Corp., Armonk, NY, USA). Baseline comparisons among the three groups were carried out with one-way analysis of variance (ANOVA) for the continuous data and Chi-squared tests for categorical data. Two-way mixed ANOVAs (3 x 3) were conducted to determine the significance of any group effect (between-subjects), time effect (within-subject), and interaction effect (group x time) under both the single- and dual-tasking conditions. For any significant between-subjects difference, a one-way ANOVA was performed followed by a post hoc analysis in each assessment period. To highlight any significant within-subject changes, repeated measures ANOVA with further contrast analysis was conducted in each group. Bonferroni adjustments were applied in all follow-up analyses. The level of significance was set at $p \leq 0.05$. Missing data were managed by carrying forward the last observation of the intention-to-treat method.

3.3.4 Results

Eighty-eight people were enrolled in the study, of whom 47 were found eligible to participate. They were randomized into the Tai Chi (n=15), conventional exercise (n=17) and control (n=15) groups. Figure 3.3.1 shows a CONSORT diagram for the study. Table 3.3.2 presents the characteristics of the subjects at baseline, showing that there was no significant difference among the three groups. No adverse effect related to the training was reported during the intervention period.

Figure 3.3.1 CONSORT diagram

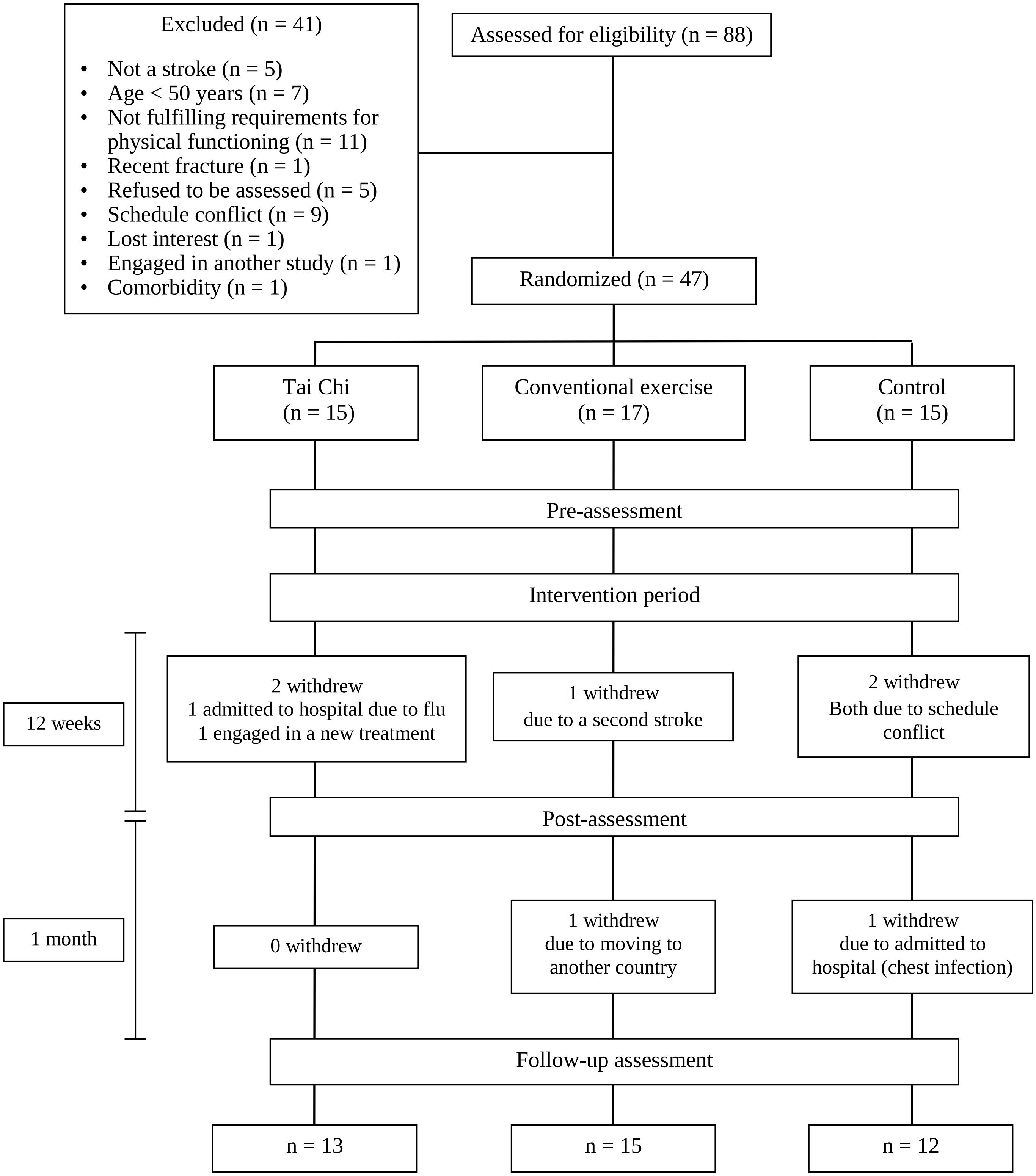


Table 3.3.2 Demographic and clinical characteristics of the subjects

		Tai Chi (n = 15)	**Conventional exercise (n = 17)**	**Control (n = 15)**	***p*-value**
Age (years)		63.0 ± 7.0	62.7 ± 7.3	62.3 ± 7.3	0.962
Gender (male : female)		9 : 6	10 : 7	8 : 7	0.924
Height (cm)		162.9 ± 6.7	163.8 ± 9.6	161.1 ± 7.9	0.655
Weight (kg)		61.3 ± 8.3	65.6 ± 10.5	61.0 ± 15.5	0.475
MMSE score		28.5 ± 1.7	27.9 ± 1.9	26.9 ± 2.9	0.142
BBS score		51.0 ± 3.3	48.2 ± 5.2	50.2 ± 5.0	0.389
TUGT (sec)		15.8 ± 6.4	17.9 ± 7.8	15.7 ± 7.2	0.717
Education (years)		9.0 ± 3.9	10.8 ± 3.6	7.8 ± 3.8	0.174
Chronicity (years)		4.6 ± 4.8	7.8 ± 6.1	5.9 ± 3.8	0.208
Affected side	Right	7	7	6	0.924
	Left	8	10	9	
Number of strokes	1	13	14	13	0.858
	2	2	2	1	
	3	0	1	1	
Type of stroke	Ischemic	12	11	12	0.631
	Hemorrhage	2	5	3	
	Both	1	1	0	
Attendance (out of 24 sessions)		21.0 ± 3.7	19.5 ± 3.7	/	0.284

Values are in mean ± standard deviation; MMSE = Mini-Mental Status Examination (Cantonese version); BBS = Berg Balance Scale; TUGT = Timed Up-and-Go test

The results of the two-way mixed ANOVA are presented in Table 3.3.3. No significant differences were observed in the auditory Stroop test results, the turning-while-walking test results, or in the dual-tasking among any of the groups after the intervention or at the follow-up.

Table 3.3.3 Changes in single-tasking and dual-tasking performance (turning-while-walking)

		Tai Chi (n = 15)			Conventional exercise (n = 17)			Control (n = 15)			*F*-value (*p*-value)		
		Pre	**Post**	**FU**	**Pre**	**Post**	**FU**	**Pre**	**Post**	**FU**	**Between-subject effect**	**Within-subject effect**	**Inter-action effect**
Single-tasking													
Auditory Stroop test	Composite score	88.9 ± 20.4	96.0 ± 18.9	96.0 ± 20.8	83.6 ± 22.4[b]	97.4 ± 21.8[b]	95.5 ± 19.9	78.6 ± 27.5[c]	86.3 ± 24.8	90.4 ± 27.8[c]	0.71 (0.497)	13.05 (< 0.001)[a]	0.69 (0.601)
Turning-while-walking	Completion time (sec)	17.2 ± 6.5	15.9 ± 5.5	15.1 ± 5.2	19.0 ± 7.2[c]	18.4 ± 8.7	17.7 ± 7.5[c]	17.8 ± 7.7	16.0 ± 8.3	16.6 ± 9.8	0.41 (0.669)	6.84 (0.002)[a]	0.64 (0.630)
	Turning duration (sec)	4.8 ± 1.5	4.6 ± 1.5	4.4 ± 1.6	5.1 ± 1.8	4.9 ± 2.0	4.8 ± 1.8	4.7 ± 1.3	4.4 ± 1.6	4.3 ± 1.5	0.36 (0.700)	4.58 (0.025)[a]	0.23 (0.858)
	Number of steps to turn	8.7 ± 1.9	8.6 ± 1.7	8.5 ± 2.4	9.0 ± 1.4	9.3 ± 2.6	8.9 ± 2.2	8.9 ± 2.0	8.7 ± 2.2	8.5 ± 2.2	0.25 (0.782)	1.05 (0.355)	0.33 (0.855)
Dual-tasking													
Auditory Stroop test	Composite score	73.1 ± 27.6[b,c]	89.9 ± 23.4[b]	91.7 ± 26.9[c]	56.3 ± 22.1	65.1 ± 24.7	77.0 ± 31.2	66.8 ± 31.0	80.3 ± 26.4	86.7 ± 30.5	2.81 (0.072)	12.67 (< 0.001)[a]	0.31 (0.868)
Turning-while-walking	Completion time (sec)	17.7 ± 6.9[c]	15.6 ± 5.2	14.9 ± 4.9[c]	18.7 ± 7.5	18.5 ± 9.4	18.1 ± 8.8	18.3 ± 8.0	16.6 ± 9.9	17.2 ± 10.4	0.34 (0.710)	5.91 (0.011)[a]	0.43 (0.245)
	Turning duration (sec)	5.0 ± 1.8	4.4 ± 1.5	4.4 ± 1.7	5.1 ± 1.7	5.1 ± 2.1	4.9 ± 1.9	5.1 ± 1.5	4.7 ± 1.8	4.6 ± 1.7	0.28 (0.757)	5.78 (0.012)[a]	0.96 (0.412)
	Number of steps to turn	8.9 ± 2.1	8.4 ± 2.0	8.4 ± 2.6	9.1 ± 2.3	9.4 ± 2.7	9.1 ± 2.1	9.0 ± 1.9	9.2 ± 2.3	8.8 ± 2.1	0.35 (0.707)	1.14 (0.326)	0.74 (0.570)

Note: Values are in mean ± standard deviation or *F*-value (*p*-value); Pre = pre-assessment; Post = post-assessment; FU = follow-up assessment; Completion time = Completion time of turning-while-walking task

[a] denotes a significant difference within subjects ($p \leq 0.05$)

[b] denotes a significant difference between the pre-assessment and the post-assessment ($p \leq 0.05$)

[c] denotes a significant difference between the pre-assessment and the follow-up assessment ($p \leq 0.05$)

In dual-tasking condition, the subjects in the Tai Chi group showed a significant improvement in their average composite score on the auditory Stroop test from the pre-assessment to the post-assessment ($p = 0.044$) and the improvement persisted during the follow-up period ($p = 0.014$). The subjects in the Tai Chi group also improved their average turning-while-walking times while dual-tasking significantly from the pre-assessment to the follow-up assessment ($p = 0.026$). No significant change was found in the single-tasking condition among the subjects of this group (Table 3.3.3).

The conventional exercise and control groups showed no significant change in their average dual-tasking performance. In the single-tasking condition, the conventional exercise group significantly improved their average auditory Stroop test scores from the pre-assessment to the post-assessment ($p = 0.018$). Subjects in the control group also showed an increase in the score from the pre-assessment to the follow-up assessment ($p = 0.035$). Besides, those in the conventional exercise group showed a significant reduction in the group's average turning-while-walking time from the pre-assessment to the follow-up assessment ($p = 0.049$) (Table 3.3.3).

3.3.5 Discussions

This study sought to document any effect of Tai Chi training on dual-tasking performance among stroke survivors. The results showed no significant difference in either the Tai Chi group, the conventional exercise group or the control group after the 12-week intervention period or at the follow-up. The lack of significant difference could be due to the small sample. Nevertheless, those who received the Tai Chi training showed a significant improvement in dual-tasking performance after the training.

The lack of significant difference among the three groups after the intervention may be attributable to an insufficient amount of training. Tai Chi is usually a lifetime hobby. In a previous study, healthy older adults demonstrated improved dual-tasking performance after 16 weeks of Tai Chi training (1.5 hours per session, three sessions per week) (Lu et al., 2016). The training dosage of that study was three-fold higher than in this current study. As the subjects' physical ability had been impaired by stroke, it may take longer for them to benefit from Tai Chi practice and achieve notable improvement in dual-tasking ability compared with that of the conventional exercises. Prospective studies that involve a higher dosage of Tai Chi training are needed.

Although no significant difference was found among the three groups after the intervention period, the within-subject analysis showed a significant improvement in dual-tasking performance after the Tai Chi training. Theoretically, dual-tasking performance can be enhanced by increasing the availability of attentional resources or the ability to properly allocate the resources (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012). A prior study has shown that experienced Tai Chi practitioners had a greater cortical thickness at the middle frontal sulcus, the right precentral gyrus, the left medial occipito-temporal sulcus, and the left lingual sulcus (Wei et al., 2013). Another event-related potential study illustrated that older Tai Chi practitioners had higher P3 amplitudes than their control counterparts in a task-switching test (Fong et al., 2014). When practicing Tai Chi, an individual performs the movement while planning and monitoring their action concurrently. Attention should also be shifted between the physical movement and the cognitive processing. Those features may explain the enhanced dual-tasking performance after Tai Chi training observed in this study. However no causal relationship among Tai Chi practice, neural plasticity, and improved dual-tasking performance has yet been established.

Although some previous studies (Lu et al., 2016; Wayne et al., 2015) have shown the beneficial effect of Tai Chi training on dual-tasking performance among healthy older adults, a study by Hall and his colleagues (2009) found no such effect. The authors ascribed the lack of significant improvement to the training method used. Their subjects were prompted by visual and verbal cues from the instructors. By contrast, the subjects in this study were encouraged to memorize the Tai Chi forms while performing the physical movements. If the aim of practicing Tai Chi is to improve dual-tasking performance, emphasizing the involvement of the cognitive processing during the training may be helpful. Indeed, it has been proposed that exercise that involves explicit learning and variation in techniques and allocation of attentional resources can enhance dual-tasking ability. Further, these elements may promote the transfer of a particular type of dual-task training to various combinations of dual-tasking (Lussier et al., 2017; Strobach et al., 2014). The improvement in dual-tasking performance after Tai Chi training may be attributable to the explicit learning, variations in techniques, and attention-shifting during the practice. On the other hand, although the subjects in this study’s conventional exercise group were simply instructed to follow the instructor's movements, it is not clear whether or not the practice involved explicit learning. That may explain the lack of significant difference between the two groups. The subjects’ neural activity was not, however, measured, so these explanations are only speculative.

The lack of significant difference in the turning-while-walking results among the three groups was unexpected. It might, however, be explained by the slow movements involved in Tai Chi. In the Tai Chi practice the subjects were asked to turn slowly with small amplitude to ensure safety. The small difference in turning times and the number of steps required to complete a turn is therefore reasonable. On the other hand, turning in Tai Chi begins with the gaze, consecutively followed by the head, trunk and pelvis, and finally the legs. This rostrocaudal reorientation sequence can be found during turning among healthy adults but is often disrupted in stroke survivors with poor physical functioning (Hollands et al., 2010a; Lamontagne & Fung, 2009). Future studies that include kinematic measurements to examine the turning performance after Tai Chi training are warranted.

3.3.6 Limitations

This study protocol had several limitations. In the first place, most of the subjects were members of local self-help groups and were self-selected. It can be assumed that they are relatively active, thus resulting in potential selection bias. Besides, they had a high level of cognitive and physical functioning (Table 3.3.2). The results of this study should not be generalized too readily to stroke survivors who are more disabled. In addition, the control subjects were not forbidden to participate in other types of exercise during the study period. That may explain why a trend of improvement was observed in that group. Moreover, a longer follow-up period may be needed to observe any carry-over effect of Tai Chi training.

3.3.7 Conclusions

The results of this study do not support any superior effect of Tai Chi training on dual-tasking among stroke survivors compared with conventional exercise. The data do show, however, Tai Chi's potential for improving dual-tasking performance in this population. Further studies with a larger sample size, more training and a longer follow-up period are needed. Including more severely disabled stroke survivors might also be informative. Kinematic outcome measures relating to the turning performance may be considered. Further studies on the relationship among Tai Chi training, neural plasticity, and dual-tasking performance are also warranted.

CHAPTER 3.4

THE EFFECT OF TAI CHI TRAINING ON DUAL-TASKING PERFORMANCE THAT INVOLVES STEPPING DOWN AMONG STROKE SURVIVORS

Submitted:

Chan, W. N., & Tsang, W. W. (2017). Effect of Tai Chi training on dual-tasking performance that involves stepping down among stroke survivors: A pilot study. *Evidence-based Complementary and Alternative Medicine*. In press.

3.4.1 Abstract

Background

Descending stairs demands attention and neuromuscular control, especially with dual-tasking. Studies have demonstrated that stroke often degrades a survivor’s ability to descend stairs. Tai Chi has been shown to improve dual-tasking performance of healthy older adults, but no such study has been conducted in stroke survivors.

Objective

This study investigated the effect of Tai Chi training on dual-tasking performance that involved stepping down and compared it with that of conventional exercise among stroke survivors.

Methods

Subjects were randomized into Tai Chi (n = 9), conventional exercise (n = 8), and control (n = 9) groups. Those in the former two groups received a 12-week training. Assessments included auditory Stroop test, stepping down test, and dual-tasking test involving both tests simultaneously. They were evaluated before (pre-assessment), after (post-assessment) and one month after (follow-up assessment) training.

Results

Tai Chi group showed significant improvement in the auditory Stroop test from the pre-assessment (64.6 ± 22.7) to the follow-up assessment (94.4 ± 20.6) when dual-tasking and the performance was significantly better than that of the conventional exercise group in follow-up assessment (55.7 ± 11.1). No significant effect was found in the stepping down task or both tasking conditions in the control group.

Conclusions

These results suggest a beneficial effect of Tai Chi training on cognitive task performance among stroke survivors without compromising physical task performance in dual-tasking. The effect was better than that of the conventional exercise group. Further research with a larger sample should be done to confirm the study results.

Keywords

Stroke; Tai Chi; Dual-tasking; Stepping down

3.4.2 Introduction

Negotiating stairs is an important indicator of independence among community-dwelling stroke survivors (Alzahrani et al., 2009) and considered one of the most difficult activities in their daily life (Tsuji et al., 1995). It demands a high level of neuromuscular control of the lower limbs, especially when descending stairs (Jacobs, 2016; Perry & Burnfield, 2010; Startzell et al., 2000). Impaired physical functioning after stroke may degrade stairs negotiation ability. Stroke survivors descend stairs slower (Novak & Brouwer, 2013) and with a greater lower limb strength demands (Novak & Brouwer, 2012) than their healthy counterparts. Apart from physical functioning, stair negotiation also involves cognition and attention to evaluate the configuration of the stairs and to integrate information from various sensory systems

(Jacobs, 2016; Ojha et al., 2009; Startzell et al., 2000). An additional cognitive task while stepping down (dual-tasking), which may be encountered in daily life, may make the already demanding movement even more challenging. Previous studies involved a stepping down test and a concurrent auditory Stroop test show that more attentional resources are needed in such a dual-tasking condition in healthy older people (Chan et al., 2016b; Lu et al., 2013b; Tsang et al., 2013). A previous study has also demonstrated altered foot clearance when stepping down among older adults under dual-tasking condition (Telonio et al., 2014). Indeed, attentional distraction is one of the commonest situations in which stair-related falls occur (Templer, 1992). Falling on the stairs, especially in descending, could result in severe injuries (Jacobs, 2016; Startzell et al., 2000) or even death (National Safety Council, 2016).

Tai Chi is a traditional Chinese martial art, which in recent decades, has been employed by different populations as an exercise to promote healthy aging and rehabilitation. Scientific studies have supported Tai Chi's training effects in terms of physical function and its utility in fall prevention among community-dwelling older adults (Chen et al., 2012; Leung et al., 2011; Lu et al., 2013a, 2013b; Tsang & Hui-Chan, 2004; Wayne et al., 2014) and stroke survivors (Au-Yeung et al., 2009; Kim et al., 2015; Taylor-Piliae et al., 2014). Tai Chi movements demand proper posture, accurate joint positioning, constant weight shifting between the two legs, and eccentric control of the lower limbs. Significant improvements in lower limb strength (Lu et al., 2013a) and neuromuscular control (Chen et al., 2012; Gatts & Woollacott, 2006) are observed after Tai Chi training, and both are important in safe and controlled stair descent (Perry & Burnfield, 2010). In addition, Tai Chi is considered a mind-body exercise. When practicing Tai Chi, attentions must be sustained to properly sequence the forms and to monitor the accuracy of the movements. The advantageous effects of Tai Chi training on cognitive functioning are demonstrated from prior studies (Kasai et al., 2010; Taylor-Piliae et al., 2010; Wayne et al., 2014). It is that cognitive involvement while performing the physical movement and maintaining balance which gives Tai Chi a dual-tasking character. Indeed, a previous randomized controlled trial has illustrated improved dual-tasking performance among community-dwelling older adults after Tai Chi training. The subjects made fewer errors in an auditory Stroop test and swayed less when stepping down in a dual-tasking condition after the intervention (Lu et al., 2016).

Given the severity of the injuries caused by stair-related falls and the increased physical and cognitive demands when descending stairs, a cost-effective exercise, which will enhance the dual-tasking ability of stroke survivors when stepping down, is needed. Beyond the work of Lu and colleagues (2016), however, there has been no similar study published addressing stroke survivors. This study was therefore designed to explore the effect of Tai Chi training on dual-tasking performance with such a population. Previous evidence with the training effects of Tai Chi on cognition, physical ability, and dual-tasking performance with healthy older adults suggests that dual-tasking performance that involves stepping down should be similarly improved among stroke survivors. We therefore hypothesized that:

1. The cognitive and physical task performance under both single-tasking and dual-tasking conditions would be improved after Tai Chi training.
2. The performance in the Tai Chi group would be better than those of the conventional exercise group after the intervention period, owing to the dual-

tasking features of Tai Chi and the lack of such characteristics in conventional exercises.

3.4.3 Methods

3.4.3.1 Participants

This study was an assessor-blinded randomized controlled trial. It was registered at ClinicalTrials.gov (Registration number: NCT03252236). Subjects were recruited from patient self-help groups and hospitals in Hong Kong. So the subjects were basically self-selected, but the following inclusion criteria were applied: 1) aged 50 or above, 2) diagnosed with stroke six or more months previously, 3) able to perform a stepping down maneuver without any physical assistance, and 4) able to follow instructions in Cantonese. The exclusion criteria were: 1) any neurological disease other than stroke, 2) severe visual or hearing impairment, 3) a score of less than 18 on the Cantonese version of the Mini-Mental Status Examination (MMSE) (Lam et al., 2008), or 4) any major surgery or severe musculoskeletal injury during the previous six months. The study was approved by the Ethics Committee of the Hong Kong Polytechnic University (Reference number: HSEARS20131023003). Written informed consent was obtained from each subject after the aims and procedures of the research had been explained. The assessment was carried out in the Department of Rehabilitation Sciences of the Hong Kong Polytechnic University, while the intervention was conducted at the university and in local community centers.

3.4.3.2 Intervention

The intervention was carried out between October 2014 and December 2016. After screening for eligibility, the subjects were stratified according to their gender and age (aged 50-59, 60-69, 70-79, or >80 years old). The subjects were then randomized into Tai Chi, conventional exercise, or control groups within their stratified group.

3.4.3.2.1 Tai Chi group

Subjects in the Tai Chi group were taught a modified 12-form Yang style Tai Chi (Table 3.3.1, p.111; Appendix II, p.188–193). The forms were selected according to the needs of stroke survivors by a senior physiotherapist and a Tai Chi master with more than 30 years of teaching experience. Another physiotherapist who is also an experienced Tai Chi practitioner instructed the training. The Tai Chi training emphasized maintaining proper posture, eccentric control of the lower limbs, and increasing weight bearing on the affected leg by continuous weight shifting. The subjects were also encouraged to memorize the sequence of the forms and to monitor their own movement while practicing. There were end-of-training tests in which the participants were required to perform the 12 forms on their own so as to maximize the cognitive involvement and dual-tasking features of the exercise.

When learning a new form which challenged balance, such as Kick With Heels, physical support was provided initially to ensure subjects' safety. They initially performed those forms by leaning against the wall and holding the back of a chair, with the instructor standing by to provide assistance if necessary. The support was gradually diminished according to the subjects’ standing ability. The class size was limited to 10 participants for close supervision. Rest periods were allowed whenever needed.

Subjects in this group attended two one-hour training sessions each week, with a total of 24 sessions. There was a 10-minute warm-up at the beginning of each session and a 5-minute cool-down at the end. The subjects were encouraged to practice outside the class for 30 minutes at least once a week. Exercise log-books were given to the subjects for recording their self-practice.

3.4.3.2.2 Conventional exercise group

Conventional exercises, including mobilization, stretching, strengthening of the upper and lower limbs and walking, were conducted in this group (Appendix III, p.194). Most of the exercises were performed in sitting except for some of the lower limb and walking exercises. Unlike the training in the Tai Chi group, all the exercises employed in this group are of single-tasking feature, which is focusing on the physical movements only. The subjects were not required to memorize the sequence of the exercises. Instead, they simply followed the movements of the instructor, who was the same one who taught in the Tai Chi group. The training dosage of the conventional exercise group was as same as that of the Tai Chi group. Subjects were also given exercise log-books for recording the self-practice.

3.4.3.2.3 Control group

No training was provided to the control group during the 12-week intervention period. They continued their regular activities. After the completion of all the assessments, Tai Chi training was given to the subjects in this group.

3.4.3.3 Assessment

Demographic data, including age, gender, height, and weight were collected at baseline. Information related to the stroke, such as the chronicity, side, number, and type of stroke were also recorded. Physical functioning was assessed with the Timed Up-and-Go test (TUGT) and the Berg Balance Scale (BBS). Cognitive ability was tested with the MMSE. All of the subjects were required to notify the research personnel of any change in their physical or medical condition, medication, exercise patterns, falls and any injury during the study period.

A single cognitive task (an auditory Stroop test), a single physical task (stepping down), and dual-tasking were assessed before (pre-assessment), after (post-assessment), and one month after (follow-up assessment) the intervention period. The order in which the three tasks were tested was randomized, but the sequence for any one subject was the same in all three assessments. The trained research assistant who conducted all the tests was blinded to the group assignments.

3.4.3.3.1 Single auditory Stroop test

An auditory Stroop test was used to quantify the executive function (Royall et al., 2002; Rozenblatt, 2011). Two Cantonese words, ‘high’ and ‘low,’ were pronounced with high and low pitches, resulting in four sound combinations. A switch with two buttons representing the high and low pitches was given to the subjects. They were instructed to ignore the meaning of the word but respond to the pitch of the sound by pressing the corresponding button with the thumb of the less-affected hand as quickly and as accurately as possible. The test was conducted while sitting. Each combination was repeated three times in random order, resulted in 12 trials.

A composite score was calculated as the outcome measure using the following formula (Springer et al., 2006):

$$\text{Composite score} = \frac{\text{Accuracy}}{\text{Averaged reaction time (s)}}$$

Accuracy was defined as the number of correct responses divided by the total number of trials. The reaction time was defined as the period between the appearance of the sound and the subject's pressing the button. Averaged reaction time was used to calculate the composite score. Both parameters were recorded with a customized LabVIEW program (version 8.6, National Instruments Corp., Austin, TX, USA).

3.4.3.3.2 Stepping down test

Stepping down was employed as the physical task. A force platform (Model OR6-5-1000, Advanced Mechanical Technologies Inc., Newton, MA, USA) was positioned in front of a 19cm high block, with a visual fixation placed two meters away from the center of the force plate at the subject's eye level to standardize the visual attention (Figure 3.2.1, p.92). Each subject was asked to stand in bare feet with the toes at the edge of the block and the legs apart at shoulder width. They then stepped down from the block, leading with the less affected leg. The movement ended when both feet were touching the force platform. The instructions called for the movement to be fast but stable. A research assistant stood next to the subject during the test to ensure safety. The task was repeated three times.

The force platform measured the sway of the center of pressure (CoP) during the stepping down movement. Data were captured as the leading leg reached the force platform, when the vertical ground reaction force exceeded zero, and the subsequent five seconds were used in the statistical analysis. The data were resampled from 1000Hz to 125Hz and filtered with a second-order Butterworth low-pass filter at a cut-off frequency of 10Hz using a customized MATLAB program (version 8.3, The MathWorks, Inc., Natick, MA, USA). The outcome measures were the anteroposterior (CoP-AP) and mediolateral (CoP-ML) sway amplitudes and the average sway velocity (VCoP), which was calculated by dividing the total CoP travel distance by five seconds. The data were normalized using each subject's height. Averages over three trials were employed in the data analysis.

3.4.3.3.3 Dual-tasking test

Dual-tasking was assessed by combining the cognitive and the physical tasks. The setting was as same as that of the single stepping down test. A pressure sensor (model FSR406, Interlink Electronics, CA, USA) was placed under the calcaneus of the leading leg at the starting position. The auditory Stroop test was triggered when the leading leg lifted and unloaded the pressure sensor. Each auditory Stroop test combination was examined once, resulting in four trials. The subjects were told that both the cognitive and physical tasks were of equal importance. The outcome measures used in the single-tasking conditions were applied in the dual-tasking.

The repeatability of the assessments was conducted in previous study (Chan et al., 2016b).

3.4.3.4 Statistical analysis

The data analysis was conducted with the Statistical Package for the Social Sciences (SPSS, version 23, IBM Corp., Armonk, NY, USA). The baseline demographic data were compared among the three groups using one-way analysis of variance (ANOVA) for the continuous data and chi-squared tests for the categorical data. Two-way mixed ANOVAs (3x3) were conducted to determine the significance of any group effect (between-subject), time effect (within-subject), and any interaction effect (group x time) for each measure. When a significant group effect was emerged, one-way ANOVA and follow-up post-hoc analyses were employed to examine the significance of any between-subject differences at each assessment period. For a significant time effect, repeated measures ANOVA with contrast analyses were conducted to investigate the within-subject changes in each intervention group. The level of significance was set at 0.05, with Bonferroni adjustments applied in all follow-up analyses. Missing data were treated by carrying the last observation forward in keeping with the intention-to-treat approach.

3.4.4 Results

Figure 3.4.1 shows a CONSORT diagram for the study. Eighty-eight subjects were enrolled in the study. After screening for eligibility, a total of 26 subjects were randomized into the Tai Chi (n = 9), conventional exercise (n = 8) or control group (n = 9). Three of the subjects in the conventional exercise group proved unable to perform the stepping down test due to fear of falling (n = 2) or knee pain (n = 1) during the assessment, so, there were only five subjects in that group. Another six subjects eventually withdrew (Tai Chi: n = 2; conventional exercise: n = 1; controls: n = 3).

Figure 3.4.1 CONSORT diagram

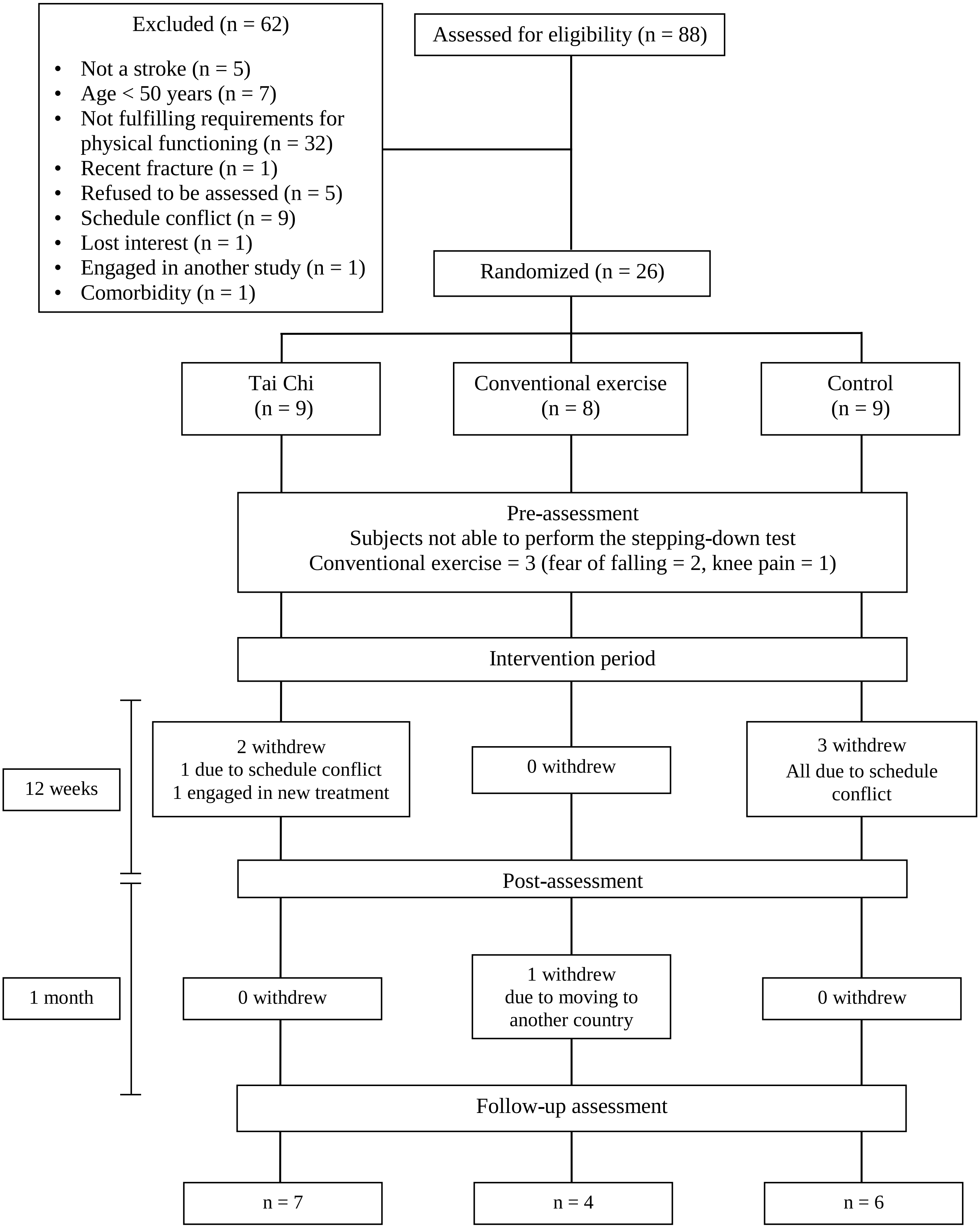


Table 3.4.1 presents demographic data describing the subjects. There was no significant difference in baseline characteristics among the three groups. No adverse effects related to the intervention or the assessment was reported.

Table 3.4.1 Demographic and clinical characteristics of the subjects

		Tai Chi (n = 9)	**Conventional exercise (n = 5)**	**Control (n = 9)**	***p*-value**
Age (year)		63.9 ± 6.1	63.2 ± 9.7	63.2 ± 6.0	0.975
Gender (male : female)		5 : 4	3 : 2	4 : 5	0.827
Height (cm)		161.4 ± 5.2	160.4 ± 5.4	162.6 ± 8.2	0.836
Weight (kg)		59.6 ± 4.5	57.4 ± 12.3	61.7 ± 16.8	0.821
MMSE score		29.2 ± 0.4	27.0 ± 1.9	27.3 ± 2.7	0.074
BBS score		51.0 ± 2.9	50.3 ± 3.2	54.2 ± 1.7	0.074
TUGT (sec)		14.5 ± 4.6	12.2 ± 2.1	12.3 ± 5.1	0.661
Education (years)		8.4 ± 2.1	9.7 ± 3.2	10.3 ± 4.7	0.624
Chronicity (years)		3.3 ± 3.0	8.8 ± 7.9	4.6 ± 3.0	0.103
Affected side	Right	5	3	8	0.254
	Left	4	2	7	
Number of strokes	1	7	5	8	0.485
	2	2	0	1	
Type of stroke	Ischemic	7	2	8	0.140
	Hemorrhage	1	3	1	
	Mixed	1	0	0	
Attendance (out of 24 sessions)		22.6 ± 1.8	18.8 ± 5.0	/	0.091

Values are in mean ± standard deviation; MMSE = Mini-Mental Status Examination (Cantonese version), BBS = Berg Balance Scale, TUGT = Timed Up-and-Go test

Table 3.4.2 displays the results of the two-way mixed ANOVA of the cognitive and physical task performance in the dual-tasking condition.

Table 3.4.2 Changes in single-tasking and dual-tasking performance (stepping down)

		Tai Chi (n = 9)			Conventional exercise (n = 5)			Control (n = 9)			*F*-value (*p*-value)		
		Pre	Post	FU	Pre	Post	FU	Pre	Post	FU	Between-subject effect	Within-subject effect	Inter-action effect
Single-tasking													
Auditory Stroop test	Composite score	85.9 ± 28.6	93.4 ± 21.7	96.2 ± 26.7	99.5 ± 17.3	108.0 ± 30.6	106.5 ± 19.5	93.8 ± 23.6	99.5 ± 19.4	98.2 ± 31.1	0.49 (0.619)	2.99 (0.062)	0.18 (0.946)
Stepping down	CoP-AP	80.4 ± 36.8	79.5 ± 17.4	85.6 ± 14.4	76.0 ± 18.6	99.6 ± 28.0	81.9 ± 21.5	83.7 ± 25.8	81.4 ± 24.9	77.4 ± 27.5	0.10 (0.905)	0.86 (0.411)	1.34 (0.279)
	CoP-ML	73.9 ± 41.6	52.7 ± 17.0	68.8 ± 27.1	84.4 ± 15.7	79.3 ± 15.5	56.7 ± 21.9	71.9 ± 31.3	59.7 ± 34.7	77.2 ± 38.0	0.22 (0.803)	1.64 (0.206)	1.53 (0.212)
	VCoP	65.8 ± 36.1	62.0 ± 19.6	62.3 ± 11.5	71.9 ± 14.1	76.2 ± 27.1	65.9 ± 16.1	68.1 ± 22.2	59.9 ± 22.6	66.0 ± 23.8	0.26 (0.771)	0.46 (0.608)	0.65 (0.608)
Dual-tasking													
Auditory Stroop test	Composite score	64.6 ± 22.7[c]	91.9 ± 19.2	94.4 ± 20.6[b,c]	66.9 ± 26.4	64.4 ± 16.0	55.7 ± 11.1[b]	86.1 ± 38.2	82.6 ± 20.7	72.9 ± 26.1	2.07 (0.153)	0.92 (0.407)	4.14 (0.007)[a]
Stepping down	CoP-AP	89.6 ± 46.7	86.0 ± 25.3	91.2 ± 18.6	97.1 ± 30.5	97.0 ± 35.5	72.1 ± 24.2	88.8 ± 25.5	80.1 ± 32.3	80.2 ± 31.9	0.11 (0.894)	1.43 (0.252)	1.32 (0.287)
	CoP-ML	72.7 ± 40.0	59.9 ± 18.9	71.4 ± 18.8	93.6 ± 29.1	80.7 ± 14.6	51.8 ± 16.7	65.5 ± 26.9	56.1 ± 30.0	77.4 ± 36.4	0.29 (0.751)	1.86 (0.169)	3.16 (0.024)[a]
	VCoP	66.2 ± 39.8	64.5 ± 16.7	64.8 ± 10.5	82.8 ± 26.1	71.6 ± 24.2	59.8 ± 12.5	66.4 ± 20.0	61.5 ± 21.0	67.7 ± 23.0	0.19 (0.825)	1.60 (0.222)	1.31 (0.292)

Values are in mean ± standard deviation or *F*-value (*p*-value); Pre = pre-assessment; Post = post-assessment; FU = follow-up assessment; CoP-AP = normalized center of pressure sway in the anteroposterior direction; CoP-ML = normalized center of pressure sway in the mediolateral direction; VCoP = average center of pressure sway velocity

[a] denotes a significant interaction effect ($p \leq 0.05$)

[b] denotes a significant difference between the Tai Chi group and the conventional exercise group in the follow-up assessment ($p \leq 0.05$)

[c] denotes a significant difference between the pre-assessment and the follow-up assessment in the Tai Chi group ($p = 0.036$)

There was a significant interaction between group and time in the composite scores on the auditory Stroop test [$F(4,40) = 4.136$, $p = 0.007$]. The composite score of the Tai Chi group was significantly higher than that of the conventional exercise group in the follow-up assessment ($p = 0.013$). Besides, improvement was observed in the Tai Chi group from the pre-assessment to the post-assessment, but the change was not significant at the study's 5% level of confidence ($p = 0.054$). The score continued to increase, however, reaching a significant improvement compared with the pre-assessment ($p = 0.036$). No significant change was displayed in either the conventional exercise group or the control group ($p > 0.05$).

Apart from the cognitive task, the CoP-ML also demonstrated a significant interaction effect [$F(4,40) = 3.162$, $p = 0.024$]. However, the group effect was not significant in all testing periods ($p > 0.05$). In the conventional exercise group, CoP-ML tended to decrease from the pre-assessment through the follow-up assessment, but a follow-up analysis showed that the changes were not statistically significant ($p = 0.051$). No significant time effect was found in the Tai Chi group and the control group ($p > 0.05$).

The other two observations from the stepping-down task, the CoP-AP and VCoP, showed no significant interaction effect, group effect or time effect (all p-values > 0.05).

For the single-tasking condition, the two-way mixed ANOVA showed no significant interaction effect, group effect, or time effect in the composite scores on the auditory Stroop test ($p > 0.05$). Likewise, no significant effects were found in any of the stepping down test results in the single-tasking condition ($p > 0.05$) (Table 3.4.2).

3.4.5 Discussion

This study investigated the effect of Tai Chi training on dual-tasking performance that involved stepping down. The expectation that Tai Chi training would improve both single-tasking and dual-tasking performance was partially supported. A significant enhancement in the average composite score on the auditory Stroop test was observed from the pre-assessment to the follow-up assessment without compromising physical task performance. However, no significant change in single tasking performance was observed in the Tai Chi group or among the others. But the Tai Chi group's significantly higher average composite score at the follow-up assessment compared with the conventional exercise group supports the idea that Tai Chi training on dual-tasking is better than the conventional exercise.

The expectation that the training effect of Tai Chi would be better to that of the conventional exercises was suggested. The composite score on the auditory Stroop test under dual-tasking was significantly higher in the Tai Chi group than in the conventional exercise group in the follow-up assessment. The subjects in the conventional exercise group were only asked to follow the instructor's movement instead of memorizing the sequence of exercise. The minimal cognitive involvement during the training may have contributed to their insignificant change in dual-tasking performance after the intervention. Indeed, current evidence is still insufficient to support the effect of physical exercise alone on improving dual-tasking performance (Agmon et al., 2014; Gobbo et al., 2014). A trend in that group's lower composite score on the auditory Stroop test but less CoP sway when stepping-down under dual-tasking suggest that more attentional resources were being allocated to the physical task rather than the cognitive task during the follow-up assessment compared with the initial one. That should improve safety in negotiating stairs while dual-tasking, but it may also imply that the attentional resources were insufficient for performing the tasks concurrently (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012). On the other hand, the Tai Chi subjects showed significant improvement in dual-tasking performance. The effect of Tai Chi training on dual-tasking performance is therefore postulated to be better than that of the conventional exercises tested. However, the strategy adopted by the subjects after the conventional exercise training was still appropriate for maintaining stability.

Our previous studies on dual-tasking that involved an auditory Stroop test and stepping down have shown motor-related cognitive interference in dual-tasking among healthy older adults (Tsang et al., 2013) and stroke survivors (Chan et al., 2016b). In this study the stroke survivors showed a significant increase in their average composite score on the cognitive task in dual-tasking after 12 weeks of Tai Chi training. The average composite score in dual-tasking during follow-up assessment (94.4 ± 20.6) was comparable to that in single-tasking (96.2 ± 26.7) and even higher than that of the healthy older subjects under dual-tasking condition that involves stepping down (91.9 ± 29.8) (Table 3.2.3, p.98).

As there has previously been no study published pertaining to the training effect of Tai Chi on dual-tasking performance among stroke survivors, the results of this study were compared with those of the prior studies with healthy older adults (Hall et al., 2009; Lu et al., 2013b; Wayne et al., 2015). Wayne and his colleagues investigated the effect of Tai Chi training on the dual-tasking performance of healthy older adults using a serial subtraction task and walking ability. The results illustrated significantly higher gait speed under dual-tasking conditions after six months of Tai Chi training (Wayne et al., 2015). Another study also found a significant increase in gait speed when dual-tasking after 12 sessions of Tai Chi training (Manor et al., 2014). Lu and colleagues (2013b) also found a significant improvement in stepping down stability and accuracy of the auditory Stroop test when dual-tasking after 16 weeks of Tai Chi training with healthy older adults. By contrast, no obvious change was revealed in an earlier study (Hall et al., 2009). The different results from those previous studies could be due to the instruction method during the Tai Chi training. In the study by Hall and colleagues (2009), rich visual cues were provided so that the participants only needed to follow the instructor's movements during practice. That presumably reduced active cognitive processing among the subjects, thus decreasing the dual-tasking impact of Tai Chi. In this study the subjects were explicitly instructed to concentrate and memorize the forms and their sequencing. They were also enjoined to monitor and adjust their movement during practice. In addition, end-of training tests were anticipated. These techniques may have increased the participants' involvement and the cognitive functioning, which should enhance dual-tasking performance.

In dual-tasking, deterioration of the performance of either task or both tasks can be explained by competition for attentional resources, which is considered a result of 1) insufficient attentional resources available to perform both tasks simultaneously, 2) inability to properly allocate or switch attentional resources between the two tasks, 3) increased attentional resources to carry out one individual task or 4) a combination of these factors (Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-

Seligmann et al., 2012). Theoretically, dual-tasking performance can be improved by modifying these factors. One explanation for the enhanced dual-tasking performance after Tai Chi training could be the increased attentional resources available to perform both the cognitive and physical tasks simultaneously. A previous cross-sectional study using fMRI showed that Tai Chi practitioners had greater cortical thickness at the middle frontal sulcus when compared with non-practitioners (Wei et al., 2013). That area is responsible for executive function, attention, working memory, and processing spatial information (Banich et al., 2000a, 2000b; Cabeza & Nyberg, 2000). The cortical thickness of the right precentral gyrus, which is activated during spatial processing, space and motion perception and imagery, orientation of attention, motor-skill learning (Cabeza & Nyberg, 2000), and the execution of motor task (Hari et al., 1998), is also found greater in Tai Chi practitioners (Wei et al., 2013), as is that of the left medial occipito-temporal sulcus and the lingual sulcus, which are responsible for retrieving and integrating spatial information (Cabeza & Nyberg, 2000; Ekstrom et al., 2003; Grön et al., 2000). As Tai Chi practice involves continuous planning of movement as well as monitoring of posture and the relative position of the body and the external environment, long-term practice may alter the structure of the corresponding brain regions. Studies seeking causal relationship between the effects of Tai Chi practice and changes in brain structure and attentional resources are warranted.

Another possible explanation for the enhanced dual-tasking performance after Tai Chi training found in this study might be an improved ability to allocate or shift attentional resources between the two tasks. Fong and his colleagues have compared task-switching performance among older Tai Chi practitioners, older adults with sedentary lifestyle, and young adults using event-related potentials (Fong et al., 2014). The results showed higher P300 amplitudes among those with Tai Chi experience compared with the older sedentary adults, which is positively related to the ability to allocate attentional resources to different tasks (Polich & Heine, 1996). The amplitude was even comparable to that of the younger subjects. When practicing Tai Chi, the practitioner should maintain attention and shift the focus between cognitive processing and physical movement in order to memorize and plan the forms while maintaining balance. The proportion of attentional resources allocated to the cognitive and physical components may differ with the complexity of the forms and one’s ability to perform them. For example, in Golden Rooster Stands on One Leg, a form that involves single-leg standing but only simple upper limb movement, more attentional resources should be allocated to the physical task of maintaining balance. By contrast, the form Wave Hands in Clouds requires coordinated movement of arms but a rather stable posture, so attentional resources should be allocated preferentially to cognitive processing. For those forms with complex motions while also challenging balance, such as Brush Knee and Twist Step, or Step Back and Whirl Arms, attentional resources must be shared more equally between the cognitive and physical functions. In this connection, there has been no published study investigating any causal relationships between Tai Chi training and neuroplasticity or neurogenesis in either healthy older adults or chronic stroke survivors. The topics of the relationship between brain activity and the allocation of attentional resources during Tai Chi practice are also understudied.

In this study, no significant changes in the performance of the single cognitive or single physical task were observed after Tai Chi training. That may imply that the improved dual-tasking performance is probably not attributable to a decreased demand for attentional resources in the individual tasks. Indeed, absence of any significant change in the single-tasking conditions was not expected, as it has been shown that Tai Chi training benefits both cognitive and physical abilities. Prior studies have revealed significantly better executive functioning in healthy older adults after Tai Chi training (Kasai et al., 2010; Nguyen & Kruse, 2012; Taylor-Piliae et al., 2010; Wayne et al., 2014). For the physical ability, a biomechanical study demonstrated that during Tai Chi practice there is a high level of prolonged eccentric control and co-contraction of the lower limb muscles (Tseng et al., 2007; Wu et al., 2004), which are important factors in lowering the body and stabilizing the lower limb joints when stepping down (Perry & Burnfield, 2010). Previous studies also exhibited significantly stronger eccentric knee extensor strength after Tai Chi training (Audette et al., 2006; Lu et al., 2013a; Mao et al., 2006). Nevertheless, the trend of decreased sway of the center of pressure in the mediolateral direction immediately after the Tai Chi training may suggest that a longer training period might allow for greater improvement. Further studies should be conducted to evaluate the effects of a long-term Tai Chi training on executive function and stepping down performance among stroke survivors.

3.4.6 Limitations

It is important to remind readers that the sample size of this study was small and the dropout rate was relatively high. Studies with a higher number of subjects should be conducted in the future. A post-hoc sample size calculation shows that a total of 45 subjects would be needed to demonstrate a significant interaction effect in the physical task (α= 0.05, power = 0.9, effect size = 0.25). Although the number of subjects participated in this study was lower than that of the calculated sample size, significant improvement in dual-tasking performance was still found. This may support the value of Tai Chi training on dual-tasking performance in stroke survivors. Another limitation was the relatively high level of cognition and physical functioning of the subjects (mean MMSE = 28.0 ± 2.1, BBS = 52.1 ± 2.9). As the dual-tasking that involves stepping-down is challenging to stroke survivors, those who have a lower cognitive and physical abilities were excluded from this study, which may result in selection bias and limit the generalizability of the study's results. Further studies on stroke survivors with a lower level of cognitive and physical functions are warranted.

3.4.7 Conclusions

This is the first study investigating the effect of Tai Chi training on dual-tasking performance that involved stepping-down among stroke survivors. These results suggest that 12 weeks of Tai Chi training (twice a week for an hour) is feasible and safe for stroke survivors and that it can be incorporated into rehabilitation programs to improve dual-tasking performance. Also, the significant results found during the follow-up period imply that continued Tai Chi practice should be encouraged after completion of the 12-week training period. In addition, subjects should be encouraged to learn the Tai Chi patterns rather than just following the instructor's movements. The results also show that Tai Chi training can improve the cognition in dual-tasking condition better than conventional exercises. However, further studies with a larger sample and involving less able subjects are needed. Moreover, the mechanisms underlying the effects demonstrated here remain unclear and are worthy of further investigation.

CHAPTER 3.5

THE EFFECTS OF TAI CHI TRAINING ON ARTERIAL COMPLIANCE, BLOOD PRESSURE, AND CARDIAC AUTONOMIC REGULATION AMONG STROKE SURVIVORS

Submitted:

Chan, W. N., & Tsang, W. W. Short-term Tai Chi training may benefit arterial compliance but not heart rate variability among stroke survivors: A randomized controlled trial. Submitted to *BMC Complementary and Alternative Medicine*. Under second review.

3.5.1 Abstract

Background

Arterial stiffening and cardiac autonomic dysregulation are common among stroke survivors. These changes increase the risk of cardiovascular problems and tend to accelerate mortality. Tai Chi has been reported to improve arterial compliance and cardiac autonomic regulation among healthy older adults. Such effects have not been examined among stroke survivors.

Objective

This study aimed at investigating the effect of Tai Chi training on arterial stiffness and the functioning of the cardiac autonomic nervous system among stroke survivors.

Methods

This was an assessor-blinded, randomized controlled trial. Fifty-six community-dwelling stroke survivors were randomized into a group which received Tai Chi training (n = 19), another which received conventional exercise training (n = 18), or control groups (n = 19). The subjects in the former two groups were trained for an hour twice a week for 12 weeks. No training was provided to the controls. The outcome measures were large and small arterial compliance, blood pressure, and heart rate variability (normalized low and high frequency power and the low frequency to high frequency ratio). Assessments were conducted before and after the intervention period. Two-way mixed analysis of variance was employed to compare the three intervention groups and the two assessment time points.

Results

On average, small arterial compliance increased about 13.5% after Tai Chi training and about 9.5% after the conventional exercise training. It decreased among the controls (-10.6%). A significant improvement in average systolic blood pressure, from 129.2 ± 17.3 mmHg in the pre-assessment to 125.0 ± 18.6 mmHg in the post-assessment, was also observed after the Tai Chi training, while no significant change was found in the other two groups. No significant change was observed in the heart rate variability parameters in any of the three groups.

Conclusions

Tai Chi training may benefit stroke survivors by decreasing small artery stiffness and reducing systolic blood pressure. However, the short term Tai Chi training did not improve cardiac autonomic regulation in this population.

Keywords

Tai Chi; stroke; arterial compliance; blood pressure; cardiac autonomic regulation; heart rate variability; randomized controlled trial

3.5.2 Introduction

Prior studies have shown that increased arterial stiffness (Sugioka et al., 2002; Tuttolomondo et al., 2011) and dysfunction of the cardiac autonomic nervous system (Dorrance & Fink, 2015; Francica et al., 2015; Sörö & Hachinski, 2012) are relatively common among stroke survivors. Such changes raise the risk of cardiovascular problems and tend to accelerate mortality (Calvet et al., 2014; Dorrance & Fink, 2015; Kim et al., 2014; Micieli & Cavallini, 2008; Xiong et al., 2013). Aerobic exercise has been suggested to reduce arterial stiffness (Cameron & Dart, 1994; Fujimoto et al., 2010; Seals et al., 2008; Tanaka et al., 2000) and improve cardiac autonomic modulation (Chang et al., 2008; De Meersman & Stein, 2007; Micieli & Cavallini, 2008; Muellen, 2007) of healthy subjects.

Tai Chi is a traditional Chinese martial art which has been employed as a rehabilitation exercise in recent decades. Previous studies have reported its effect on arterial compliance (Lu et al., 2013a) and cardiac autonomic regulation (Audette et al., 2006; Chang et al., 2008) among older adults. Tai Chi is considered a mind-body exercise of moderate intensity with aerobic features (Lan et al., 1996). When practicing Tai Chi, the practitioner should maintain a relaxed state of mind and breathe slowly but deeply. These features have been found to reduce arterial stiffness (Cameron & Dart, 1994; Clarkson et al., 1999; De Meersmann & Stein, 2007; DeSouza et al., 2000; Micieli & Cavllini, 2008; Muellet, 2007; O’Rourke & Hashimoto, 2008; Sakuragi & Abhayaratna, 2010; Seals et al., 2008) and benefit the regulation of sympathetic and parasympathetic activities (Cole et al., 2010; Figueroa et al., 2012; Fong et al., 2015; Lu & Kuo, 2014) among healthy older adults.

Tai Chi benefits arterial stiffness and cardiac autonomic regulation among healthy older adults suggests that the exercise may also benefit stroke survivors. This randomized controlled trial was therefore designed to explore the effect of Tai Chi training on arterial stiffness and functioning of cardiac autonomic nervous system among stroke survivors. The expectation was that subjects being trained in Tai Chi would show reduced arterial stiffness and improved autonomic modulation of the heart. Owing to the unique features of this mind-body exercise, Tai Chi was expected to be more beneficial than conventional exercise.

3.5.3 Methods

3.5.3.1Participants

This study was an assessor-blinded randomized controlled trial. It was registered at ClinicalTrials.gov (Registration number: NCT03252236). The study was conducted from October 2014 to December 2016. Community-dwelling stroke survivors were recruited through patient self-help groups and hospitals in Hong Kong. Subjects were included if they were aged at least 50, had suffered a stroke at least six months previously, were able to walk unaided for five meters indoors, and were able to follow verbal instructions. Those suffered from any neurological disease other than stroke, had received any cardiac surgery, had received any major surgery during the previous six months or who scored less than 18 on the Cantonese version of the Mini-Mental State Examination (Lam et al., 2008) were excluded. This study was approved by the Ethics Committee of the Hong Kong Polytechnic University (Reference number: HSEARS20131023003). Written informed consent was obtained from every subject after the aims and procedures of the study had been fully explained. The intervention was conducted at the Hong Kong Polytechnic University and in community centers. The assessment was carried out at the university.

3.5.3.2 Intervention

There were three intervention groups: Tai Chi group, conventional exercise group, and control group. Eligible subjects were first stratified according to their gender and age (aged 50–59, 60–69, 70–79, or ≥80 years old) and then randomized into one of the three intervention groups by drawing lots.

Subjects in the Tai Chi and conventional exercise groups were trained in hour-long sessions twice a week for 12 weeks. They were also asked to practice outside of the class for at least 30 minutes once a week. Exercise log-books were given to the subjects in which they were instructed to record the amount of self-training. The class began with a 10-minute warm-up, followed by 45 minutes of the corresponding exercises and a 5-minute cooling down period.

3.5.3.2.1 Tai Chi group

According to the ability and needs of the stroke survivors, traditional Yang-style Tai Chi was modified into 12 forms (Table 3.3.1, p.111; Appendix II, p.188–193) by a senior physiotherapist and a Tai Chi master with more than 30 years of experience in teaching Tai Chi. The training was instructed by another physiotherapist who is also a Tai Chi practitioner. The class size was limited to 10 participants in order to provide adequate supervision for each subject and to ensure safety. Physical support and standby assistance by the instructor were provided if necessary. The support was gradually withdrawn once the subjects were able to maintain balance on their own. Resting periods were allowed whenever needed. During the training, the subjects were encouraged to breathe slowly and deeply. They were also asked to concentrate and relaxed during the practice.

3.5.3.2.2 Conventional exercise group

The subjects in the conventional exercise group performed exercises included mobilization, stretching, muscle strengthening and walking (Appendix III, p.194). The same physiotherapist who conducted the Tai Chi classes instructed the class. No specific instructions were given on the breathing pattern, concentration, or relaxation.

3.5.3.2.3 Control group

No training was provided to subjects in the control group. They were also not encouraged to do any special exercise during the study period, but were allowed to continue any physical activities they had been practicing before enrolling in the study. After the completion of all the assessments, the subjects in this group were given the Tai Chi training.

3.5.3.3 Assessment

Demographic data and information related to the stroke were collected at baseline. The presence of any comorbidity that might affect arterial compliance and cardiac autonomic regulation including hypertension, cardiovascular diseases, diabetes mellitus, and dyslipidemia were recorded (Cavalcante et al., 2011). Any changes in these conditions and the medication the subjects were taking were tracked during the study period along with the regular exercise habits of all the subjects.

Assessments were conducted before the experiment and after the entire intervention period. The measurements were carried out between 9 am and 1 pm in a controlled environment kept at 22 ± 1 °C. The subjects were instructed to refrain from consuming beverages containing alcohol or caffeine and to avoid aerobic exercise during the day before the measurements. Subjects rested in a supine posture for at least 10 minutes before being assessed (Laurent et al., 2006; Nickel et al., 2011; Xiong et al., 2013).

3.5.3.3.1 Arterial compliance and blood pressure

Arterial stiffness was measured with a non-invasive CR-2000 cardiovascular profiling system (Hypertension Diagnostics, Inc., Eagan, Minnesota, USA). Brachial blood pressure was measured with a conventional blood pressure cuff positioned around the subject's upper arm on the affected side while lying supine. An arterial tonometer sensor was placed over the wrist of the less-affected arm where the radial pulsation was the maximum to record the waveforms in the artery for 30 seconds. The wrist was stabilized to minimize any movement during the measurements. The diastolic decay of the waveforms was analyzed to calculate the compliance of the large and small arteries by applying a modified Windkessel model (Cohn, 2006; Cohn et al., 1995; Nichols et al., 2011). The measurements were conducted three times, and the averages of the large and small arterial compliance and the brachial systolic and diastolic blood pressure were treated as outcome measures. This method of measuring arterial compliance has been validated and shown to have good repeatability (Prisant et al., 2002; Zimlichman et al., 2005).

3.5.3.3.2 Cardiac autonomic regulation

Autonomic regulation of the heart was evaluated in terms of heart rate variability. The RR interval was recorded for five minutes with the subject supine using a Model RS800 heart rate monitoring instrument (Polar Electro Ltd., Kempele, Finland). That device has been shown to be validated and reliable (Nunan et al., 2009). The variability in the RR interval was transformed into the frequency domain of heart rate variability using a fast Fourier transform spectral analysis algorithm (version 13.2.2, Nevrokard, Slovenia). Low frequency (0.04 – 0.15 Hz) and high frequency (0.15 – 0.40 Hz) power spectral densities were generated. The low and high frequency power were normalized using the total power, and together with the low frequency to high frequency ratio were employed as the outcome measures. The high frequency power of heart rate variability has been suggested to represent parasympathetic activity, while the low frequency power reflects both sympathetic and parasympathetic activities. The low frequency to high frequency ratio has been regarded as an indicator of the balance between the sympathetic and parasympathetic activities (Task Force of the European Society of Cardiology, the North American Society of Pacing Electrophysiology, 1996).

3.5.3.4 Statistical analysis

Baseline comparisons among the three groups were conducted using one-way analysis of variance (ANOVA) for the continuous data and chi-squared values for the categorical data. Two-way mixed ANOVA (group x time) was employed to compare the three intervention groups and the two assessment time points. Post-hoc analysis was adjusted for the least significant difference. The significance level was set at 0.05. Missing data were handled by carrying forward the last observation according to the intention-to-treat method. Subjects who changed their medications for treating hypertension, diabetes mellitus, dyslipidemia, cardiac disease or any blood-related problems were treated as having dropped out from the study. Any parameter found significantly different among the three groups in the baseline measurement was treated as a covariate in the two-way mixed ANOVA.

3.5.4 Results

Figure 3.5.1 shows the CONSORT diagram describing the study. Eighty-eight subjects were enrolled initially. After screening for eligibility, 56 subjects were randomized into the Tai Chi group (n = 19), the conventional exercise group (n = 18), or the control group (n = 19). There was a significant difference in the number of subjects who suffered from diabetes mellitus among the three groups so that the factor is treated as a covariate. Table 3.5.1 presents demographic data describing the subjects.

No adverse effects related to the assessment or the interventions were reported.

Figure 3.5.1 CONSORT diagram

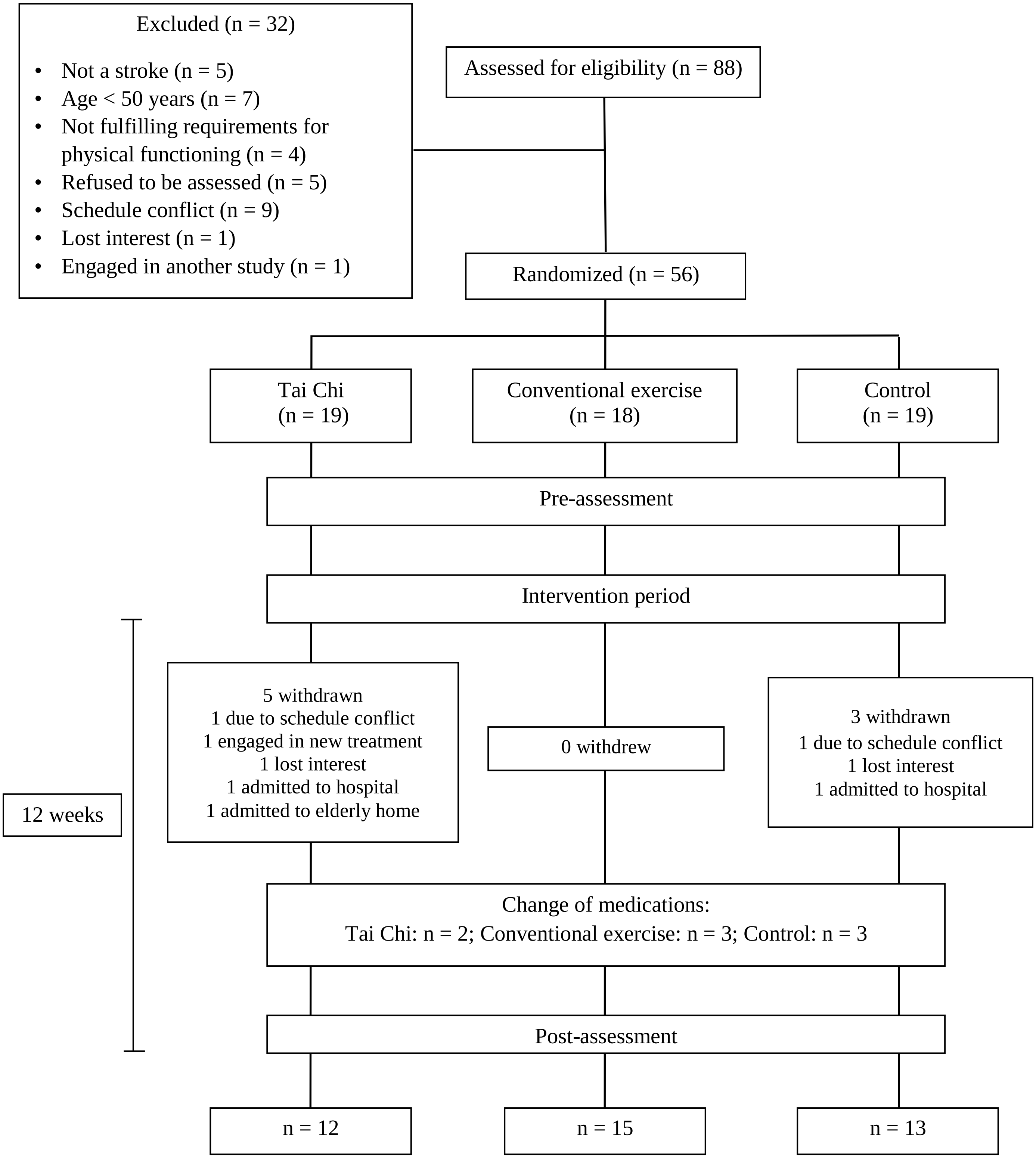


Table 3.5.1 Demographic and clinical characteristics of the subjects

		Tai Chi (n = 19)	Conventional exercise (n = 18)	Controls (n = 19)	*p*-value
Age (years)		64.2 ± 8.2	62.2 ± 7.4	61.8 ± 7.3	0.584
Gender (male : female)		10 : 9	10 : 8	8 : 11	0.688
Height (cm)		161.4 ± 7.0	163.3 ± 9.5	160.3 ± 7.0	0.516
Weight (kg)		60.9 ± 8.1	64.1 ± 10.1	57.4 ± 11.2	0.132
Comorbidities (number)					
	Hypertension	14	11	11	0.500
	Diabetes mellitus	7	7	1	0.024*
	Dyslipidemia	9	9	10	0.981
	Cardiac disease	3	7	1	0.138
Chronicity (years)		5.6 ± 6.4	9.5 ± 11.9	5.3 ± 4.1	0.226
Affected side	Right	9	7	8	0.870
	Left	10	11	11	
Number of strokes	1	14	14	16	0.631
	2	4	2	2	
	3	0	1	1	
	> 3	1	1	0	
Type of stroke	Ischemic	14	10	12	0.377
	Hemorrhage	3	6	7	
	Both	2	2	0	
Attendance (out of 24 sessions)		21.3 ± 3.6	19.3 ± 3.8	/	0.124

Values are in means ± standard deviation
* denotes a significant difference between the Tai Chi group and the control group or between the conventional exercise group and the control group

3.5.4.1 Arterial compliance and blood pressure

Table 3.5.2 presents the blood pressure and arterial compliance results. The average small arterial compliance was significantly lower in the Tai Chi group than in either of the other groups at baseline. Those data were therefore treated as a covariate in the statistical analysis.

A significant interaction effect was found in the small arterial compliance data [*F* (2,49) = 4.26, *p* = 0.02]. Follow-up analysis revealed that the control group differed from the Tai Chi group (*p* = 0.01) and the conventional exercise group (*p* = 0.02) in the post-assessment when the baseline values and the number of diabetic subjects in each group were treated as covariates. Both the Tai Chi group and the conventional exercise group showed increases in the average small arterial compliance (of 13.5% and 9.5%, respectively), while a reduction was observed in the controls (-10.6%). Moreover, the change in small arterial compliance was significant in the Tai Chi group (*p* = 0.05). No significant between-subject or within-subject differences in large arterial compliance were observed.

Significant within-subject changes in systolic blood pressure [*F* (1,49) = 3.14, *p* = 0.05] were observed. Follow-up analysis showed a reduction in average systolic blood pressure in the Tai Chi group after the intervention (*p* = 0.004). No significant change was detected in the conventional exercise or control group averages. In the post-assessment, however, there was no significant difference among the three groups. There was a significant group difference in diastolic blood pressure [*F* (2,49) = 4.149, *p* = 0.02]. Further analysis revealed a significantly lower value in the conventional exercise group than the control group (*p* = 0.003).

Table 3.5.2 Changes in arterial compliance and blood pressure

	Tai Chi (n = 19)		**Conventional exercise (n = 18)**		**Control (n = 19)**		***F*-value (*p*-value)**		
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Between-subject effect**	**Within-subject effect**	**Interaction effect**
Large arterial compliance (ml/mmHg*10)	10.8 ± 4.3	10.9 ± 4.3	12.5 ± 3.6	13.4 ± 4.4	12.0 ± 2.8	11.5 ± 3.0	1.05 (0.35)	1.15 (0.29)	1.30 (0.28)
Small arterial compliance (ml/mmHg*100)	3.7 ± 2.0^{a,c}	4.2 ± 2.2^{b,c}	4.2 ± 2.0^{a}	4.6 ± 2.4^{b}	4.7 ± 2.0^{a}	4.2 ± 2.1^{b}	0.61 (0.44)	1.34 (0.25)	4.26 (0.02)*
SBP (mmHg)	129.2 ± 17.3^{c}	125.0 ± 18.6^{c}	120.5 ± 10.5	118.5 ± 8.1	120.1 ± 13.5	120.1 ± 15.8	0.94 (0.40)	0.62 (0.44)	3.14 (0.05)*
DBP(mmHg)	70.8 ± 7.6	70.3 ± 7.6	66.9 ± 5.9	65.8 ± 5.8^{d}	70.8 ± 7.3	71.7 ± 8.1^{d}	4.15 (0.02)*	2.34 (0.13)	1.30 (0.08)

Values are in mean ± standard deviation; Pre = pre-assessment; Post = post-assessment; SBP = systolic blood pressure; DBP = diastolic blood pressure

* denotes a significant effect in two-way mixed ANOVA ($p \leq 0.05$)

[a] denotes a significant difference between the Tai Chi group and the control group or between the conventional exercise group and the control group in the pre-assessment ($p \leq 0.05$)

[b] denotes a significant difference between the Tai Chi group and the control group or between the conventional exercise group and the control group in the post-assessment ($p \leq 0.05$)

[c] denotes a significant difference between the pre-assessment and the post-assessment ($p \leq 0.05$)

[d] denotes a significant difference between the conventional exercise group and the control group in the post-assessment ($p \leq 0.05$)

3.5.4.2 Cardiac autonomic regulation

Table 3.4.3 presents the heart rate variability data. No significant changes were observed either within a group or among the three groups.

Table 3.4.3 Changes in heart rate variability

	Tai Chi (n = 19)		Conventional exercise (n = 18)		Control (n = 19)		*F*-value (*p*-value)		
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Between-subject effect**	**Within-subject effect**	**Interaction effect**
nLF (nu)	47.9 ± 24.8	45.7 ± 18.4	42.6 ± 16.8	44.7 ± 18.6	42.3 ± 19.4	45.4 ± 17.6	0.25 (0.78)	0.13 (0.72)	0.11 (0.90)
nHF (nu)	40.5 ± 22.4	43.0 ± 16.5	45.8 ± 17.4	45.2 ± 19.3	48.5 ± 17.6	45.9 ± 16.8	0.34 (0.72)	0.28 (0.60)	0.14 (0.87)
LF/HF	2.2 ± 2.3	1.6 ± 1.5	1.3 ± 1.2	1.6 ± 2.2	1.3 ± 1.4	1.4 ± 1.6	0.42 (0.66)	0.16 (0.70)	1.12 (0.34)

Values are means ± standard deviation; Pre = pre-assessment; Post = post-assessment; nLF = normalized low frequency; nHF = normalized high frequency; LF/HF = the ratio of low frequency to high frequency

3.5.5 Discussions

After adjusting for the baseline differences, the subjects in the Tai Chi and conventional exercise groups showed significantly greater small arterial compliance than the controls after the interventions. Indeed, the data demonstrate enhanced small arterial compliance in the Tai Chi and conventional exercise groups, but a decline in the control group. The subjects in the Tai Chi group also showed a significant reduction in average systolic blood pressure after the training. However, no significant change was observed in their average large arterial compliance, diastolic blood pressure or heart rate variability after the 12 weeks of training.

The difference in average arterial stiffness among the three groups observed in the post-assessment may imply a beneficial effect of Tai Chi and conventional exercise in terms of delaying the deterioration of small arterial compliance among stroke survivors. These results agree with those of prior studies focusing on elderly women (Lu et al., 2013a) and women with rheumatoid arthritis (Shin et al., 2015). Small arterial compliance has been suggested as an independent predictor of cardiovascular events (Grey et al., 2003). Improving it may also protect organs such as the brain, which have low vascular resistance to stress, from large pressure force (Kim et al., 2016). Slowing the process of small artery stiffening through Tai Chi or other training may therefore reduce the risk of cardiovascular disease and the recurrence of stroke among stroke survivors. The lack of any significant difference between the Tai Chi group and the conventional exercise group implies that the two types of training have similar effects on small arterial compliance.

The observed changes in small arterial compliance may be explained by the aerobic nature of the exercises. Moderate intensity exercises like Tai Chi (Lan et al., 1996) have been shown to decrease arterial stiffness (Cameron & Dart, 1994; Fujimoto et al., 2010; Seals et al., 2008; Tanaka et al., 2000). The exact mechanism of that effect is still not completely understood, but it is generally accepted that improved endothelial function and increased bioavailability of nitric oxide in the arterial system may be involved (Cameron & Dart, 1994; Clarkson et al., 1999; DeSouza et al., 2000; O'Rourke & Hashimoto, 2008; Sakuragi & Abhayaratna, 2010; Seals et al., 2008). Indeed, prior studies have documented better endothelial function in older, experienced Tai Chi practitioners (Wang et al., 2002) and in women with rheumatoid arthritis after three months of Tai Chi training (Shin et al., 2015). Another study has shown that 12 weeks of Tai Chi training can upregulate nitric oxide in the blood among patients with untreated hypertension (Pan et al., 2015). These studies may provide some insight into how Tai Chi training would enhance arterial compliance. Nevertheless, further studies have to be conducted to elucidate the exact mechanisms involved.

In contrast to small arterial compliance, no significant difference in large arterial compliance was observed in comparing the three groups. Previous studies have suggested that the effect of aging in terms of structural changes in the arterial system is more prominent in the large than in the small arteries. The large arteries may therefore take longer to show any significant change in response to exercise training (Cameron & Dart, 1994; Cohn, 2006; Nickel et al., 2011; Seals et al., 2008; Tanaka et al., 2000). Whether a longer period of Tai Chi training would benefit large arterial compliance needs to be further investigated.

A recent meta-analysis has suggested that Tai Chi training can lower blood pressure among healthy older adults (Zheng et al., 2015). The results of this study probably extend that finding to stroke survivors. However, it should be pointed out that no significant difference was found among the three groups in the post-assessment. So, the hypothesis that Tai Chi is better than the conventional exercise in terms of blood pressure control was not supported in this study.

The hypothesized improved cardiac autonomic regulation also was not supported by the data. Previous clinical trials have demonstrated a significant decrease in the low frequency power and a significant increase in the high frequency power of heart rate variability after Tai Chi training (Audette et al., 2006; Chang et al., 2008). That would imply a reduction in sympathetic activity and enhanced parasympathetic activity. The mechanisms proposed for such effects refer to the slow and deep breathing (Figueroa et al., 2012; Lu & Kuo, 2003, 2014) and concentration and relaxation (Curiati et al., 2005; Fong et al., 2015; Lazar et al., 2000) involved during Tai Chi practice. All of the subjects in this study displayed some degree of physical disability. It is possible that they needed more attention to maintain balance and longer practice to acquire good Tai Chi technique. Thus, they may not have been able to focus sufficiently on relaxation and slow, deep breathing during the practice. Indeed, prior studies of older people with no physical impairment have found that it took a total of 36 hours of Tai Chi training to generate a significant improvement in heart rate variability (Audette et al., 2006; Chang et al., 2008). That is 12 hours more than in this study. Future investigation employing a longer training period and better emphasizing concentration, relaxation, and slow, deep breathing is needed if autonomic regulation is the main concern.

3.5.6 Limitations

In interpreting these results, it is important to recall that the subjects were self-recruited. They probably represent a more active group within the population. In addition, the requirement that they be able to walk five meters unaided indoor may have eliminated many more feeble yet otherwise typical stroke survivors. These selection biases tend to limit the generalizability of the study's results only to relatively able stroke survivors. Another limitation is the small sample size. Further studies with a larger sample are needed because with this small sample, sub-group analysis based on the side and location of the stroke were not possible (Sörös et al., 2012). A limitation related to the assessment is that the breathing rate was not controlled. It is known to affect heart rate variability (Lu & Kuo, 2014). However, slow and deep breathing is an intrinsic characteristic of Tai Chi, so controlling the breathing rate during the assessment may have biased the heart rate variability results.

3.5.7 Conclusions

The data suggest a beneficial effect of Tai Chi training in terms of delaying the decline in small arterial compliance and reducing systolic blood pressure among stroke survivors. These effects were not, however, significantly better than those achievable through conventional exercise. The data were insufficient to support the expectation that short-term Tai Chi training would improve cardiac autonomic regulation in this population. Studies with a larger sample and employing a longer term of Tai Chi training are warranted. The mechanisms of the effects of Tai Chi on arterial compliance and cardiac autonomic regulation also require further exploration.

CHAPTER 4

GENERAL DISCUSSION

4.1 Summary of the findings and discussion

The main objectives of stroke rehabilitation are to regain daily function and prevent cardiovascular disease. Dual-tasking is a common daily activity. It has also been related to both falls and functional ability in stroke survivors.

Tai Chi is a dual-tasking exercise requiring its practitioners to perform physical movement and maintain balance while memorizing and planning the Tai Chi forms. Further, Tai Chi is a mind-body exercise that may benefit cardiovascular function. It therefore seems that the features of Tai Chi meet the aims of stroke rehabilitation. This study, therefore, is designed to explore the effects of Tai Chi training on both dual-tasking performance and cardiovascular function in stroke survivors.

There were two phases to this study. The first was a cross-sectional study investigating how stroke survivors responded to dual-tasking. The second was a randomized controlled trial that examined the effect of Tai Chi training on both dual-tasking performance and cardiovascular function in stroke survivors.

The first phase of the study investigated how stroke survivors reacted to dual-tasking challenges in two situations. The first was an auditory Stroop test combined with a turning-while-walking test. The other was the same cognitive test combined with a stepping down test. The results showed that stroke survivors tended to compromise the cognitive task performance to preserve physical stability when dual-tasking.

While previous research on dual-tasking in stroke survivors focused on straight line walking, this study is the first to involve stepping down as the physical task. The results of this study also provide new information on how stroke survivors react to dual-tasking that involves turning-while-walking with no specific instruction on task prioritization, reflecting their natural response.

The decrease in performance when dual-tasking can be explained by the theory of competition for attentional resources (Al-Yahya et al., 2011; Woollacott & Shumway-Cook, 2002). Stroke survivors may not either have sufficient attentional resources or be able to allocate resources properly when conducting two tasks simultaneously, at least in these combinations of tasks. The increased demand for resources to carry out the individual tasks may also contribute to the decline in dual-tasking ability. The result that performance of the cognitive task was degraded but not performance of the physical task was unexpected. However, these results may imply that stroke survivors employed a posture-first strategy to maintain balance and prevent falling while dual-tasking (Kizony et al., 2010; Lacour et al., 2008; Yogev-Seligmann et al., 2012).

Like the stroke survivors in this study, in previous investigations healthy older adults also compromised cognitive task performance to maintain physical balance when stepping down with a concurrent cognitive task (Lu et al., 2013b; Telonio et al., 2014; Tsang et al., 2013). Conversely, those studies that involved turning-while-walking revealed a different conclusion; there was a reduction in physical task performance when dual-tasking (Hollands et al., 2014; Manaf et al., 2014a, 2014b, 2017). The discrepancy could be explained by the instructions given regarding task prioritization (Jansen et al., 2016) and the cognitive task being such that internal or external interference was involved (Al-Yahya et al., 2011). However, further studies are needed to investigate the effect of these factors on dual-tasking performance in stroke survivors.

When compared with non-stroke controls, stroke survivors showed a significantly poorer performance in both single-tasking and dual-tasking situations. The results were in accord with our hypothesis that this is caused by the cognitive and physical impairments after a stroke. Dual-tasking performance is related to falling (Baetens et al., 2013), balancing ability (Manaf et al., 2014a), and gait performance (Plummer-D’Amato & Altmann, 2012). Additionally, the mean turning duration for stroke survivors in this study was more than the cutoff for turning difficulties (3.18 ± 0.28 sec) (Thigpen et al., 2000). Further, stroke survivors swayed more than controls when stepping down. The reduced performance found in stroke survivors, regardless of single-tasking or dual-tasking, is noteworthy especially for rehabilitation assessment and treatment.

The second phase of this study was a randomized controlled trial investigating the effects of Tai Chi training on dual-tasking ability and cardiovascular functioning in in stroke survivors. Subjects with stroke were randomized into one of three groups with either Tai Chi training, conventional exercise or the control group. Those in the former two groups received two one-hour training sessions each week, with a total of 24 sessions. The Tai Chi training focused on dual-tasking, deep and slow breathing, concentration, and relaxation. By contrast, subjects in the conventional exercise group were instructed to follow the instructor’s movement with minimal involvement of cognition, concentration, and relaxation. No training was provided to the subjects in the control group during the intervention period. The two dual-tasking situations used in the cross-sectional part of this study were used to investigate the effect of Tai Chi training. Cardiovascular function was evaluated by arterial compliance, blood pressure, and cardiac autonomic regulation. Assessments were conducted before, immediately after, and one month after the intervention period. Comparisons were made within the group across the assessments and across the three groups.

For the dual-tasking tests, subjects in the Tai Chi group showed improved performance in the auditory Stroop test in both the post-assessment and 1-month follow-up assessment and a decreased completion time for the turning-while-walking test in the follow-up assessment. Improvement in the auditory Stroop test was also observed for dual-tasking conditions involving the stepping down test. Moreover, subjects in the Tai Chi group showed a significantly higher composite score for the cognitive task than did those in the conventional exercise group when dual-tasking during the follow-up period. However, single-tasking performance was similar after the Tai Chi training. On the other hand, no significant change was found in dual-tasking performance between the conventional exercise group and the control group, although subjects in the conventional exercise group demonstrated significant improvements in the single auditory Stroop test and single turning-while-walking test.

This study was the first to investigate the effect of Tai Chi training on dual-tasking performance in stroke survivors. The strength of this study is the inclusion of both an exercise control group and a passive control group. Previous studies of this topic among healthy older adults (Hall et al., 2009; Lu et al., 2013b; Manor et al., 2014; Wayne et al., 2015) and stroke survivors that investigated different functioning (Au-Yeung et al., 2009; Kim et al., 2015) involved only a Tai Chi group and a control group.

According to the theory of competition for attentional resources (Al-Yahya et al., 2011; Lacour et al., 2008; Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2012), the improved dual-tasking performance after Tai Chi training may be explained by increased attentional resources being available for dual-tasking (Wei et al., 2013), or by the ability to allocate resources properly when dual-tasking (Fong et al., 2014). Further, as single-tasking performance is similar after the intervention, the enhancement of dual-tasking ability is not likely to be due to a decreased demand for attentional resources from the individual tasks. However, the exact mechanisms of improvement of dual-tasking ability after the Tai Chi training warrant further investigation.

The effect of Tai Chi training on dual-tasking performance involving stepping down was greater than that of conventional exercise. However, it must be acknowledged that the sample size was small and further studies with a larger sample should be conducted. The nature and learning processes of the two types of exercise may explain the resulting difference in dual-tasking performance. Subjects in the Tai Chi group were encouraged to memorize and concentrate on the Tai Chi movement to maximize the dual-tasking feature of this training. On the other hand, those in the conventional exercise group were only required to follow the instructor’s movements and the exercises were therefore of single-tasking in nature. This dual-tasking feature of Tai Chi may therefore explain the better results in the group. Further, it has been suggested that explicit learning, which involves cognitive functions to learn a new skill intentionally, is more effective at improving dual-tasking ability than implicit learning, which does not require attention (Caljouw et al., 2016). Thus, the explicit learning process of Tai Chi movement and the implicit learning of the conventional exercise training may contribute to the study results. Certainly, previous studies did not demonstrate any effect of single-tasking exercise on dual-tasking ability (Agmon et al., 2014; de Haart et al., 2004; Gobbo et al., 2014; Roerdink et al., 2006, 2009). Consequently, Tai Chi may not improve dual-tasking performance effectively if it is learned implicitly, (i.e., rich visual and verbal instructions are provided so that the subjects only have to follow the instructor’s movement) (Hall et al., 2009). However, further studies are needed to test how the instruction strategy and learning method affect the effect of Tai Chi training on dual-tasking performance.

The improved effect of Tai Chi training over conventional exercise was only observed in dual-tasking involving stepping down, but not in turning-while-walking. A possible explanation is that the effect of Tai Chi training on dual-tasking may be more obvious when the task is more challenging, as stepping down is when compared with the turning-while-walking test in this study. Also, the mean completion time of the timed up-and-go test was 16.5 sec among subjects in the turning-while-walking part (Table 3.3.2, p.117) but in the stepping down was 13.5 sec (Table 3.4.1, p.137). It has been suggested that older adults who took 13.5 second or more to complete the test have a higher risk of falling (Shumway-Cook et al., 2000). The difference in the risk of falling may affect the effectiveness of Tai Chi training in improving dual-tasking performance. Nevertheless, these explanations are only speculative. Further studies are required to examine the effect of Tai Chi training on various combinations of dual-tasking.

The improved dual-tasking performance of the Tai Chi group demonstrated in this study may suggest a transfer effect between Tai Chi training and other combinations of dual-tasking. The transfer effect of dual-task training is important as there are numerous combinations of dual-tasking in the daily life. However, no study has supported the transfer effect of a specific type of dual-task training. It has been suggested that training that includes the participation of executive function and variation in the distribution of attentional resources facilitates the transfer effect of dual-tasking exercise (Lussier et al., 2017). Although the types of cognitive functioning involving during Tai Chi practice has not been studied, previous research demonstrated improved executive function after Tai Chi training (Kasai et al., 2010; Nguyen & Kruse, 2012; Taylor-Piliae et al., 2010; Wayne et al., 2014). In addition, as discussed in section 1.2.1.3 (p.45–47), subjects had to shift their attention between physical movement and cognitive functioning according to the complexity and demand for maintaining physical balance of a particular Tai Chi form. These features may therefore explain the transfer effect of Tai Chi to different types of dual-tasking as shown in this study. The exact mechanisms of the transfer effect after Tai Chi training is worthy of further investigation.

The third part of the randomized controlled trial investigated the effect of Tai Chi training on the cardiovascular function of stroke survivors. Arterial compliance, blood pressure, and cardiac autonomic regulation were assessed before and after the intervention period. The results showed that small arterial compliance and systolic blood pressure were improved significantly after Tai Chi training. Conversely, large arterial compliance, diastolic blood pressure, and cardiac autonomic regulation were similar before and after the intervention. Although subjects in the Tai Chi group demonstrated a significantly greater improvement in small arterial compliance than the control group, this difference was not observed between the Tai Chi group and the conventional exercise group.

This was the first study to examine the effect of Tai Chi training on arterial compliance and heart rate variability in stroke survivors. The result of significant improvements in small arterial compliance and systolic blood pressure after the Tai Chi training was compatible with those of previous studies targeting at healthy older adults (Lu et al., 2013a; Zheng et al., 2015). As Grey et al. (2003) have suggested that small arterial compliance predicts cardiovascular events, this result infers that Tai Chi training may lower the risk of cardiovascular disease among stroke survivors. The exact mechanisms through which Tai Chi may benefit small arterial compliance warrant further study, but its aerobic feature may play a role (Cameron & Dart, 1994; Fujimoto et al., 2010; Seals et al., 2008; Tanaka et al., 2000). On the other hand, the lack of significant change in large arterial compliance can be attributed to the short intervention period (Cameron & Dart, 1994; Cohn et al., 2006; Nickel et al., 2011; Seals et al., 2008; Tanaka et al., 2000). Again, further studies are needed to see if such changes can be observed if long-term Tai Chi training is adopted.

No significant difference was noted in cardiac autonomic regulation as reflected by heart rate variability after Tai Chi training. The result contradicted previous studies targeting healthy older adults (Audette et al., 2006; Chang et al., 2008). It has been suggested that the advantageous effect of Tai Chi training on the autonomic nervous system is attributable to concentration and a relaxed state of mind (Curiati et al., 2005; Fong et al., 2015; Lazar et al., 2000) as well as to the slow and deep breathing pattern (Figneroa et al., 2012; Lu & Kuo, 2003, 2014). However, due to impaired physical and cognitive functions, subjects with stroke might find it difficult to focus on the physical movement and memorize the sequence of the Tai Chi forms. Therefore, they might not be able to maintain a peaceful mind and breathe slowly during practice. In addition, previous studies that showed an improvement in heart rate variability employed a total of 36 hours of Tai Chi training, 12 hours more than this study. The small amount of training may explain the discrepancy in the results but further research that employed a longer training period and higher training dosage is needed.

4.2 Limitations

There are several limitations to this study. The first is the small sample size. Stroke survivors who showed an interest in the study hesitated to enroll due to the perceived challenge of performing the Tai Chi movement, making subject recruitment difficult. Another limitation is that the subjects had a high level of cognitive and physical function, which may lead to selection bias and confine generalization of the study results to relatively high functioning stroke survivors. In addition, the training period and dosage may not be sufficient for the stroke survivors to acquire Tai Chi movements and techniques. However, a longer training period and higher dosage were not adopted in this study because of practical limitations. The initial plan for this study was to employ a training dosage of 1.5 hours per session, three sessions a week for 16 weeks. However, interested stroke survivors perceived that the amount of the training was too high and did not enroll. Therefore, the training dosage was decreased in the current study in order to encourage stroke patients to participate.

4.3 Clinical relevance

The compromised dual-tasking performance observed in stroke survivors demands concern in clinical practice. Stroke survivors who show difficulties in turning-while-walking or stepping down are required to be tested under these dual-tasking conditions when considering their integration into the community. However, further studies into the predictive value of dual-tasking ability involving the two physical tasks on functional independence and reduced incidence of falling are needed before considering these tests as part of routine clinical assessment.

The study also showed that Tai Chi practice is feasible and safe for stroke survivors, but sufficient safety measures must be provided. The training period and dosage employed in this study are enough to show some effects on dual-tasking, arterial stiffness, and systolic blood pressure but not on cardiac autonomic regulation. Training specificity may be important when delivering Tai Chi exercises to stroke survivors. Both the instructors and practitioners should be clear about the aims of the Tai Chi training and thus practice the exercise accordingly. For instance, the dual-tasking feature of Tai Chi should be emphasized when the training aim is to improve dual-tasking function. On the other hand, relaxation and deep breathing should be the focus of the training when the objective is to enhance autonomic regulation. However, further studies are needed to provide support for this argument. The results of this study did not show a superior training effect of Tai Chi over conventional exercise. Therefore, Tai Chi may be considered as an alternative exercise for stroke rehabilitation but not to the exclusion of conventional exercise training. Further studies are needed before recommending Tai Chi as a routine exercise for stroke rehabilitation, to determine the optimal amount of training, the underlying mechanisms for the beneficial effects of Tai Chi, and the cost-effectiveness of adopting the exercise into routine clinical practice.

4.4 Future research suggestions

Future studies with larger sample size and including more highly disabled stroke survivors are needed to improve the generality of the results. Research that employs a longer training period and a higher training dosage of Tai Chi is also justified. Most importantly, the mechanisms of how Tai Chi benefits dual-tasking ability and cardiovascular function in stroke survivors must be addressed. It is hoped that by understanding the mechanisms, health care providers and Tai Chi practitioners will know which features of the exercise should be emphasized during the Tai Chi practice to maximize its therapeutic effects and meet the aim of the training. Furthermore, studies that explore how dual-tasking performance and the effect of Tai Chi training in stroke survivors can be transferred to clinical practice, as discussed above, should be conducted.

CHAPTER 5

CONCLUSIONS

5 Conclusions

There were two phases in this study. The first was a cross-sectional study investigated dual-tasking performance in stroke survivors. The second was a randomized controlled trial that examined the effects of Tai Chi training on dual-tasking ability and cardiovascular function among stroke survivors. The following are the results:

- Stroke survivors tended to compromise performance of the auditory Stroop test in order to maintain balance when dual-tasking involving either turning-while-walking or stepping down.
- Stroke survivors performed worse than non-stroke controls under both dual-tasking conditions.
- The modified 12-form Tai Chi with adequate safety measures is feasible and safe to practice with stroke survivors.
- Tai Chi training is effective in improving the composite score of the auditory Stroop test under both dual-tasking conditions. Completion time of the turning-while-walking test when dual-tasking also reduced significantly after Tai Chi training. By contrast, no significant improvement in dual-tasking was found among subjects in either the conventional exercise group or the control group.
- The effect of Tai Chi training on dual-tasking performance that involved stepping down was better than that of conventional exercise. However, the sample size was small and further studies with a larger sample are needed. On the other hand, conventional exercise may improve single-tasking performance but not dual-tasking performance.

- Tai Chi training is effective in improving small arterial compliance and systolic blood pressure among stroke survivors. However, the training effects of Tai Chi practice were similar to those of conventional exercise.
- The current Tai Chi training dosage (1 hour per session, 2 times per week, for 12 weeks) is insufficient to improve cardiac autonomic regulation as measured by heart rate variability in the stroke survivors.
- Further studies with a larger sample size, a longer training period and higher training dosage are warranted. The underlying mechanisms on the potential training effect of Tai Chi on dual-tasking performance and cardiovascular function are also worthy of study.

APPENDICES

APPENDIX I Information sheet and consent form

INFORMATION SHEET

Effects of mind-body exercise on cardiovascular functions and dual-tasking performance in chronic stroke survivors – a randomized controlled trial

You are invited to participate in a study conducted by the Department of Rehabilitation Sciences in The Hong Kong Polytechnic University. The study is aiming at investigating the effects of Tai Chi training on cardiovascular function and balance performance during dual tasking in chronic stroke survivors. The study helps us to understand the relationship between such population and the aforementioned bodily functions. The project has been approved by the Human Subjects Ethics Sub-committee (HSESC) (or its Delegate) of The Hong Kong Polytechnic University (HSESC Reference Number: HSEARS20131023003).

Participants will be assessed on their cardiovascular functions and balance ability when performing a cognitive task. Researcher will explain the details of assessment beforehand. The assessment will last for around 2 hours and resting period will be given. Participants will then be randomized into either Tai Chi group or control group. Adapted Tai Chi or exercise will be practiced and instructors will adjust the movement according to individuals' needs. The intervention will last for 12 weeks, with 2 sessions per week and 1 hour per session. Second and third assessment will be carried out immediately after intervention and one month afterwards, respectively.

There will be no direct risk or benefit in participating in this study. You have every right to withdrawn from the study before or during the measurement without penalty of any kind. Your personal information and data will not be disclosed to any person not being in the research team. Your name or photo will not appear on any published materials.

If you would like to get more information about this study, please contact Dr. William Tsang Wai Nam on tel. no. 2766 6717 or Miss Chan Wing Nga on tel. no. 2766 6713. If you have any complaints about the conduct of this research study, please do not hesitate to contact Ms Gloria Man Wing Kam, Secretary of Research committee, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University on tel. no. 2766 4394.

Thank you for your interest in participating in this study.

Dr. William Tsang Wai Nam
Associate Professor
Department of Rehabilitation Sciences
The Hong Kong Polytechnic University

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

CONSENT TO PARTICIPATE IN RESEARCH

Effects of mind-body exercise on cardiovascular functions and dual-tasking performance in chronic stroke survivors – a randomized controlled trial

I ________________________ hereby consent to participate in the captioned research.

I understand that information obtained from this research may be used in future research and published. However, my right to privacy will be retained, i.e. my personal details will not be revealed.

The procedure as set out in the attached information sheet has been fully explained. I understand the benefit and risks involved. My participation in the project is voluntary.

I acknowledge that I have the right to question any part of the procedure and can withdraw at any time without penalty of any kind.

Name of participant ____

Signature of participant ____

Name of Parent or Guardian (if applicable) __________________________

Signature of Parent or Guardian (if applicable) _______________________

Name of researcher ____

Signature of researcher ____

Date ____

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

太極或運動訓練對患慢性中風長者的心血管功能及進行雙重活動時的平衡能力的影響：一個隨機控制實驗

理工大學康復治療科學系現正進行一項有關「太極或運動訓練對患慢性中風長者的心血管功能及進行雙重活動時的平衡能力的影響」的研究。是項研究旨在了解慢性中風長者在練習太極或運動訓練後，他們的心血管功能以及進行雙重運動時保持平衡的能力等是否有改善。這項研究的結果將有助我們了解太極及運動訓練的好處及當中的原理。本研究已通過理工大學康復治療科學系科研委員會 (HSESC) 的審批 (參考號碼: HSEARS20131023003) 。

本學系的研究人員將用隨機方法，安排閣下接受太極或運動訓練，訓練為期十二週，每週兩次，每次一小時。閣下將被邀請進行數項的測試，包括：動脈順應性、心跳率的變化性、腦部前額葉的帶氧水平和同時進行走下階梯及聽覺認知測試時的平衡能力。研究人員將會向閣下詳細解釋測試的方法。此身體檢查約需三小時，期間設有休息時間。測試將會在訓練前、後期及訓練後一個月進行。

此項研究不會帶來直接的風險或得益。您有權在任何時候、無任何原因之情況下放棄參與此次研究，而此舉將不會導致您受到任何懲罰或不公平的對待。您的資料也不會洩露予與此研究無關的人員，您的名字或相片亦不會出現在任何出版物上。

如閣下需要更多有關此項研究的資料，可以致電 2766 6717 來聯繫此次問卷調查的負責人，曾偉男博士。若您對此研究的科研人員有任何投訴，亦可以聯繫文詠琴女士（部門科研委員會秘書），電話：2766 4394。

多謝閣下參與此項研究。

曾偉男博士
香港理工大學康復治療科學系副教授

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

參與研究同意書

太極或運動訓練對患慢性中風長者的心血管功能及進行雙重活動時的平衡能力的影響：一個隨機控制實驗

本人____________________同意參與上述研究。

本人知悉此研究所得的資料可能被用作日後的研究及發表，但本人的私隱權利將得以保留，即本人的個人資料不會被公開。

研究人員已向本人清楚解釋列在所附資料卡上的研究程序，本人明瞭當中涉及的利益及風險；本人自願參與研究項目。

本人知悉本人有權就程序的任何部分提出疑問，並有權隨時退出而不受任何懲處。

參與者姓名 ______________________________________

參與者簽署 ______________________________________

家長或監護人(如適用) 姓名 _________________________

家長或監護人(如適用) 簽署 _________________________

研究人員姓名 _____________________________________

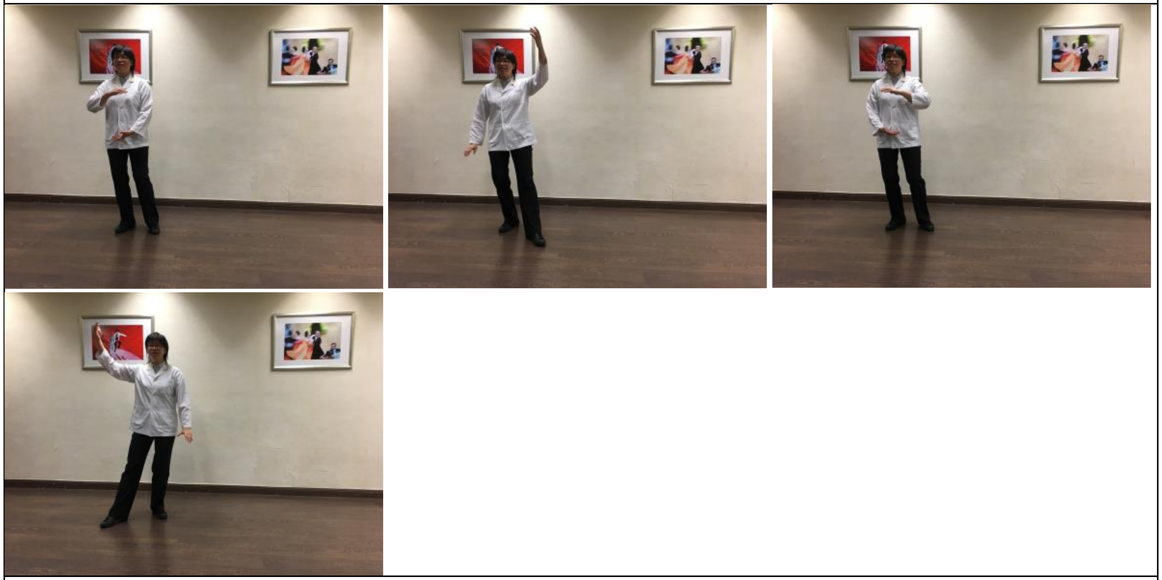
研究人員簽署 _____________________________________

日期 ____

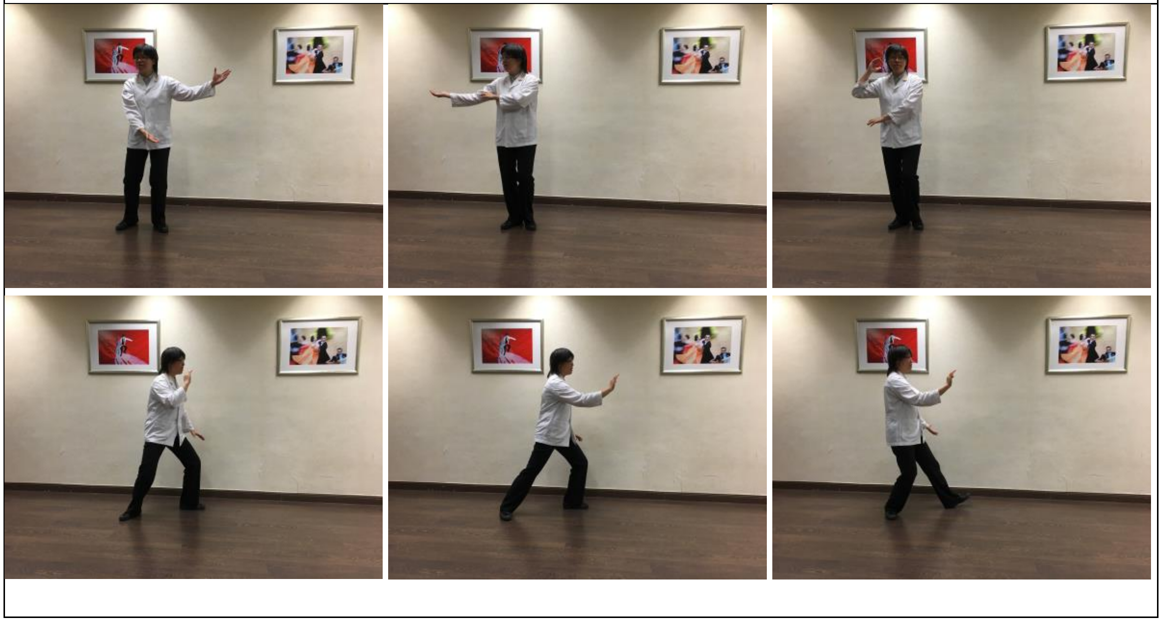
APPENDIX II Details of the 12-form Tai Chi

1. Commencing (起式)

2. White Crane Spreads Its Wings (白鶴亮翅)

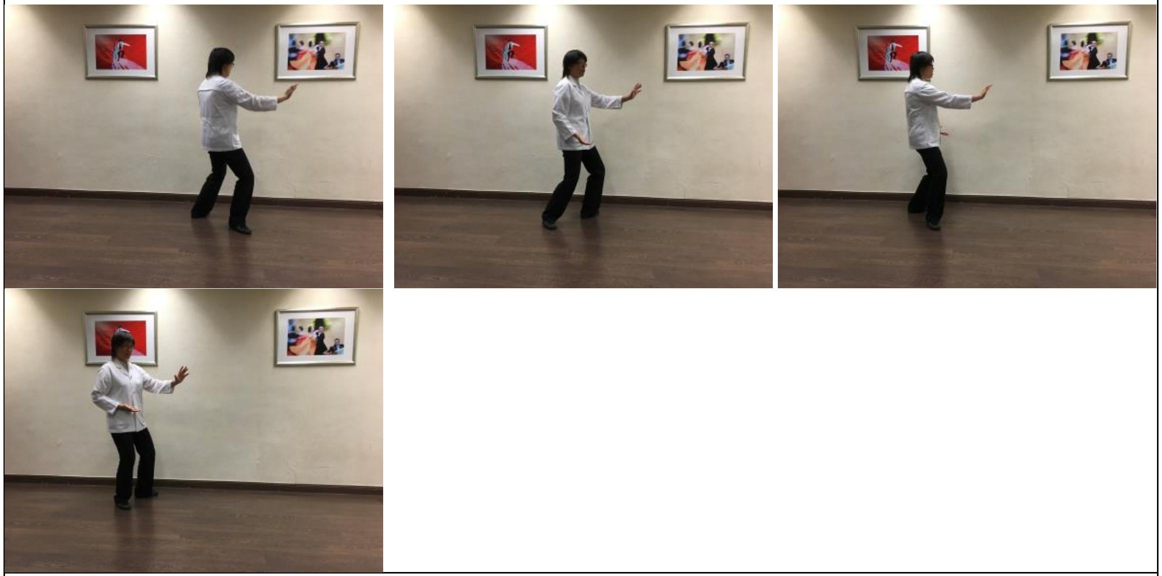


3. Brush Knee And Twist Step (摟膝拗步)

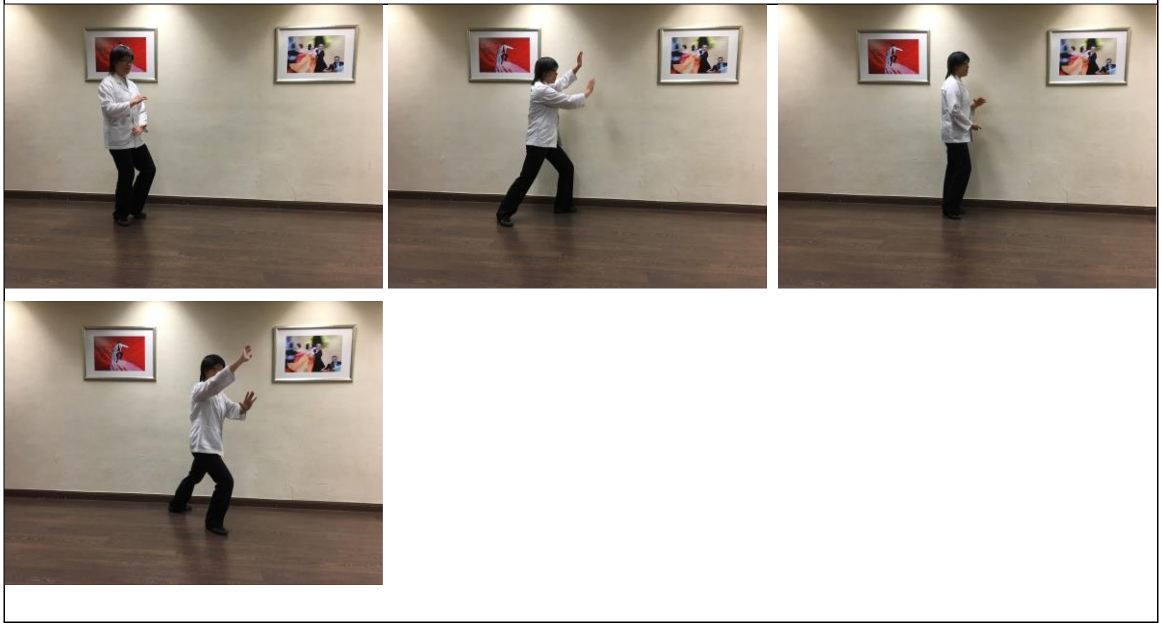


		
		
		
4. Hand Strums The Lute (手揮琵琶)		
		

5. Step Back And Whirl Arms (倒卷肱)



6. Work At Shuttles On Both Sides (左右穿梭)



7. Needle At The Sea Bottom (海底針)




8. Wave Hands In Clouds (雲手)



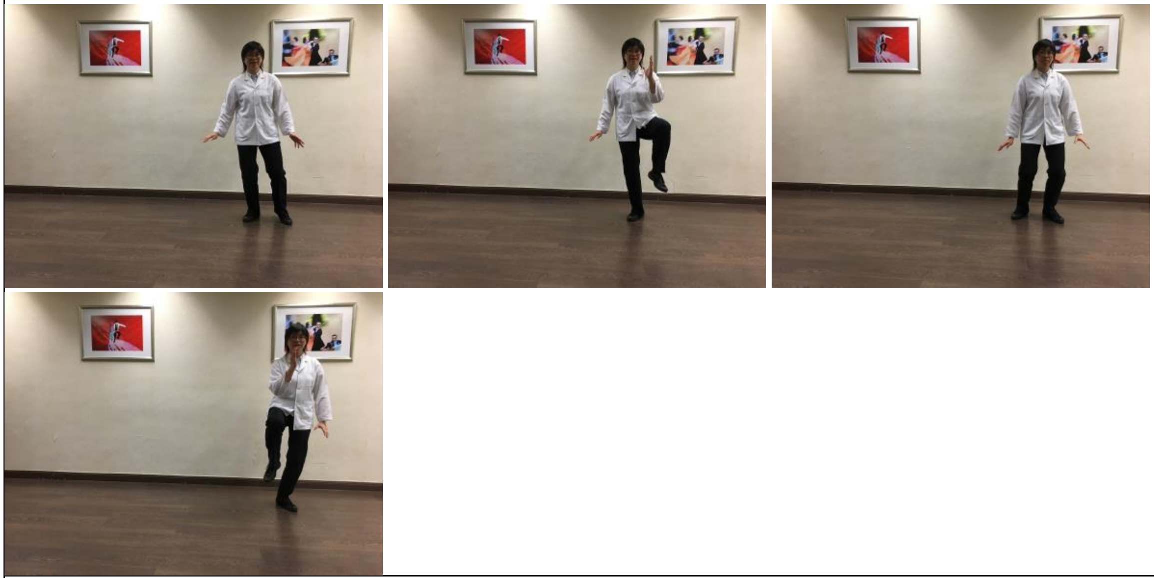




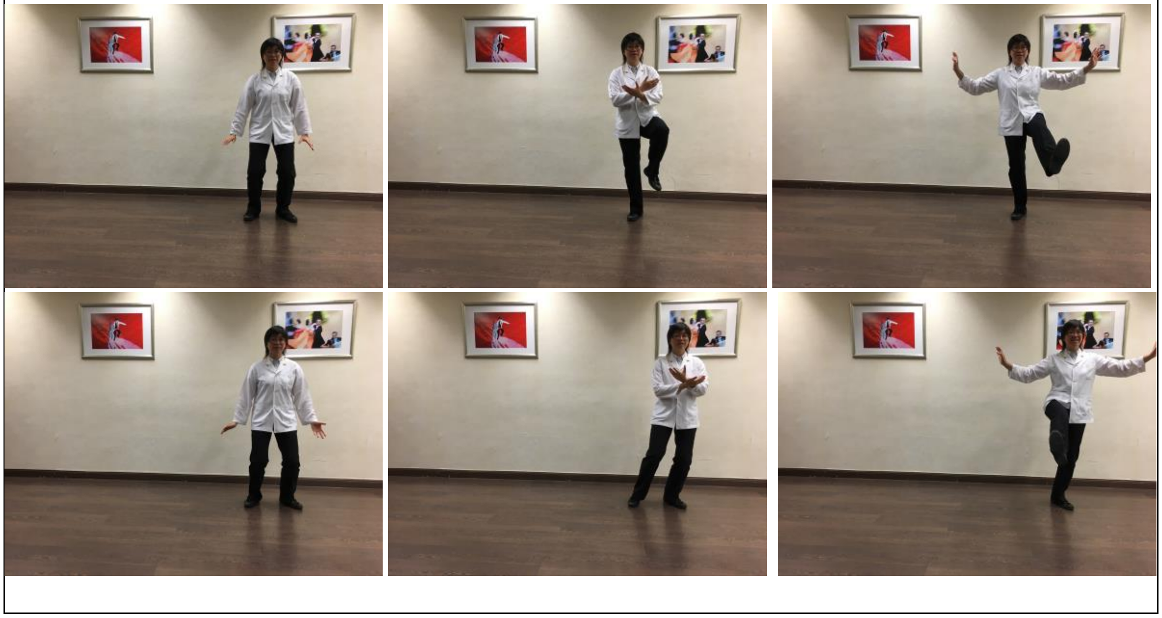


Repeated for three times

9. Golden Rooster Stands On One Leg (金雞獨立)



10. Kick With Heels (左右蹬腿)



11. Strike Ears With Both Fists (雙峰貫耳)




12. Closing (收式)



APPENDIX III Details of the conventional exercise

Types	Details
Mobilization exercises*	Shoulder (flexion/extension, abduction/adduction, circumduction) Elbow (flexion/extension) Wrist (flexion/extension, circumduction) Fingers (flexion/extension) Trunk (bilateral side flexion and rotation) Hip and knee (flexion/extension) Ankle (dorsiflexion/plantarflexion
Stretching exercises*	Upper trapezius Pectoralis major Biceps humerus Triceps humerus Wrist flexors Wrist extensors Gluteal muscles Quadriceps Hamstrings Tibialis anterior Calf muscles
Strengthening exercises*	Shoulder (rotator cuff, abductors, retractors) Hip and knee extensors
Walking	Forward and backward stepping Side stepping Forward walking

*All mobilization, stretching and strengthening exercises were performed on both sides

REFERENCES

References

Acampa, M., Guideri, F., Di Donato, I., Tassi, R., Marotta, G., Lo Giudice, G., ... Martini, G. (2014). Arterial stiffness in patients with deep and lobar intracerebral hemorrhage. *Journal of stroke, 16*(3), 184–188. doi:10.5853/jos.2014.16.3.184

Agmon, M., Belza, B., Nguyen, H. Q., Logsdon, R. G., & Kelly, V. E. (2014). A systematic review of interventions conducted in clinical or community settings to improve dual-task postural control in older adults. *Clinical Interventions in Aging, 9*, 477–492. doi:10.2147/CIA.S54978

Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., & Cockburn, J. (2011). Cognitive motor interference while walking: A systematic review and meta-analysis. *Neuroscience and Biobehavioral Reviews, 35*(3), 715–728. doi:10.1016/j.neubiorev.2010.08.008

Albert, S. J., & Kesselring, J. (2012). Neurorehabilitation of stroke. *Journal of Neurology, 259*(5), 817–832. doi:10.1007/s00415-011-6247-y

Alzahrani, M. A., Dean, C. M., & Ada, L. (2009). Ability to negotiate stairs predicts free-living physical activity in community-dwelling people with stroke: An observational study. *Australian Journal of Physiotherapy, 55*(4), 277–281. doi:10.1016/S0004-9514(09)70008-X

APDM (2014, August 18). Mobility Lab User’s Guide. APDM. Retrieved from: http://share.apdm.com/mobility_lab/docs/MobilityLab_UserGuide.pdf

Au-Yeung, S. S., Hui-Chan, C. W., & Tang, J. C. (2009). Short-form Tai Chi improves standing balance of people with chronic stroke. *Neurorehabilitation and Neural Repair, 23*(5), 515–522. doi:10.1177/1545968308326425

Audette, J. F., Jin, Y. S., Newcomer, R., Stein, L., Duncan, G., & Frontera, W. R. (2006). Tai Chi versus brisk walking in elderly women. *Age and Ageing, 35*(4), 388–393. doi:10.1093/ageing/afl006

Avolio, A., Butlin, M., Liu, Y., Viegas, K., Avadhanam, B., & Lindesay, G. (2011). Regulation of arterial stiffness: Cellular, molecular and neurogenic mechanisms. *Artery Research, 5*(4), 122–127. doi:10.1016/j.artres.2011.10.002

Baetens, T., De Kegel, A., Palmans, T., Oostra, K., Vanderstraeten, G., & Cambier, D. (2013). Gait analysis with cognitive-motor dual tasks to distinguish fallers from nonfallers among rehabilitating stroke patients. *Archives of Physical Medicine and Rehabilitation, 94*(4), 680–686. doi: 10.1016/j.apmr.2012.11.023

Baltgaile, G. (2012). Arterial wall dynamics. *Perspectives in Medicine, 1*(1-12), 146–151. doi:10.1016/j.permed.2012.02.049

Banich, M. T., Milham, M. P., Atchley, R., & Cohen, N. J. (2000a). FMRI studies of Stroop tasks reveal unique roles of anterior and posterior brain systems in attentional selection. *Journal of Cognitive Neuroscience, 12*(6), 988–1000. doi:10.1162/08989290051137521

Banich, M. T., Milham, M. P., Atchley, R. A., Cohen, N. J., Webb, A., Wszalek, T., … Brown, C. (2000b). Prefrontal regions play a predominant role in imposing an attentional ‘set’: Evidence from fMRI. *Brain Research. Cognitive Brain Research, 10*(1-2), 1–9. doi:10.1016/S0926-6410(00)00015-X

Bonnyaud, C., Pradon, D., Bensmall, D., & Roche, N. (2015a). Dynamic stability and risk of tripping during the timed up and go test in hemiparetic and healthy subjects. *PLoS ONE, 10*(10), e0140317. doi:10.1371/journal.pone.0140317

Bonnyaud, C., Pradon, D., Vuillerme, N., Bensmail, D., & Roche, N. (2015b). Spatiotemporal and kinematic parameters relating to oriented gait and turn performance in patients with chronic stroke. *PLoS ONE, 10*(6), e0129821. doi:10.1371/journal.pone.0129821

Boutouyrie, P., Lacolley, P., Girerd, X., Beck, L., Safar, M., & Laurent, S. (1994). Sympathetic activation decreases medium-sized arterial compliance in humans. *American Journal of Physiology, 267*(4), H1368–H1376

Bowen, A., Wenman, R., Mickelborough, J., Foster, J., Hill, E., & Tallis, R. (2001). Dual-task effects of talking while walking on velocity and balance following a stroke. *Age and Ageing, 30*(4), 319–323. doi:10.1093/ageing/30.4.319

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience,12*(1), 1–47. doi:10.1162/08989290051137585

Caleo, M. (2015). Rehabilitation and plasticity following stroke: Insights from rodent models. *Neuroscience, 311*, 180–194. doi:10.1016/j.neuroscience.2015.10.029

Caljouw, S. R., Veldkamp, R., & Lamoth, C. J. (2016). Implicit and explicit learning of a sequential postural weight-shifting task in young and older adults. *Frontiers in Psychology, 7*, 733. doi:10.3389/fpsyg.2016.00733

Calvet, D., Touzé, E., Laurent, S., Varenne, O., Sablayrolles, J. L., Boutouyrie, P., & Mas, J. L. (2014). Aortic stiffness measurement improves the prediction of asymptomatic coronary artery disease in stroke/transient ischemic attack patients. *International Journal of Stroke, 9*(3), 291–296. doi:10.1111/ijs.12015

Cameron, J. D., & Dart, A. M. (1994). Exercise training increases total systemic arterial compliance in humans. *American Journal of Physiology, 266*(2), H693–H701.

Cavalcante, J. L., Lima, J. A., Redheuil, A., & Al-Mallah, M. H. (2011). Aortic stiffness: Current understanding and future directions. *Journal of the American College of Cardiology, 57*(14), 1511–1522. doi:10.1016/j.jacc.2010.12.017

Chan, W. N., Xiao, J., & Tsang, W. W. N. (2016a, October). *Comparing dual-tasking performance, with turning-while-walking as physical task, between healthy older adults and chronic stroke survivors.* Paper presented at the 10th Singapore-International Physiotherapy Congress, Singapore.

Chan, W. N., Xiao, J., & Tsang, W. W. N. (2016b, November). *Comparing performance of stepping down with and without a concurrent cognitive task in controls and chronic stroke survivors.* Paper presented at the 10th Pan-Pacific Conference on Rehabilitation, Shanghai, China.

Chang, R. Y., Koo, M., Yu, Z. R., Kan, C. B., Chu, I. T., Hsu, C. T., & Chen, C. Y. (2008). The effect of t'ai chi exercise on autonomic nervous function of patients with coronary artery disease. *The Journal of Alternative and Complementary Medicine, 14*(9), 1107–1113. doi:10.1089/acm.2008.0166

Chen, E. W., Fu, A. S., Chan, K. M., & Tsang, W. W. (2012). The effects of Tai Chi on the balance control of elderly persons with visual impairment: A randomised clinical trial. *Age and Ageing, 41*(2), 254–259. doi:10.1093/ageing/afr146

Chersi, F., Mirolli, M., Pezzulo, G., & Baldassarre, G. (2013). A spiking neuron model of the cortico-basal ganglia circuits for goal-directed and habitual action learning. *Neural Networks, 41*, 212–224. doi:10.1016/j.neunet.2012.11.009

Clarkson, P., Montgomery, H. E., Mullen, M. J., Donald, A. E., Powe, A. J., Bull, T., ... Deanfield, J. E. (1999). Exercise training enhances endothelial function in young men. *Journal of the American College of Cardiology*, *33*(5), 1379–1385. doi:10.1016/S0735-1097(99)00036-4

Cockburn, J., Haggard, P., Cock, J., & Fordham, C. (2003). Changing patterns of cognitive-motor interference (CMI) over time during recovery from stroke. *Clinical Rehabilitation*, *17*(2), 167–173. doi:10.1191/0269215503cr597oa

Cohn, J. N. (2006). Arterial stiffness, vascular disease, and risk of cardiovascular events. *Circulation, 113*(5), 601–603. doi:10.1161/CIRCULATIONAHA.105.600866

Cohn, J. N., Finkelstein, S., McVeigh, G., Morgan, D., LeMay, L., Robinson, & J., Mock, J. (1995). Noninvasive pulse wave analysis for the early detection of vascular disease. *Hypertension, 26*(3), 503–508. doi:10.1161/01.HYP.26.3.503

Colcombe, S. J., Erickson, K. I., Raz, N., Webb, A. G., Cohne, N. J., McAuley, E., & Kramer, A. F. (2003). Aerobic fitness reduces brain tissue loss in aging humans. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 58*(2), 176–180. doi:10.1093/gerona/58.2.M176

Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., ... Kramer, A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 61*(11), 1166–1170. doi:10.1093/gerona/61.11.1166

Cole, A. R., Wijarnpreecha, K., Chattipakorn, S. C., & Chattipakorn, N. (2016). Effects of Tai Chi exercise on heart rate variability. *Complementary Therapies in Clinical Practice*, *23*, 59–63. doi:10.1016/j.ctcp.2016.03.007

Collier, S. R., Kanaley, J. A., Carhart, R. Jr., Frechette, V., Tobin, M. M., Hall, A. K., … Fernhall, B. (2008). Effect of 4 weeks of aerobic or resistance exercise training on arterial stiffness, blood flow and blood pressure in pre- and stage-1 hypertensives. *Journal of Human Hypertension, 22*(10), 678–686. doi:10.1038/jhh.2008.36

Cumming, R. G., & Klineberg, R. J. (1994). Fall frequency and characteristics and the risk of hip fractures. *Journal of the American Geriatrics Society, 42*(7), 774–778. doi:10.1111/j.1532-5415.1994.tb06540.x

Curiati, J. A., Bocchi, E., Freire, J. O., Arantes, A. C., Braga, M., Garcia, Y., … Fo, W. J. (2005). Meditation reduces sympathetic activation and improves the quality of life in elderly patients with optimally treated heart failure: A prospective randomized study. *Journal of Alternative and Complementary Medicine, 11*(3), 465–472. doi:10.1089/acm.2005.11.465

De Haart, M., Geurts, A. C., Huidekoper, S. C., Fasotti, L., & van Limbeek, J. (2004). Recovery of standing balance in postacute stroke patients: A rehabilitation cohort study. *Archives of Physical Medicine and Rehabilitation, 85*(6), 886–895. doi:10.1016/j.apmr.2003.05.012

De Meersman, R. E., & Stein, P. K. (2007). Vagal modulation and aging. *Biological Psychology, 74*(2), 165–173. doi:10.1016/j.biopsycho.2006.04.008

Dennis, A., Dawes, H., Elsworth, C., Collett, J., Howells, K., Wade, D. T., ... Cockburn, J. (2009). Fast walking under cognitive-motor interference conditions in chronic stroke. *Brain Research, 1287,* 104–110. doi:10.1016/j.brainres.2009.06.023

DeSouza, C. A., Shapiro, L. F., Clevenger, C. M., Dinenno, F. A., Monahan, K. D., Tanaka, H., & Seals, D. R. (2000). Regular aerobic exercise prevents and restores age-related declines in endothelium-dependent vasodilation in healthy men. *Circulation, 102*(12), 1351–1357. doi:10.1161/01.CIR.102.12.1351

Dite, W., & Temple, V. A. (2002). Development of a clinical measure of turning for older adults. *American Journal of Physical Medicine & Rehabilitation, 81*(11), 857–866. doi:10.1097/01.PHM.0000030730.93135.50

Dorrance, A. M., & Fink, G. (2015). Effects of stroke on the autonomic nervous system. *Comprehensive Physiology, 5*(3), 1241–1263. doi:10.1002/cphy.c140016

Ekstrom, A. D., Kahana, M. J., Caplan, J. B., Fields, T. A., Isham, E. A., Newman, E. L., & Fried, I. (2003). Cellular networks underlying human spatial navigation. *Nature, 425*(6954), 184–188. doi:10.1038/nature01964

Figueroa, M. A., DeMeersman, R. E., & Manning, J. (2012). The autonomic and rate pressure product response of Tai Chi practitioners. *North American Journal of Medical Sciences, 4*(6), 270–275. doi:10.4103/1947-2714.97208

Fong, D. Y., Chi, L. K., Li, F., & Chang, Y. K. (2014). The benefits of endurance exercise and Tai Chi Chuan for the task-switching aspect of executive function in older adults: An ERP study. *Frontiers in Aging Neuroscience, 6*, 295. doi:10.3389/fnagi.2014.00295

Fong, S. S., Wong, J. Y., Chung, L. M., Yam, T. T., Chung, J. W., Lee, Y. M., … Ng, S. S. (2015). Changes in heart-rate variability of survivors of nasopharyngeal cancer during Tai Chi Qigong practice. *Journal of Physical Therapy Science, 27*(5), 1577–1579. doi:10.1589/jpts.27.1577

Francica, J. V., Bigongiari, A., Mochizuki, L., Scapini, K. B., Moraes, O. A., Mostarda, C., ... Rodrigues, B. (2015). Cardiac autonomic dysfunction in chronic stroke women is attenuated after submaximal exercise test, as evaluated by linear and nonlinear analysis. *BMC Cardiovascular Disorders, 15*, 105. doi:10.1186/s12872-015-0099-9

Fujimoto, N., Prasad, A., Hastings, J. L., Arbab-Zadeh, A., Bhella, P. S., Shibata, S., … Levine, B. D. (2010). Cardiovascular effects of 1 year of progressive and vigorous exercise training in previously sedentary individuals older than 65 years of age. *Circulation, 122*(18), 1797–1805. doi:10.1161/CIRCULATIONAHA.110.973784

Gąsecki, D., Rojek, A., Kwarciany, M., Kowalczyk, K., Boutouyrie, P., Nyka, W., ... Narkiewicz, K. (2012a). Pulse wave velocity is associated with early clinical outcome after ischemic stroke. *Atherosclerosis, 225*(2), 348–352. doi:10.1016/j.atherosclerosis.2012.09.024

Gąsecki, D., Rojek, A., Kwarciany, M., Kubach, M., Boutouyrie, P., Nyka, W., ... Narkiewicz, K. (2012b). Aortic stiffness predicts functional outcome in patients after ischemic stroke. *Stroke, 43*(2), 543–544. doi:10.1161/STROKEAHA.111.633487

Gatts, S. K., & Woollacott, M. H. (2006). Neural mechanisms underlying balance improvement with short term Tai Chi training. *Aging Clinical and Experimental Research, 18*(1), 7–19. doi:10.1007/BF03324635

Gatts, S. K., & Woollacott, M. H. (2007). How Tai Chi improves balance: Biomechanics of recovery to a walking slip in impaired seniors. *Gait & Posture, 25*(2), 205–214. doi:10.1016/j.gaitpost.2006.03.011

Go, A. S., Mozaffarian, D., Roger, V. L., Benjamin, E. J., Berry, J. D., Borden, W. B., … American Heart Association Statistics Committee and Stroke Statistics Subcommittee (2013). Heart disease and stroke statistics – 2013 update: a report from the American Heart Association. *Circulation, 127*(1), e6–e245. doi:10.1161/CIR.0b013e31828124ad

Gobbo, S., Bergamin, M., Sieverdes, J. C., Ermolao, A., & Zaccaria, M. (2014). Effects of exercise on dual-task ability and balance in older adults: A systematic review. *Archives of Gerontology and Geriatrics, 58*(2), 177–187. doi:10.1016/j.archger.2013.10.001

Grey, E., Bratteli, C., Glasser, S. P., Alinder, C., Finkelstein, S. M., Lindgren, B. R., & Cohn, J. N. (2003). Reduced small artery but not large artery elasticity is an independent risk marker for cardiovascular events. *American Journal of Hypertension, 16*(4), 265–269. doi:10.1016/S0895-7061(02)03271-5

Grön, G., Wunderlich, A. P., Spitzer, M., Tomczak, R., & Riepe, M. W. (2000). Brain activation during human navigation: Gender-different neural networks as substrate of performance. *Nature Neuroscience, 3*(4), 404–408. doi:10.1038/73980

Hackney, M. E., & Wolf, S. L. (2014). Impact of Tai Chi Chu'an practice on balance and mobility in older adults: An integrative review of 20 years of research. *Journal of Geriatric Physical Therapy, 37*(3), 127–135. doi:10.1519/JPT.0b013e3182abe784

Hall, C. D., Miszko, T., & Wolf, S. L. (2009). Effects of Tai Chi intervention on dual-task ability in older adults: A pilot study. *Archives of Physical Medicine and Rehabilitation, 90*(3), 525–529. doi:10.1016/j.apmr.2008.09.566

Hamilton, P. K., Lockhart, C. J., Quinn, C. E., & McVeigh, G. E. (2007). Arterial stiffness: Clinical relevance, measurement and treatment. *Clinical Science, 113*(4), 157–170. doi:10.1042/CS20070080

Hankey, G. J. (2014). Secondary stroke prevention. *Lancet Neurology, 13*(2), 178–194. doi:10.1016/S1474-4422(13)70255-2

Hari, R., Forss, N., Avikainen, S., Kirveskari, E., Salenius, S., & Rizzolatti, G. (1998). Activation of human primary motor cortex during action observation: A neuromagnetic study. *Proceedings of the National Academy of Sciences, 95*(25), 15061–15065

Hart, J., Kanner, H., Gilboa-Mayo, R., Haroeh-Peer, O., Rozenthul-Sorokin, N., & Eldar, R. (2004). Tai Chi Chuan practice in community-dwelling persons after stroke. *International Journal of Rehabilitation Research, 27*(4), 303–304

Hase, K., & Stein, R. B. (1999). Turning strategies during human walking. *Journal of Neurophysiology, 81*(6), 2914–2922

Hollands, K. L., Agnihotri, D., & Tyson, S. F. (2014). Effects of dual task on turning ability in stroke survivors and older adults. *Gait & Posture, 40*(4), 564–569. doi:10.1016/j.gaitpost.2014.06.019

Hollands, K. L., Hollands, M. A., Zietz, D., Wing, A. M., Wright, C., & van Vliet, P. (2010a). Kinematics of turning 180 degrees during the timed up and go in stroke survivors with and without falls history. *Neurorehabilitation and Neural Repair, 24*(4), 358–367. doi:10.1177/1545968309348508

Hollands, K. L., Pelton, T., Wimperis, A., Whitham, D., Jowett, S., Sackley, C., … van Vliet, P. (2013). Visual cue training to improve walking and turning after stroke: A study protocol for a multi-centre, single blind randomised pilot trial. *Trials, 14*, 276. doi:10.1186/1745-6215-14-276

Hollands, K. L., van Vliet, P., Zietz, D., Wing, A., Wright, C., & Hollands, M. A. (2010b). Stroke-related differences in axial body segment coordination during preplanned and reactive changes in walking direction. *Experimental Brain Research, 202*(3), 591–604. doi:10.1007/s00221-010-2162-1

Hotta, H., & Uchida, S. (2010). Aging of the autonomic nervous system and possible improvements in autonomic activity using somatic afferent stimulation. *Geriatrics & Gerontology International, 10*(Suppl. 1), S127–S136. doi:10.1111/j.1447-0594.2010.00592.x

Hsue, B. J., & Su, F. C. (2014). Effects of age and gender on dynamic stability during stair descent. *Archives of Physical Medicine and Rehabilitation, 95*(10), 1860–1869. doi:10.1016/j.apmr.2014.05.001

Huang, Y. T., Wang, C. H., & Wu, Y. F. (2011). Adhering to a Tai Chi Chuan exercise program improves vascular resistance and cardiac function. *International Journal of Gerontology, 5*(3), 150–154. doi:10.1016/j.ijge.2011.09.037

Hyndman, D., Ashburn, A., & Stack, E. (2002). Fall events among people with stroke living in the community: Circumstances of falls and characteristics of fallers. *Archives of Physical Medicine and Rehabilitation, 83*(2), 165–170. doi:10.1053/apmr.2002.28030

Jacobs, J. V. (2016). A review of stairway falls and stair negotiation: Lessons learned and future needs to reduce injury. *Gait & Posture, 49,* 159–167. doi:10.1016/j.gaitpost.2016.06.030

Jansen, R. J., van Egmond, R., & de Ridder, H. (2016). Task prioritization in dual-tasking: Instructions versus preferences. *PLos ONE, 11*(7), e0158511. doi:10.1371/journal.pone.0158511

Je, H. D., Ma, S. Y., & Kim, H. D. (2011). The influence of a cognitive task on stair descent by younger adults. *Journal of Physical Therapy Science, 23*(1), 85–89. doi:10.1589/jpts.23.85

Jiménez-Martin, P. J., & Hernández-Neira, J. L. (2014). Biomechanical considerations of foot-ground contact in T'ai Chi Chuan. *The Journal of Alternative and Complementary Medicine, 20*(10), 743–749. doi:10.1089/acm.2014.0035

Jin, H., Jiang, Y., Wei, Q., Chen, L., & Ma, G. (2013). Effects of aerobic cycling training on cardiovascular fitness and heart rate recovery in patients with chronic stroke. *NeuroRehabilitation, 32*(2), 327–335. doi:10.3233/NRE-130852

Kasai, J. Y., Busse, A. L., Magaldi, R. M., Soci, M. A., Rosa Pde, M., Curiati, J. A., & Jacob Filho, W. (2010). Effects of Tai Chi Chuan on cognition of elderly women with mild cognitive impairment. *Einstein (São Paulo), 8*(1), 40–45. doi:10.1590/S1679-45082010AO1470

Kelly-Hayes, M., Beiser, A., Kase, C. S., Scaramucci, A., D'Agostino, R. B., Wolf, P. A. (2003). The influence of gender and age on disability following ischemic stroke: The Framingham study. *Journal of Stroke and Cerebrovascular Disease, 12*(3), 119–126. doi:10.1016/S1052-3057(03)00042-9

Kim, H. D. (2009). A comparison of the center of pressure during stair descent in young and healthy elderly adults. *Journal of Physical Therapy Science, 21*(2), 129–134. doi:10.1589/jpts.21.129

Kim, H. Y., Kim, L. Y., & Lee, S. M. (2015). Effects of therapeutic Tai Chi on balance, gait, and quality of life in chronic stroke patients. *International Journal of Rehabilitation Research, 38*(2), 156–161. doi:10.1097/MRR.0000000000000103

Kim, J., Song, T. J., Song, D., Lee, K. J., Kim, E. H., Lee, H. S., ... Heo, J. H. (2014). Brachial-ankle pulse wave velocity is a strong predictor for mortality in patients with acute stroke. *Hypertension, 64*(2), 240–246. doi:10.1161/HYPERTENSIONAHA.114.03304

Kim, Y. B., Park, K. Y., Chung, P. W., Kim, J. M., Moon, H. S., & Youn, Y. C. (2016). Brachial-ankle pulse wave velocity is associated with both acute and chronic cerebral small vessel disease. *Atherosclerosis, 245,* 54–59. doi:10.1016/j.atherosclerosis.2015.12.006

Kizony, R., Levin, M. F., Hughey, L., Perez, C., & Fung, J. (2010). Cognitive load and dual-task performance during locomotion poststroke: A feasibility study using a functional virtual environment. *Physical Therapy, 90*(2), 252–260. doi:10.2522/ptj.20090061

Krakauer, J. W. (2006). Motor learning: Its relevance to stroke recovery and neurorehabilitation. *Current Opinion in Neurology, 19*(1), 84–90. doi:10.1097/01.wco.0000200544.29915.cc

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: Models and posture-analysis methods. *Clinical Neurophysiology, 38*(6), 411–421. doi:10.1016/j.neucli.2008.09.005

Lam, L. C., Chau, R. C., Wong, B. M., Fung, A. W., Tam, C. W., Leung, G. T., ... Chan, W. M. (2012). A 1-year randomized controlled trial comparing mind body exercise (Tai Chi) with stretching and toning exercise on cognitive function in older Chinese adults at risk of cognitive decline. *Journal of the American Medical Directors Association, 13*(6), 568.e15–20. doi:10.1016/j.jamda.2012.03.008

Lam. L. C., Tam, C. W., Lui, V. W, Chan, W. C., Chan, S. S., Chiu, H. F., ... Chan, W. M. (2009). Modality of physical exercise and cognitive function in Hong Kong older Chinese community. *International Journal of Geriatric Psychiatry, 24*(1), 48–53. doi:10.1002/gps.2072

Lam, L. C., Tam, C. W., Lui, V. W., Chan, W. C., Chan, S. S., Wong, S., … Chiu, H. F. (2008). Prevalence of very mild and mild dementia in community-dwelling older Chinese people in Hong Kong. *Internal Psychogeriatrics, 20*(1), 135–148. doi:10.1017/S1041610207006199

Lam, T., & Luttmann, K. (2009). Turning capacity in ambulatory individuals poststroke. *American Journal of Physical Medicine & Rehabilitation, 88*(11), 873–883. doi:10.1097/PHM.0b013e3181bc0ddf

Lamontagne, A, & Fung, J. (2009). Gaze and postural reorientation in the control of locomotor steering after stroke. *Neurorehabilitation and Neural Repair, 23*(3), 256–266. doi:10.1177/1545968308324549

Lan, C., Lai, J. S., Wong, M. K., & Yu, M. L. (1996). Cardiorespiratory function, flexibility, and body composition among geriatric Tai Chi Chuan practitioners. *Archives of Physical Medicine and Rehabilitation, 77*(6), 612–616. doi:10.1016/S0003-9993(96)90305-6

Lark, S. D., Buckley, J. G., Bennett, S., Jones, D., & Sargeant, A. J. (2003). Joint torques and dynamic joint stiffness in elderly and young men during stepping down. *Clinical Biomechanics, 18*(9), 848–855. doi:10.1016/S0268-0033(03)00150-5

Laurent, S., Cockcroft, J., van Bortel, L., Boutouyrie, P., Giannattasio, C., Hayoz, D., ... Struijker-Boudier, H. (2006). Expert consensus document on arterial stiffness: Methodological issues and clinical applications. *European Heart Journal, 27*(21), 2588–2605. doi:10.1093/eurheartj/ehl254

Lazar, S. W., Bash, G., Gollub, R. L., Fricchione, G. L., Khalsa, G., & Benson, H. (2000). Functional brain mapping of the relaxation response and meditation. *Neuroreport, 11*(7), 1581–1585. doi:10.1097/00001756-200005150-00041

Lee, H. J., & Chou, L. S. (2007). Balance control during stair negotiation in older adults. *Journal of Biomechanics, 40*(11), 2530–2536. doi:10.1016/j.biomech.2006.11.001

Lee, Y. H., Park, S. H., Yoon, E. S., Lee, C. D., Wee, S. O., Fernhall, B., & Jae, S. Y. (2015). Effects of combined aerobic and resistance exercise on central arterial stiffness and gait velocity in patients with chronic poststroke hemiparesis. *American Journal of Physical Medicine & Rehabilitation, 94*(4), 687–695. doi:10.1097/PHM.0000000000000233

Leung, D. P., Chan, C. K., Tsang, H. W., Tsang, W. W., & Jones, A. Y. (2011). Tai chi as an intervention to improve balance and reduce falls in older adults: A systematic and meta-analytical review. *Alternative Therapies in Health and Medicine, 17*(1), 40–48.

Leung, E. S., & Tsang, W. W. (2008). Comparison of the kinetic characteristics of standing and sitting Tai Chi forms. *Disability and Rehabilitation, 30*(25), 1891–1900. doi:10.1080/09638280802358563

Lista, I., & Sorrentino, G. (2010). Biological mechanisms of physical activity in preventing cognitive decline. *Cellular and Molecular Neurobiology, 30*(4), 493–503. doi:10.1007/s10571-009-9488-x

Lu, W. A., & Kuo, C. D. (2003). The effect of Tai Chi Chuan on the autonomic nervous modulation in older persons. *Medicine & Science in Sports & Exercise*, *35*(12), 1972–1976. doi:10.1249/01.MSS.0000099242.10669.F7

Lu, W. A., & Kuo, C. D. (2006). Comparison of the effects of Tai Chi Chuan and Wai Tan Kung exercises on autonomic nervous system modulation and on hemodynamics in elder adults. *American Journal of Chinese Medicine, 34*(6), 959–968. doi:10.1142/S0192415X06004430

Lu, W. A., & Kuo, C. D. (2013). Three months of Tai Chi Chuan exercise can reduce serum triglyceride and endothelin-1 in the elderly. *Complementary Therapies in Clinical Practice, 19*(4), 204–208. doi:10.1016/j.ctcp.2013.06.007

Lu, W. A., & Kuo, C. D. (2014). Breathing frequency-independent effect of Tai Chi Chuan on autonomic modulation. *Clinical Autonomic Research, 24*(2), 47–52. doi:10.1007/s10286-014-0224-3

Lu, X., Hui-Chan, C. W., & Tsang, W. W. (2013a). Effects of Tai Chi training on arterial compliance and muscle strength in female seniors: a randomized clinical trial. *European Journal of Preventive Cardiology, 20*(2), 238–245. doi:10.1177/2047487311434233

Lu, X., Siu, K. C., Fu, S. N., Hui-Chan, C. W., & Tsang, W. W. (2013b). Tai Chi practitioners have better postural control and selective attention in stepping down with and without a concurrent auditory response task. *European Journal of Applied Physiology, 113*(8), 1939–1945. doi:10.1007/s00421-013-2624-9

Lu, X., Siu, K. C., Fu, S. N., Hui-Chan, C. W., & Tsang, W. W. (2016). Effects of Tai Chi training on postural control and cognitive performance while dual tasking - A randomized clinical trial. *Journal of Complementary & Integrative Medicine, 13*(2), 181–187. doi:10.1515/jcim-2015-0084

Lussier, M., Brouillard, P., & Bherer, L. (2017). Limited benefits of heterogeneous dual-task training on transfer effects in older adults. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 72*(5), 801–812. doi:10.1093/geronb/gbv105

Macdonald, R. L. (2014). Delayed neurological deterioration after subarachnoid haemorrhage. *Nature Reviews Neurology, 10*(1), 44–58. doi:10.1038/nrneurol.2013.246

Madehkhaksar, F., & Egges, A. (2016). Effect of dual task type on gait and dynamic stability during stair negotiation at different inclinations. *Gait & Posture*, *43*, 114–119. doi: 10.1016/j.gaitpost.2015.09.009

Mäkikallio, M., Mäkikallio, T. H., Korpelainen, J. T., Sotaniemi, K. A., Huikuri, H. V., & Myllylä, V. V. (2004). Heart rate dynamics predict poststroke mortality. *Neurology, 62*(10), 1822–1826. doi:10.1212/01.WNL.0000125190.10967.D5

Man, D. W., Tsang, W. W., & Hui-Chan, C. W. (2010). Do older t'ai chi practitioners have better attention and memory function? *Journal of Alternative and Complementary Medicine*, *16*(12), 1259–1264. doi:10.1089/acm.2009.0462

Manaf, H., Justine, M., & Goh, H. T. (2015). Effects of attentional loadings on gait performance before turning in stroke survivors. *PM&R, 7*(11), 1159–1166. doi:10.1016/j.pmrj.2015.05.007

Manaf, H., Justine, M., & Goh, H. T. (2017). Axial segmental coordination during turning: Effects of stroke and attentional loadings. *Motor Control, 21*(1), 42–57. doi:10.1123/mc.2015-0040

Manaf, H., Justine, M., & Omar, M. (2014a). Functional balance and motor impairment correlations with gait parameters during timed Up and Go test across three attentional loading conditions in stroke survivors. *Stroke Research and Treatment, 2014*(2014), 439304. doi: 10.1155/2014/439304

Manaf, H., Justine, M., Ting, G. H., & Latiff, L. A. (2014b). Comparison of gait parameters across three attentional loading conditions during timed up and go test in stroke survivors. *Topics in Stroke Rehabilitation, 21*(2), 128–136. doi:10.1310/tsr2102-128

Manno, E. M. (2012). Update on intracerebral hemorrhage. *Continuum: Lifelong Learning in Neurology, 18*(3), 598–610. doi:10.1212/01.CON.0000415430.99394.3e

Manor, B., Lough, M., Gagnon, M. M., Cupples, A., Wayne, P. M., & Lipsitz, L. A. (2014). Functional benefits of tai chi training in senior housing facilities. *Journal of American Geriatric Society, 62*(8), 1484–1489. doi:10.1111/jgs.12946

Mao, D. W., Hong, Y., & Li, J. X. (2006). Characteristics of foot movement in Tai Chi exercise. *Physical Therapy, 86*(2), 215–222. doi:10.1093/ptj/86.2.215

Mattace-Raso, F. U., van der Cammen, T. J., Hofman, A., van Popele, N. M., Bos, M. L., Schalekamp, M. A., ... Witteman, J. C. (2006). Arterial stiffness and risk of coronary heart disease and stroke: The rotterdam study. *Circulation, 113*(5), 657–663. doi:10.1161/CIRCULATIONAHA.105.555235

McCulloch, K. L., Mercer, V., Giuliani, C., & Marshall, S. (2009). Development of a clinical measure of dual-task performance in walking: Reliability and preliminary validity of the walking and remembering test. *Journal of Geriatric Physical Therapy, 32*(1), 2–9.

McLaren, A., Kerr, S., Allan, L., Steen, I. N., Ballard, C., Allen, J., ... Kenny, R. A. (2005). Autonomic function is impaired in elderly stroke survivors. *Stroke, 36*(5), 1026–1030. doi:10.1161/01.STR.0000160748.88374.ce

Micieli, G., & Cavallini, A. (2008). The autonomic nervous system and ischemic stroke: A reciprocal interdependence. *Clinical Autonomic Research, 18*(6), 308–317. doi:10.1007/s10286-008-0495-7

Miller, S. M., & Taylor-Piliae, R. E. (2014). Effects of Tai Chi on cognitive function in community-dwelling older adults: A review. *Geriatric Nursing, 35*(1), 9–19. doi:10.1016/j.gerinurse.2013.10.013

Miyasike-deSilva, V. & McIlroy, W. E. (2016). Gaze shifts during dual-tasking stair descent. *Experimental Brain Research, 234*(11), 3233–3242. doi:10.1007/s00221-016-4721-6

Moodithaya, S., & Avadhany, S. T. (2012). Gender differences in age-related changes in cardiac autonomic nervous function. *Journal of Aging Research, 2012*, 679345. doi:10.1155/2012/679345

Motivala, S. J., Sollers, J., Thayer, J., & Irwin, M. R. (2006). Tai Chi Chih acutely decreases sympathetic nervous system activity in older adults. *The Journal of Gerontology. Series A, Biological Sciences and Medical Sciences, 61*(11), 1177–1180. doi:10.1093/Gerona/61.11.1177

Mueller, P. J. (2007). Exercise training and sympathetic nervous system activity: Evidence for physical activity dependent neural plasticity. *Clinical and Experimental Pharmacology and Physiology, 34*(4), 377–384. doi:10.1111/j.1440-1681.2007.04590.x

Muir-Hunter, S. W., & Wittwer, J. E. (2016). Dual-task testing to predict falls in community-dwelling older adults: A systematic review. *Physiotherapy, 102*(1), 29–40. doi: 10.1016/j.physio.2015.04.011

National Safety Council. (2016). *Injury facts* (2016 ed.). Itasca, IL: National Safety Council.

Nguyen, M. H., & Kruse, A. (2012). A randomized controlled trial of Tai chi for balance, sleep quality and cognitive performance in elderly Vietnamese. *Clinical Interventions in Aging, 7,* 185–190. doi:10.2147/CIA.S32600

Nichols, W., O'Rourke, M., & McDonald, D. (2011). McDonald's blood flow in arteries: Theoretical, experimental and clinical principles (6th ed). London: Hodder Arnold.

Nickel, K. J., Acree, L. S., & Gardner, A. W. (2011). Effects of a single bout of exercise on arterial compliance in older adults. *Angiology, 62*(1), 33–37. doi:10.1177/0003319710381993

Njemanze, H., Warren, C., Eggett, C., MacGowan, G. A., Bates, M. G., Siervo, M., ... Jakovljevic, D. G. (2016). Age-related decline in cardiac autonomic function is not attenuated with increased physical activity. *Oncotarget, 7*(47), 76390–76397. doi:10.18632/oncotarget.12403

Novak, A. C., & Brouwer, B. (2012). Strength and aerobic requirements during stair ambulation in persons with chronic stroke and healthy adults. *Archives of Physical Medicine and Rehabilitation, 93*(4), 683–689. doi:10.1016/j.apmr.2011.10.009

Novak, A. C., & Brouwer, B. (2013). Kinematic and kinetic evaluation of the stance phase of stair ambulation in persons with stroke and healthy adults: A pilot study. *Journal of Applied Biomechanics, 29*(4), 443–452. doi:10.1123/jab.29.4.443

Nunan, D., Donovan, G., Jakovljevic, D. G., Hodges, L. D., Sandercock, G. R., & Brodie, D. A. (2009). Validity and reliability of short-term heart-rate variability from the Polar S810. *Medicine & Science in Sports & Exercise, 41*(1), 243–250. doi:10.1249/MSS.0b013e318184a4b1

O'Rourke, M. F., & Hashimoto, J. (2008). Arterial stiffness. A modifiable cardiovascular risk factor? *Journal of Cariopulmonary Rehabilitation and Prevention, 28*(4), 225–237. doi:10.1097/01.HCR.0000327179.21498.38

Ojha, H. A., Kern, R. W., Lin, C. H., & Winstein, C. J. (2009). Age affects the attentional demands of stair ambulation: Evidence from a dual-task approach. *Physical Therapy, 89*(10), 1080–1088. doi:10.2522/ptj.20080187

Orendurff, M. S., Segal, A. D., Berge, J. S., Flick, K. C., Spanier, D., & Klute, G. K. (2006). The kinematics and kinetics of turning: Limb asymmetries associated with walking a circular path. *Gait & Posture, 23*(1), 106–111. doi:10.1016/j.gaitpost.2004.12.008

Page, S. J., Gater, D. R., & Bach-Y-Rita, P. (2004). Reconsidering the motor recovery plateau in stroke rehabilitation. *Archives of Physical Medicine and Rehabilitation, 85*(8), 1377–1381. doi:10.1016/j.apmr.2003.12.031

Pan, X., Zhang, Y., & Tao, S. (2015). Effects of Tai Chi exercise on blood pressure and plasma levels of nitric oxide, carbon monoxide and hydrogen sulfide in real-world patients with essential hypertension. *Clinical and Experimental Hypertension, 37*(1), 8–14. doi:10.3109/10641963.2014.881838

Patel, P., & Bhatt, T. (2014). Task matters: Influence of different cognitive tasks on cognitive-motor interference during dual-task walking in chronic stroke survivors. *Topics in Stroke Rehabilitation, 21*(4), 347–357. doi:10.1310/tsr2104-347

Pekna, M., Pekny, M., & Nilsson, M. (2012). Modulation of neural plasticity as a basis for stroke rehabilitation. *Stroke, 43*(10), 2819–2828. doi:10.1161/STROKEAHA.112.654228

Perry, J., & Burnfield, J. (2010). *Gait analysis: Normal and pathological function* (2nd ed.). Thorofare, NJ: SLACK. pp. 367-384.

Pescatello, L., Arena, R., Riebe, D., Thompson, P., & American College of Sports Medicine. (2014). *ACSM's guidelines for exercise testing and prescription.* (9th ed.). Baltimore, Md.: Wolters Kluwer/Lippincott Williams & Wilkins.

Pibarot, P., & Dumesnil, J. G. (2012). Improving assessment of aortic stenosis. *Journal of the American College of Cardiology, 60*(3), 169–180. doi:10.1016/j.jacc.2011.11.078

Plummer, P., Eskes, G., Wallace, S., Giuffrida, C., Fraas, M., Campbell, G., ... Skidmore, E. R. (2013). Cognitive-motor interference during functional mobility after stroke: State of the science and implications for future research. *Archives of Physical Medicine and Rehabilitation, 94*(12), 2565–2574. doi:10.1016/j.apmr.2013.08.002

Plummer, P., Villalobos, R. M., Vayda, M. S., Moser, M., & Johnson, E. (2014). Feasibility of dual-task gait training for community-dwelling adults after stroke: A case series. *Stroke Research and Treatment, 2014*(2014), 538602. doi:10.1155/2014/538602

Plummer-D'Amato, P., & Altmann, L. J. (2012). Relationships between motor function and gait-related dual-task interference after stroke: A pilot study. *Gait & Posture, 35*(1), 170-172. doi:10.1016/j.gaitpost.2011.08.015

Plummer-D'Amato, P., Altmann, L. J., Behrman, A. L., & Marsiske, M. (2010). Interference between cognition, double-limb support, and swing during gait in community-dwelling individuals poststroke. *Neurorehabilitation and Neural Repair, 24*(6), 542–549. doi:10.1177/1545968309357926

Plummer-D'Amato, P., Altmann, L. J., Saracino, D., Fox, E., Behrman, A. L., & Marsiske, M. (2008). Interactions between cognitive tasks and gait after stroke: A dual-task study. *Gait & Posture, 27*(4), 683–688. doi: 10.1016/j.gaitpost.2007.09.001

Pohl, P. S., Kemper, S., Siengsukon, C. F., Boyd, L., Vidoni, E., & Herman, R. E. (2011). Older adults with and without stroke reduce cadence to meet the demands of talking. *Journal of Geriatric Physical Therapy, 34*(1), 35–40. doi:10.1519/JPT.0b013e31820aa8e6

Polich, J., & Heine, M. R. (1996). P300 topography and modality effects from a single-stimulus paradigm. *Psychophysiology, 33*(6), 747–752. doi:10.1111/j.1469-8986.1996.tb02371.x

Prisant, L. M., Pasi, M., Jupin, D., & Prisant, M. E. (2002). Assessment of repeatability and correlates of arterial compliance. *Blood Pressure Monitoring, 7*(4), 231–235.

Qu, X., & Hu, X. (2014). Lower-extremity kinematics and postural stability during stair negotiation: Effects of two cognitive tasks. *Clinical Biomechanics, 29*(1), 40–46. doi:10.1016/j.clinbiomech.2013.11.006

Redgrave, P., Rodriguez, M., Smith, Y., Rodriguez-Oroz, M. C., Lehericy, S., Bergman, H., ... Obeso, J. A. (2010). Goal-directed and habitual control in the basal ganglia: Implications for Parkinson’s disease. *Nature Reviews Neuroscience, 11*(11), 760–772. doi:10.1038/nrn2915

Reid, S. M., Novak, A. C., Brouwer, B., & Costigan, P. A. (2011). Relationship between stair ambulation with and without a handrail and centre of pressure velocities during stair ascent and descent. *Gait & Posture, 34*(4), 529–532. doi:10.1016/j.gaitpost.2011.07.008

Roerdink, M., de Haart, M., Daffertshofer, A., Donker, S. F., Geurts, A. C. H., & Beek, P. J. (2006). Dynamical structure of center-of-pressure trajectories in patients recovering from stroke. *Experimental Brain Research, 174*(2), 256–269. doi:10.1007/s00221-006-0441-7

Roerdink, M., Geurts, A. C. H., de Haart, M., & Beek, P. J. (2009). On the relative contribution of the paretic leg to the control of posture after stroke. *Neurorehabilitation and Neural Repair, 23*(3), 267–274. doi:10.1177/1545968308323928

Royall, D. R., Lauterbach, E. C., Cummings, J. L., Reeve, A., Rummans, T. A., Kaufer, D. I., ... Coffey, C. E. (2002). Executive control function: A review of its promise and challenges for clinical research. A report from the Committee on Research of the American Neuropsychiatric Association. *The Journal of Neuropsychiatry and Clinical Neuroscience, 14*(4), 377–405. doi:10.1176/jnp.14.4.377

Rozenblatt, S. (2011). Stroop color word test (adult). In: J. Kreutzer, B. Caplan, & J. DeLuca (Eds.). *Encyclopedia of Clinical Neuropsychology*. (pp.2404-205). SpringerLink e-books.

Sakuragi, S. & Abhayaratna, W. P. (2010). Arterial stiffness: Methods of measurement, physiologic determinants and prediction of cardiovascular outcomes. *International Journal of Cardiology*, *138*(2), 112–118. doi:10.1016/j.ijcard.2009.04.027

Salarian, A., Horak, F. B., Zampieri, C., Carlson-Kuhta, P., Nutt, J. G., & Aminian, K. (2010). iTUG, a sensitive and reliable measure of mobility. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *18*(3), 303–310. doi: 10.1109/TNSRE.2010.2047606

Sato, S., Makita, S., Uchida, R., Ishihara, S., & Masuda, M. (2010). Effect of Tai Chi training on baroreflex sensitivity and heart rate variability in patients with coronary heart disease. *International Heart Journal, 51*(4), 238–241. doi:10.1536/ihj.51.238

Seals, D. R., DeSouza, C. A., Donato, A. J., & Tanaka, H. (2008). Habitual exercise and arterial aging. *Journal of Applied Physiology, 105*(4), 1323–1332. doi: 10.1152/japplphysiol.90553.2008

Sedgman, R., Goldie, P., & Iansek, R. (1994). Development of a measure of turning during walking. In *Proceedings of the Advancing Rehabilitation Conference Proceedings* (pp. 26–31). Melbourne, Australia, Latrobe University. doi:10.1097/01.PHM.0000030730.93135.50

Shaffer, F., McCraty, R., & Zerr, C. L. (2014). A healthy heart is not a metronome: An integrative review of the heart's anatomy and heart rate variability. *Frontiers in Psychology, 5*, 1040. doi:10.3389/fpsyg.2014.01040

Shin, J. H., Lee, Y., Kim, S. G., Choi, B. Y., Lee, H. S., & Band, S. Y. (2015). The beneficial effects of Tai Chi exercise on endothelial function and arterial stiffness in elderly women with rheumatoid arthritis. *Arthritis Research & Therapy, 17*, 380. doi:10.1186/s13075-015-0893-x

Shirwany, N. A., & Zou, M. H. (2010). Arterial stiffness: A brief review. *Acta Pharmacologica Sinica*, *31*(10), 1267–1276. doi:10.1038/aps.2010.123

Shumway-Cook, A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical Therapy, 80*(9), 896–903. doi:10.1093/ptj/77.8.812

Shumway-Cook, A., & Woollacott, M. (2007). *Motor control: Translating research into clinical practice* (3rd ed.). Philadelphia: Lippincott Williams & Wilkins.

Smulders, K., van Swigchem, R., de Swart, B. J., Geurts, A. C., & Weerdesteyn, V. (2012). Community-dwelling people with chronic stroke need disproportionate attention while walking and negotiating obstacles. *Gait & Posture, 36*(1), 127–132. doi:10.1016/j.gaitpost.2012.02.002

Sörös, P., & Hachinski, V. (2012). Cardiovascular and neurological causes of sudden death after ischaemic stroke. *Lancet Neurol, 11*(2), 179–188. doi:10.1016/S1474-4422(11)70291-5

Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E. S., & Hausdorff, J. M. (2006). Dual-tasking effects on gait variability: The role of aging, falls, and executive function. *Movement Disorders, 21*(7), 950–957. doi:10.1002/mds.20848

Startzell, J. K., Owens, D. A., Mulfinger, L. M., & Cavanagh, P. R. (2000). Stair negotiation in older people: A review. *Journal of the American Geriatrics Society, 48*(5), 567–580. doi:10.1111/j.1532-5415.2000.tb05006.x

Stern, M., Chang, D., Odell, M., & Sperber, K. (2006). Rehabilitation implications of non-traumatic subarachnoid haemorrhage. *Brain Injury, 20*(7), 679–685. doi:10.1080/02699050600744269

Strobach, T., Salminen, T., Karbach, J., & Schubert, T. (2014). Practice-related optimization and transfer of executive functions: A general review and a specific realization of their mechanisms in dual tasks. *Psychological Research, 78*(6), 836–851. doi:10.1007/s00426-014-0563-7

Strong, K., Mathers, C., & Bonita, R. (2007). Preventing stroke: Saving lives around the world. *Lancet Neurology*, *6*(2), 182–187. doi:10.1016/S1474-4422(07)70031-5

Sugioka, K., Hozumi, T., Sciacca, R. R., Miyake, Y., Titova, I., Gaspard, G., … Di Tullio, M. R. (2002). Impact of aortic stiffness on ischemic stroke in elderly patients. *Stroke, 33*(8), 2077–2081. doi:10.1161/01.STR.0000021410.83049.32

Sun, H., Zou, X., & Liu, L. (2013). Epidemiological factors of stroke: A survey of the current status in China. *Journal of Stroke, 15*(2), 109–114. doi:10.5853/jos.2013.15.2.109

Takatori, K., Matsumoto, D., Okada, Y., Nakamura, J., & Shomoto, K. (2012). Effect of intensive rehabilitation on physical function and arterial function in community-dwelling chronic stroke survivors. *Topic in Stroke Rehabilitation, 19*(5), 377–383. doi:10.1310/tsr1905-377

Tanaka, H., Dinenno, F. A., Monahan, K. D., Clevenger, C. M., DeSouza, C. A., & Seals, D. R. (2000). Aging, habitual exercise, and dynamic arterial compliance. *Circulation, 102*(11), 1270–1275. doi:10. 161/01.CIR.102.1270

Tang, A., Eng, J. J., Brasher, P. M., Madden, K. M., Mohammadi, A., Krassioukov, A. V., & Tsang, T. S. (2014). Physical activity correlates with arterial stiffness in community-dwelling individuals with stroke. *Journal of Stroke and Cerebrovascular Disseases, 23*(2), 259–266. doi:10.1016/j.jstrokecerebrovasdis.2013.01.020

Task Force of the European Society of Cardiology, the North American Society of Pacing Electrophysiology (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *Circulation, 93*(5), 1043–65. doi:10.1161/01.CIR.93.5.1043

Taylor-Piliae, R. E., & Coull, B. M. (2012). Community-based Yang-style Tai Chi is safe and feasible in chronic stroke: A pilot study. *Clinical Rehabilitation, 26*(2), 121–131. doi:10.1177/0269215511419381

Taylor-Piliae, R. E., Hoke, T. M., Hepworth, J. T., Latt, L. D., Najafi, B., & Coull, B. M. (2014). Effect of Tai Chi on physical function, fall rates and quality of life among older stroke survivors. *Archives of Physical Medicine and Rehabilitation, 95*(5), 816–824. doi:10.1016/j.apmr.2014.01.001

Taylor-Piliae, R. E., Newell, K. A., Cherin, R., Lee, M. J., King, A. C., & Haskell, W. L. (2010). Effects of Tai Chi and Western exercise on physical and cognitive functioning in healthy community-dwelling older adults. *Journal of Aging and Physical Activity, 18*(3), 261–279. doi:10.1123/japa.18.3.261

Telonio, A., Blanchet, S., Maganaris, C. N., Baltzopoulos, V., Villeneuve, S., & McFadyen, B. J. (2014). The division of visual attention affects the transition point from level walking to stair descent in healthy, active older adults. *Experimental Gerontology, 50*, 26–33. doi:10.1016/j.exger.2013.11.007

Templer, J. (1992). *The staircase: Studies of hazards, falls, and safer design.* Cambridge, Mass.: MIT Press.

Thigpen, M. T., Light, K. E., Creel, G. L., & Flynn, S. M. (2000). Turning difficulty characteristics of adults aged 65 years or older. *Physical Therapy, 80*(12), 1174–1187. doi:10.1093/ptj/80.12.1174

Tsang, W. W., & Hui-Chan, C. W. (2003). Effects of tai chi on joint proprioception and stability limits in elderly subjects. *Medicine and Science in Sports and Exercise, 35*(12), 1962–1971. doi:10.1249/01.MSS.0000099110.17311.A2

Tsang, W. W., & Hui-Chan, C. W. (2004). Effect of 4- and 8-wk intensive Tai Chi training on balance control in the elderly. *Medicine & Science in Sports & Exercise, 36*(4), 648–657. doi:10.1249/01.MSS.0000121941.57669.BF

Tsang, W. W., & Hui-Chan, C. W. (2008). Sensorimotor control of balance: A Tai Chi solution for balance disorders in older subjects. *Medicine and Sport Science, 52*(1), 104–114. doi:10.1159/000134290

Tsang, W. W., Lam, N. K., Lau, K. N., Leung, H. C., Tsang, C. M., & Lu, X. (2013). The effects of aging on postural control and selective attention when stepping down while performing a concurrent auditory response task. *European Journal of Applied Physiology, 113*(12), 3021–3026. doi:10.1007/s00421-013-2740-6

Tseng, S. C., Liu, W., Finley, M., & McQuade, K. (2007). Muscle activation profiles about the knee during Tai-Chi stepping movement compared to the normal gait step. *Journal of Electromyography and Kinesiology, 17*(3), 372–380. doi:10.1016/j.jelekin.2005.12.005

Tsivgoulis, G., Bogiatzi, C., Heliopoulos, I., Vadikolias, K., Boutati, E., Tsakaldimi, S., ... Papanas, N. (2012). Low ankle-brachial index predicts early risk of recurrent stroke in patients with acute cerebral ischemia. *Atherosclerosis, 220*(2), 407–412. doi:10.1016/j.atherosclerosis.2011.11.009

Tsivgoulis, G., Vemmos, K., Papamichael, C., Spengos, K., Manios, E., Stamatelopoulos, K., ... Zakopoulos, N. (2006). Common carotid artery intima-media thickness and the risk of stroke recurrence. *Stroke, 37*(7), 1913–1916. doi:10.1161/01.STR.0000226399.13528.0a

Tsuji, T., Sonoda, S., Domen, K., Saitoh, E., Liu, M., & Chino, N. (1995). ADL structure for stroke patients in Japan based on the functional independence measure. *American Journal of Physical Medicine & Rehabilitation*, *74*(6), 432–438. doi:10.1097/00002060-199511000-00007

Tuttolomondo, A., Di Sciacca, R., Di Raimondo, D., Serio, A., D'Aguanno, G., Pinto, A., & Licata, G. (2010). Arterial stiffness indexes in acute ischemic stroke: Relationship with stroke subtype. *Atherosclerosis, 211*(1), 187–194. doi:10.1016/j.atherosclerosis.2010.02.010

Umpierre, D., & Stein, R. (2007). Hemodynamic and vascular effects of resistance training: Implications for cardiovascular disease. *Arquivos Brasileiros de Cardiologia, 89*(4), 256–262. doi:10.1590/S0066-782X2007001600008

Väänänen, J., Xusheng, S., Wang, S., Laitinen, T., Pekkarinen, H., Länsimies, E. (2002). Taichiquan acutely increases heart rate variability. *Clinical Physiology and Functional Imaging, 22*(1), 2–3. doi:10.1046/j.1475-097X.2002.00355.x

Van Sloten, T. T., Sedaghat, S., Laurent, S., London, G. M., Pannier, B., Ikram, A., ... Stehouwer, C. D. (2015). Carotid stiffness is associated with incident stroke: A systematic review and individual participant data meta-analysis. *Journal of the American College of Cardiology, 66*(19), 2116–2125. doi:10.1016/j.jacc.2015.08.888

Verheyden, G., & Ashburn, A. (2012). Stroke. In E. Stack, & M. Stokes M (Eds), *Physical management for neurological conditions* (3rd ed.) (pp.9–28). United Kingdom: Elsevier Churchill Livingstone.

Voss, M. W., Prakash, R. S., Erickson, K. I., Basak, C., Chaddock, L., Kim, J. S., ... Kramer, A. F. (2010). Plasticity of brain networks in a randomized intervention trial of exercise training in older adults. *Frontiers in Aging Neuroscience, 2*, 32. doi:10.3389/fnagi.2010.00032

Walsh, J. N., Manor, B., Hausdorff, J., Novak, V., Lipsitz, L., Gow, B., … Wayne, P. M. (2015). Impact of short- and long-term Tai Chi mind-body exercise training on cognitive function in healthy adults: Results from a hybrid observational study and randomized trial. *Global Advances in Health and Medicine, 4*(4), 38–48. doi:10.7453/gahmj.2015.058

Wang, J. S., Lan, C., Chen, S. Y., & Wong, M. K. (2002). Tai Chi Chuan training is associated with enhanced endothelium-dependent dilation in skin vasculature of healthy older men. *Journal of the American Geriatrics Society, 50*(6), 1024–1030. doi:10.1046/j.1532-5415.2002.50256.x

Wayne, P. M., Hausdorff, J. M., Lough, M., Gow, B. J., Lipsitz, L., Novak, V., … Manor, B. (2015). Tai Chi training may reduce dual task gait variability, a potential mediator of fall risk, in healthy older adults: Cross-sectional and randomized trial studies. *Frontiers in Human Neuroscience, 9*, 332. doi:10.3389/fnhum.2015.00332

Wayne, P. M., Walsh, J. N., Taylor-Piliae, R. E., Wells, R. E., Papp, K. V., Donovan, N. J., & Yeh, G. Y. (2014). Effect of tai chi on cognitive performance in older adults: Systematic review and meta-analysis. *Journal of the American Geriatrics Society, 62*(1), 25–39. doi:10.1111/jgs.12611

Wei, G. X., Xu, T., Fan, F. M., Dong, H. M., Jiang, L. L., Li, H. J., … Zuo, X. N. (2013). Can Taichi reshape the brain? A brain morphometry study. *PLoS ONE, 8*(4), e61038. doi:10.1371/journal.pone.0061038

WHO MONICA Project (1998). The World Health Organization MONICA project (monitoring trends and determinants in cardiovascular diseases): A major international collaboration. *Journal of Clinical Epidemiology, 41*(2), 105–114

Wichi, R. B., De Angelis, K., Jones, L., & Irigoyen, M. C. (2009). A brief review of chronic exercise intervention to prevent autonomic nervous system changes during the aging process. *Clinics, 64*(3), 253–258. doi:10.1590/S1807-59322009000300017

Wieloch, T., & Nikolich, K. (2006). Mechanisms of neural plasticity following brain injury. *Current Opinion in Neurobiology, 16*(3), 258–264. doi:10.1016/j.conb.2006.05.011

Wolf, S. L., Barnhart, H. X., Kutner, N. G., McNeely, E., Coogler, C., & Xu, T. (1996). Reducing frailty and falls in older persons: An investigation of Tai Chi and computerized balance training. Atlanta FICSIT Group. Frailty and injuries:

Cooperative studies of intervention techniques. *Journal of the American Geriatrics Society, 44*(5), 489–497. doi:10.1111/j.1532-5415.1996.tb01432.x

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait & Posture*, *16*(1), 1–14. doi:10.1016/S0966-6362(01)00156-4

Wu, G., Liu, W., Hitt, J., & Millon, D. (2004). Spatial, temporal and muscle action patterns of Tai Chi gait. *Journal of Electromyography and Kinesiology*, *14*(3), 343–354. doi:10.1016/j.jelekin.2003.09.002

Xi, G., Keep, R. F., & Hoff, J. T (2006). Mechanisms of brain injury after intracerebral haemorrhage. *Lancet Neurology, 5*(1), 53–63. doi:10.1016/S1474-4422(05)70283-0

Xiong, L., Leung, H. H., Chen, X. Y., Han, J. H., Leung, T. W., Soo, Y. O., ... Wong, L. K. (2013). Comprehensive assessment for autonomic dysfunction in different phases after ischemic stroke. *International Journal of Stroke, 8*(8), 645–651. doi:10.1111/j.1747-4949.2012.00829.x

Xu, D., Hong, Y., Li, J., & Chan, K. (2004). Effect of tai chi exercise on proprioception of ankle and knee joints in older people. *British Journal of Sports Medicine, 38*(1), 50–54. doi:10.1136/bjsm.2002.003335

Yamada, M., Higuchi, T., Mori, S., Uemura, K., Nagai, K., Aoyama, T., & Ichihashi, N. (2012). Maladaptive turning and gaze behavior induces impaired stepping on multiple footfall targets during gait in older individuals who are at high risk of falling.

Archives of Gerontology and Geriatrics, 54(2), e102–e108. doi:10.1016/j.archger.2011.08.012

Yang, S. J., Hong, H. C., Choi, H. Y., Yoo, H. J., Cho, G. J., Hwang, T. G., … Choi, K. M. (2011). Effects of a three-month combined exercise programme on fibroblast growth factor 21 and fetuin-A levels and arterial stiffness in obese women. *Clinical Endocrinology, 75*(4), 464–469. doi:10.1111/j.1365-2265.2011.04078.x

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2012). Do we always prioritize balance when walking? Towards an integrated model of task prioritization. *Movement Disorders, 27*(6), 765–770. doi:10.1002/mds.24963

Zeiler, S. R., & Krakauer, J.W. (2013). The interaction between training and plasticity in the poststroke brain. *Current Opinion in Neurology, 26*(6), 609–616. doi:10.1097/WCO.0000000000000002

Zheng, G., Li, S., Huang, M., Liu, F., Tao, J., Chen, L. (2015). The effect of Tai Chi training on cardiorespiratory fitness in healthy adults: A systematic review and meta-analysis. *PLoS ONE, 10*(2), e0117360. doi:10.1371/journal.pone.0117360

Zimlichman, R., Shargorodsky, M., Boaz, M., Duprez, D., Rahn, K. H., Rizzoni, D., … McVeigh, G. (2005). Determination of arterial compliance using blood pressure waveform analysis with the CR-2000 system: Reliability, repeatability, and establishment of normal values for healthy European population – The Seven European Sites Study (SESS). *American Journal of Hypertension, 18*(1), 65–71. doi:10.1016/j.amjhyper.2004.08.013

Zorzi, E., Nardello, F., Fracasso, E., Franchi, S., Clauti, A., Cesari, P., & Zamparo, P. (2015). A kinematic and metabolic analysis of the first Lu of Tai Chi in experts and beginners. *Applied Physiology, Nutrition, and Metabolism*, *40*(10), 1082–1085. doi:10.1139/apnm-2015-0064