

**Dynamic Postural Stability of Old Tai Chi Practitioners during
Obstacle-crossing**

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A thesis submitted to the

Faculty of Graduate and Postdoctoral Studies

in partial fulfillment of the requirements

for the MSC degree in Human Kinetics

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Abstract

Falls are the leading cause of injuries among Canadians who are aged at 65 years and over. The assessment of dynamic stability has been proved as an effective method to identify fall-prone elderly individuals, which is essential to fall prevention. Tai Chi has been recommended as an effective exercise to prevent falls by the American Geriatric Society and British Geriatric Society. It is important to examine dynamic stability among Tai Chi practitioners and to explore the mechanisms of the effects of Tai Chi practice on fall prevention. This study examined the dynamic postural stability which is assessed by center of mass (COM) range of motion, COM - center of pressure (COP) separation, and temporospatial measures of gait during obstacle-walking in two groups: Tai Chi group and healthy controls. Fifteen participants in each group were asked to complete two walking conditions, level walking and 20cm-obstacle walking. Results showed that when compared with Tai Chi group, control group adopted a conservative crossing strategy with a significantly smaller crossing stride, higher heel clearance, and smaller pre horizontal distance to make obstacle crossing as safe as possible. This conservative strategy indicates the inability to cross obstacle casually and it may be associated with the decline in muscle strength and proprioception. It also showed that Tai Chi practitioners displayed a significantly larger COM range of motion in both anteroposterior (AP) and mediolateral (ML) direction ($p < 0.05$) and a significantly larger COM-COP separation in ML direction ($p < 0.01$), as compared with control group. The larger range of motion of COM and distance between COM and COP indicates that Tai Chi practitioners have a better ability to tolerate unsteadiness, which means if perturbation occurs, Tai Chi practitioners have a larger range to shift COM in the boundary of base of support.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to my supervisor Dr. Li, Jing Xian for her unwavering support and mentorship throughout this project. From choosing a research topic in the beginning to the process of writing thesis, Dr. Li offers her unreserved help and guidance and lead me to finish my thesis step by step. Her expertise, understanding, and patience added considerably to my graduate experience. Without her guidance and persistent help, this thesis would not have been possible.

I would also like to thank everyone in the Human Movements Biomechanics Laboratory. Special thanks go to Nok-Yeung Law for helping me recruit participants, to Veronica Brynaert for all the help you gave me during data collection, and to Hou Wei for developing the Matlab scrips used in data process.

I am also hugely appreciative to all the volunteers, members of the Ottawa Tai Chi Chuan Association and Taoist Tai Chi Community, and also members of Ottawa Chinese Bible Church. Without your support and cooperative, the data collection cannot be completed in such a short period and in such a success. Special mentions go to Peter Chan and Roger Chagnon for helping me introduce my study and find volunteers in their Tai Chi community. I would also like to thank Rob Duan who offered free ride to volunteers living far away from our lab.

Last but not least, I would like to express my gratitude to my family for their unflinching love and unconditional support throughout my life and studies. Thank you for encouraging me in all of my pursuits and inspiring me to follow my dreams.

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List of Relevant Acronyms

1. COM = center of mass
2. COP = center of pressure
3. COG = center of gravity
4. ROM = range of motion
5. GRF = ground reaction force
6. EMG = electromyography

7. AP = anteroposterior direction
8. ML= mediolateral direction
9. COM-COP AP = the distance between COM and COP in anteroposterior direction
10. COM-COP ML = the distance between COM and COP in mediolateral direction

Chapter 1: Introduction

1.1 Research Background

The occurrence of falling is common among seniors. Each year, 28-32% of adults aged 65 and older will fall at least once and their chance of recurrence is 12-17% (Tinetti, Speechley, & Ginter, 1988; Campbell, Borrie, & Spears, 1989; Graafmans et al., 1996; O'Loughlin, Robitaille, Boivin, & Suissa, 1993; Kelsey, Browner, Seeley, Nevitt, & Cummings, 1992; Tromp, Smit, Deeg, Bouter, & Lips, 1998). In 2001, the immediate medical costs for both fatal and non-fatal injuries resulting from falls has totaled \$19.2 billion in the United States (Stevens, Corso, Finkelstein, Miller, & 2006). Aside from the financial problems, fall-related injuries, such as fractures, joint dislocations or head traumas, can lead to moderate to severe health problems (Sterling, O'Connor, & Bonadies, 2001; Alexander, Rivara, & Wolf, 1992; Tromp et al., 2001). In 2002, over 12900 seniors in US have died as a result of falling, and 1.67 million seniors were treated in emergency departments (ED) for fall-related injuries (Stevens et al., 2006).

The ability to maintain balance in the presence of interference, such as crossing an obstacle, which will challenge dynamic postural stability, is very important, particularly to seniors. Dynamic postural stability is defined as an individual's ability to maintain balance while transitioning from a dynamic state to a static state (Wikstrom, Tillman, Smith & Borsa, 2005). The act of falling happens when an individual has poor ability of maintaining dynamic postural stability DPS which can result from muscle weakness, impaired vision and decreased proprioception etc. The assessment of dynamic stability has been identified as an effective method to identify fall-prone elderly individuals, which is essential to fall prevention (Lockhart & Liu, 2008; Reynard, Vuadens, Deriaz, &

Terrier, 2013). More intriguingly, an increasing number of published papers show that stability in the medial-lateral direction is strongly associated with previous falls (Lord, Rogers, Howland, & Fitzpatrick, 1999), future fall risks (Maki, Holliday, & Topper, 1994), and recurrence of falls (Stel, Smit, Pluijm, & Lips, 2003). Consequently, it is proposed that the instability in the medial-lateral direction is highly related to the occurrence of falls. In other words, a good dynamic postural stability in the medial-lateral direction plays a vital role in decreasing the rate of fall occurrence. Therefore, by understanding the control mechanism of postural dynamic stability in the medial-lateral direction during movement, such as Tai Chi, may help people to improve their dynamic postural stability which would contribute to fall prevention.

Dynamic postural stability is associated with muscle strength, joint flexibility, proprioception and neuromuscular control. Biomechanical studies have shown that, with the increase of age, there is a tendency of decrease in muscle strength, joint flexibility, proprioception and neuromuscular control, which are major factors that relate to falls in the elderly individuals (Guralnik, Ferrucci, Simonsick, Salive, & Wallace, 1995; Kerrigan et al., 1998). Based on the main factors, seniors are recommended to exercise in order to counter the functional decline. It has been proposed that Tai Chi is one of the most effective and proper exercises for seniors in order to prevent falls (Harmer & Li, 2008). It has been recommended by the American Geriatric Society and British Geriatric Society as an effective intervention to decrease the incidence of falls (Prevention & Panel, 2001), mostly because regular Tai Chi practice has been linked to significant increase in muscle strength, improved joint flexibility and the ability to maintain balance (Choi, Moon, & Song, 2005; Li, Xu, & Hong, 2009; Hong, Li, & Robinson, 2000), all of which

are associated with fall prevention. All these benefits have potential positive influences on improving dynamic postural stability (Lord, Ward, & Williams, 1996; Scarborough, Krebs, & Harris, 1999). Evidently, regular practice of Tai Chi would lead to improvements on dynamic postural stability. Many Tai Chi movements, such as “Wave Hands in Clouds” involve displacements in the medial-lateral direction which would help increase postural stability in this direction. However, past knowledge of Tai Chi effects on postural stability is based on static postural stability studies only. The present study is currently conducting a research based on the effects of regular Tai Chi practice on dynamic postural stability and exploring the mechanism of balance control among regular Tai Chi practitioners during locomotion.

In order to understand how stability is maintained during locomotion, measurements of dynamic stability are needed (Dingwell, Cusumano, Cavanagh, & Sternad, 2001). Previous studies on dynamic postural stability have either used the whole body center of mass (COM) motion or center of pressure (COP) under feet which are separately used as indicators to examine an individual’s dynamic stability. However, it cannot predict COM movements from COP since the mechanism of balance control during a dynamic task involves maintaining the COM within the COP. Therefore, research should be focused on the relationship between them (Woollacott & Tang, 1997). It has been demonstrated that the interaction of center of gravity (COG), the vertical projection of COM, with COP is a better measurement in understanding the postural control system (Yu et al., 2008). For the most part, biomechanical or intervention studies on stability improvement have been limited to the study of static stability. The situation in which the base of support continually moves during locomotion is different with that in

a static condition and more research is needed to examine dynamic stability during locomotion. Based on the research gaps, in the present study, COP-COG was used to assess dynamic postural stability during obstacle-crossing. Obstacle-crossing is a challenging task for seniors and it is commonly encountered in daily life. Obstacle-crossing has a higher demand on maintaining dynamic postural stability because the base of support decreases in size when one foot leaves the ground resulting in higher chance of falls to occur by stepping on or tripping over obstacles (Bessot et al., 2011). Thus, investigating dynamic postural stability during obstacle-crossing is more practical and meaningful. This is expected to provide more clues to the mechanism of balance control among Tai Chi practitioners when facing some perturbations.

The purpose of this study was to examine the difference in dynamic postural stability during obstacle crossing between Tai Chi practitioners and healthy seniors who have been matched by age and physical activity during obstacle-crossing. It was expected that Tai Chi practitioners would have a better postural dynamic stability during obstacle-crossing in comparison to healthy controls. The result of this study may add understanding to the mechanism of balance control among Tai Chi practitioners and the effects of Tai Chi on dynamic postural stability.

1.2 Research question

The purpose of this study is to investigate dynamic postural stability during obstacle crossing, while focusing on the medial-lateral direction, in Tai Chi practitioners and healthy controls who are matched in age, mental condition and physical activity during obstacle-crossing. The research question is to determine if there is a difference of dynamic postural stability between Tai Chi practitioners and healthy controls when they

cross an obstacle through comparison of the measures. It was expected that the Tai Chi group would have a better dynamic postural stability than the healthy controls. The research will contribute to understand the mechanisms of how regular Tai Chi practice improves the ability to maintain dynamic postural stability and may contribute to fall prevention. Dynamic postural stability was investigated by examining variables, including: step velocity, step length, step width, hip joint angles, obstacle clearance and COM velocity, COM displacement and distance between COG and COP.

1.3 Variables

a) Step velocity, step length and step width of crossing step

The step velocity, step length and step width of the crossing step were examined in two groups (Figure 1). The crossing step is the completion from a heel-strike of the trailing limb before stepping over an obstacle to a heel-strike of the leading limb after crossing an obstacle. According to previous research, seniors walked slower during obstacle-crossing because they adopt a more conservative walking pattern (Galna, Peters, Murphy, & Morris, 2009; Chen, Ashton, Miller-Alexander, & Schultz 1991). Studies on gait patterns of healthy young adults and seniors with falling history have found a decrease of crossing speed, stride length and step width among seniors compared with young adults when crossing obstacles (Lu, Chen H, & Chen S, 2006; Hahn & Chou, 2004; Woollacott & Tang, 1997). It was proposed that seniors adopt a shorter step length in order to reduce the ground reaction force because of the instability in the sagittal plane which is difficult in maintaining an upright posture (Stegemöller et al., 2012). Also, using smaller step width among the seniors could minimize

lateral instability by reducing gravitational moment of the center of mass in the ML direction (Stegemöller et al., 2012). The time of a single limb stance while the other limb crosses the obstacle was obtained because studies on postural stability have shown participants who have a poor dynamic stability, such as Parkinson patients, spent a longer time in single limb support when the swing leg clears the obstacle (Schrodt, Mercer, Giuliani & Hartman, 2004).

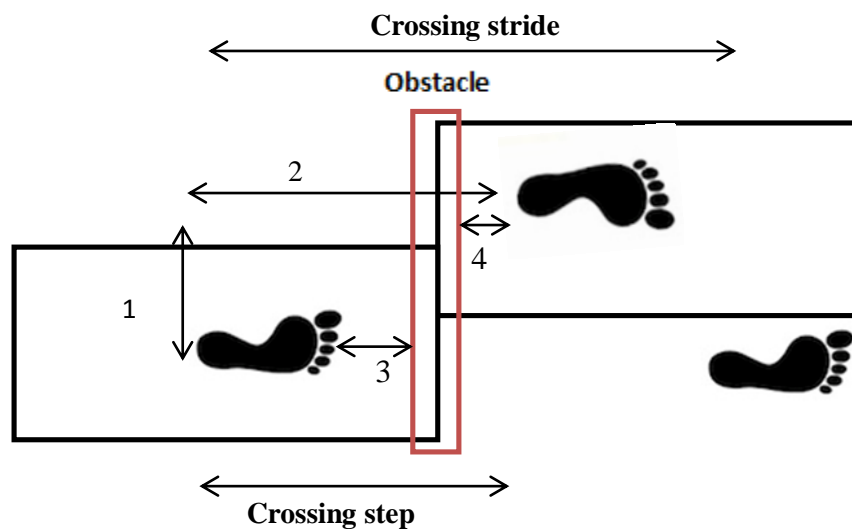


Figure 1. Illustration of crossing stride and crossing step during obstacle walking

Note: 1 step width; 2 step length; 3 pre-horizontal clearance; 4 post-horizontal clearance

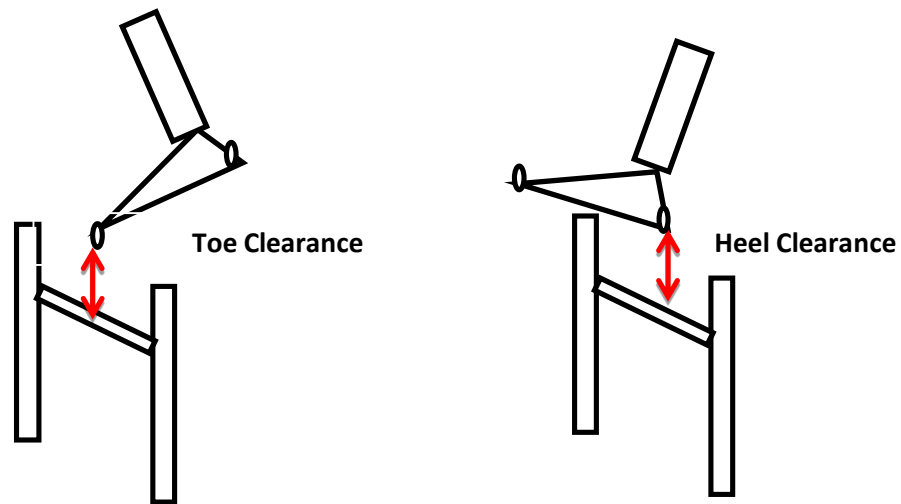


Figure 2. Illustration of vertical clearance parameters

b) Obstacle Clearance Distance

The horizontal and vertical clearance distance for both leading and trailing limb was measured. Horizontal clearance distance consists of pre and post horizontal clearance. Pre horizontal clearance is defined as the distance between toe marker on the trailing leg and the obstacle prior to crossing. Post horizontal clearance is defined as the distance between heel marker on the leading foot and the obstacle after crossing (Figure 1). A shorter pre horizontal distance before crossing and a shorter post horizontal distance after crossing have been found among participants who have a poor postural stability compared to their counterparts based on previous studies, which implied an increase in risk of tripping (Stegemöller et al., 2012; Schrodt et al., 2004; Chou, Kaufman, Rabatin,

Walker-Brey & Basford, 2004). The vertical clearance consists of toe or heel clearance (Figure 2) for the leading and trailing feet and is defined as the minimum vertical distance between the top of the obstacle and the toe or heel at the moment when the foot passes over the top of the obstacle (Chen et al., 1994). A greater mean vertical clearance (toe and heel clearance) has been found in people with poor postural stability, such as people with Parkinson disease (Stegemöller et al., 2012).

c) Hip flexion and abduction angle

Hip flexion and abduction angles of the leading foot when the limb is above the obstacle were measured during this study. Studies have shown greater leading hip crossing flexion when seniors cross the obstacle in order to make the COM closer to the leading stance foot (Hahn & Chou, 2004). As the activity of hip abductors during the swing phase determines the foot placement in the ML direction (Winter, 1995), and seniors demonstrate a more flexed and adducted angles at the hip of the supporting limb during obstacle-crossing (Galna et al., 2009). Hip flexion and abduction angles provide important information in postural stability during obstacle-crossing.

d) COM velocity and displacement, and COM-COP separation distance

In this research, COM velocity and displacement in the mediolateral direction were studied. COM motion in ML direction has been used to evaluate postural stability (Winter, 1995). Elderly patients with imbalance show significantly greater range of motion in the ML displacement and greater peak velocity compared to healthy seniors during obstacle-crossing (Chou et al., 2003).

Moreover, COM-COP separation distance (COM-COP) was examined. It is defined as the distance between the COM and corresponding COP when the leading foot crosses over the obstacle. COM-COP separation consists of the separation distance in the AP direction (COM-COP AP) and that in the ML direction (COM-COP ML) (Stegemöller et al., 2012). Studies have shown participants with balance problems maintain a significantly greater COM-COP separation during obstacle-crossing in the ML direction than their matched control participants (Chou et al., 2004).

Independent variables	Dependent variables
Tai Chi group & healthy control group	Primary variables: COM velocity (cm/s) and displacement (cm) in ML direction COM-COP AP (cm) COM-COP ML(cm)
	Secondary primary variables: Step length/step width (cm)/Step velocity (cm/s) Single limb stance time while the other limb crossing the obstacle (s) Toe clearance/heel clearance (cm) Pre/post horizontal distance (cm) Hip crossing flexion and abduction of leading and trailing foot (°)

1.4 Hypothesis

It was hypothesized that the variables which are associated with dynamic postural stability would be different between the Tai Chi group and control group. In comparison, when the Tai Chi group crosses the obstacle,

- a) Step length, step width and step velocity will be greater.
- b) Single limb stance time of the trailing limb while the other limb crosses the obstacle will be shorter
- c) Toe clearance/heel clearance distance will be smaller while pre/post horizontal clearance distance will be larger
- d) Hip flexion and abduction angles of the crossing limb will be different during obstacle-crossing.
- e) COM velocity and displacement in the ML direction will be smaller.
- f) COM-COP separation in AP and COM-COP in ML direction will be smaller

Chapter 2: Review of Literature

2.1 Tai Chi, beneficial effect on postural stability, and Tai Chi biomechanics

Tai Chi, meaning “supreme ultimate boxing” originated in China as a style of martial art based on the Taoist Philosophical principles (Sandlund & Norlander, 2000). Tai Chi which is well known for its slow and supple movements has been developed since the 17th century in China (China Sports Editorial Board, 1983). Initially, Tai Chi was practiced as a fighting form for attacking and defending. Through time it has been evolved into a slow, gentle and soft form of exercise which has beneficial effect on

improving muscle strength, balance and flexibility (Choi et al., 2005; Li et al., 2009; Hong et al., 2000). There are many different styles of Tai Chi. Five Tai Chi styles which are practiced most commonly today are the Yang, Chen, Wu, Sun and Woo styles. However, all Tai Chi styles are derived from the original Chen style and include common movements that are typical Tai Chi movements. Different Tai Chi styles differ in movement speed, frame size and other details. For example, the Chen style is the most vigorous one characterized by starting still and suddenly bursting out with fastest speed (Zhao, 2011; Wang, 2010) while the Yang style is more gentle. Although different Tai Chi styles have their own unique traits, the principle of performing Tai Chi has remained unchanged (Zhao, 2011; Wang, 2010). Nowadays, no matter what styles of Tai Chi, they are practiced primarily for health benefits by people of all ages.

Beneficial effects on postural stability

Postural stability can be defined as the ability of an individual to maintain the position of the body, or more specifically, its center of mass, within specific boundaries of space (Lord, Sherrington, Menz, & Close, 2007). Poor postural stability is one of the reasons leading to falls in elderly people. Studies have shown that elderly people who regularly practice Tai Chi have a better postural stability than those who do not (Wu et al., 2002; Wong, Lin, Chou, & Tang, 2001; Li, Xu, & Hong, 2008). Wong, Lin, Chou, & Tang (2001) examined postural stability between elderly Tai Chi practitioners and age-matched healthy controls using a series of static and dynamic balance tests. They found significant differences between the two groups in some complicated conditions, such as eye closed on sway surface and the Tai Chi group had better performances (Wong et al., 2001).

Good postural stability is associated with muscle strength, proprioception and neuromuscular control (Orr, 2010; Wu et al., 2002; Scarborough et al., 1999). Numerous studies have found regular Tai Chi practices have positive effect on improving muscle strength and proprioception (Choi et al., 2005; Li et al., 2009; Hong et al., 2000). A Tai Chi intervention of 12 weeks (Choi et al, 2005) and 16 weeks (Xu et al, 2006), in older people who were healthy or fall prone old people demonstrated significant improvement in knee and ankle joint muscle strength.

In terms of the benefit on proprioception, cross-sectional studies showed that practicing Tai Chi regularly for more than 4 years significantly improve proprioception of knee and ankle joints (Xu, Hong, Li, & Chan, 2004) and a 16-week Tai Chi intervention had a significant improvement on proprioception of the knee (Hong, Li, & Xu, 2008). Based on the large body of scientific evidence on Tai Chi's benefits on postural stability and contribution to fall prevention, the American Geriatric Society and British Geriatric Society have recommended Tai Chi as an effective intervention to decrease the incidence of falls (Prevention & Panel, 2001)

Tai Chi biomechanics

Understanding the movement characteristics of an exercise is a premise of enhancing health and preventing injury through practicing it and exploring the mechanism of its benefits. This section will review the published studies on Tai Chi biomechanics, including characteristic of Tai Chi foot movements, and joint motions, as well as changes of COM, COG and COP during Tai Chi movements.

Various foot movements are included in Tai Chi. Mao, Hong, and Li (2006) studied Tai chi foot movements by conducting motion analysis and summarized 7 foot support patterns and 6 step directions in 42-form Tai chi. They demonstrated that foot movements and step directions in Tai Chi are more various than those in normal walking. In the study, 16 experienced Tai chi practitioners performed a whole set of 42-form Tai chi. Foot double and single support durations and stepping direction were identified and compared with normal walking. They found that Tai Chi movement had more double-limb support and less single-limb support in terms of total duration. The duration of each support pattern was longer, and transitioning movement from one pattern to the next was considerably slow. The duration of each step direction was short, and changes in direction were frequent. The author concluded that the slowly changed support patterns, and various step directions is better than walking in simulating gait challenges. The characteristics of foot support pattern in this study are consistent with the results presented in several papers (Chau & Mao 2006; Wu, Liu, Hitt, & Millon, 2003). Based on the findings, it was indicated that Tai chi's effects on improving postural stability and muscle strength should be associated with its foot movement characteristics. It is obvious that more information in stride width, stride length and stride speed during Tai Chi will help in understand Tai Chi biomechanics.

In terms of joint motion, Wu and her colleagues examined the difference between Tai Chi gait and normal gait (Wu et al., 2003). The authors defined Tai Chi gait as a cyclic motion with both legs alternating between bow-leg stance (i.e. a flexed knee stance) and high swing (i.e. large knee and hip flexion) while traveling forward. They found that the maximum range of motion (ROM) of each joint in the lower extremity during Tai Chi

gait was significantly larger than that during normal gait (Wu et al., 2003, P. 347). Ankle dorsi/plantar flexion, knee flexion, hip flexion, and hip abduction were significantly larger during Tai chi gait than those during normal gait ($40\pm 9^\circ$ vs $20\pm 8^\circ$, $82\pm 8^\circ$ vs $53\pm 10^\circ$, $81\pm 7^\circ$ vs $24\pm 4^\circ$, $20\pm 8^\circ$ vs $0\pm 3^\circ$, respectively). They demonstrated that Tai Chi movements have a large ROM at the hip, knee and ankle. The large ROM could help in improving joint flexibility because joint flexibility refers to the absolute range of movements in a joint or series of joints. A study conducted by Xu, Li, and Hong (2003) examined a typical movement in Tai Chi brush knees and twist steps in six Tai Chi masters. It showed a large ROM at the knee and ankle joints while performing the movement, which were near the largest ROM of the knee and ankle joint. Recently, Law and Li (2014) reported ROM of performing two typical Tai Chi movements: “Repulse Monkey” (RM) and “Wave Hands in Clouds (WHC), which are characterized by backward walking and walking sideways respectively. The ROM of ankle in sagittal and frontal plane during RM was significantly larger than that during normal walking (Law & Li, 2014). Larger ROM may have good effect on postural stability. Many proprioceptors are located in our skin, muscles, and joints. It has been shown mechanoreceptors are activated selectively at specific angles. Some of them cannot be activated if we only do some regular exercises only involved in a small ROM, such as, running or jogging. While performing Tai Chi, which is nearly extreme of joint motion, is better at activating the different proprioceptors (Xu, Li & Hong, 2003).

Changes in center of mass (COM) and center of gravity (COG) during Tai Chi were examined for understanding postural stability in several studies. Postural stability refers to the ability to return the body close to the equilibrium point when exposed to a

perturbation (Karlsson & Frykberg, 2000). In other words, it is the ability to maintain COM over the base of foot support (BOS). The COM is a point equivalent of the total body mass in the global reference system and is the weighted average of the COM of each body segments in 3D space (Winter, 1995). COG is often defined as the vertical projection of the COM (Winter, 1995). COM and COG are measured commonly by their velocity, displacements and trajectory in three dimensions (Law & Li, 2013; Xu, Li, & Hong, 2003; Chan, Luk, & Hong, 2003). The measurements of COM and COG have been used in the evaluation of walking, running and other movements (Jurcevic & Muftic, 2002). Furthermore, they also have been used in studying balance control in which COM and COG are indicative variables of postural stability (Winter, 1995).

Studying COM is important because several reports have shown the angular deviation of COM from BOS could reflect the ability to control balance, which would be very helpful in the study of fall prevention in the elderly (Winter, 1995). In Tai Chi, practitioners constantly shift their body weight while they maintain their balance. It is necessary to examine COM during Tai Chi or the effect of practicing Tai Chi on COM, from which we can know the difference in motion control between Tai Chi and other sports. This will further our understanding of the mechanism of balance control among Tai Chi practitioners. So far to our knowledge, there are only two published papers investigating COM during Tai Chi movements. Xu, Li and Hong examined the COM displacements in six young Tai Chi master while performing Tai Chi brush knees and twist steps (BKTS). BKTS is a typical and representative movement in Tai Chi and it is included in all Tai Chi styles. Results showed that the displacements of COM in three dimensions were very large (0.54 ± 0.11 m medial-lateral direction, 0.18 ± 0.02 m

superior-inferior direction, and 1.22 ± 0.14 m anterior-posterior direction) with a slow rate of movements (Xu et al., 2003). Similar findings of COM displacements were obtained while performing two Tai Chi movements, “Repulse Monkey” and “Wave Hands in Clouds” (WHC), in 15 experienced Tai Chi practitioners aged 65 to 75 (Law & Li, 2014). Results showed vertical displacement of COM was larger for both movements compared with walking. Also, WHC has larger ML displacement of COM compared with walking. It was proposed that the large displacements of COM in Tai Chi would be very good to train postural stability because the larger COM displacements require considerable amounts of muscle strength, endurance and the capacity of neuromuscular control (Law & Li, 2014).

In terms of Tai Chi study on COG, Chan, Luk and Hong (2003) examined the characteristics of COG in a Tai chi master (49 years old) during a push movement which included ward off, roll back, press and push. The results showed the speed of the COG movements in AP and ML direction were very slow and the COG of the Tai Chi master showed a very consistent trajectory from successive pushing movements with very small variation among the trials. Based on the result, it was proposed that the master had a good control of his body because the trajectory of COG movement was steady even though he needed to shift body weight continually. The characteristics of COM and COG motion in Tai Chi suggest that it would benefit postural stability and balance.

Center of pressure (COP) is defined as the point location of the vertical ground reaction force vector and it represents a weighted average over the contact surface (Winter, 1995). The ground reaction force refers to the total force between a physical object and its contact surface. COP displacements, mean velocity of COP, and COP

trajectory are commonly used in biomechanics to evaluate human balance. The pathway of COP can predict the mode of locomotion and sense of balance (Han, Paik, & Im, 1999). A study by Wu and her colleagues examined COP excursion during static stance between a Tai Chi group with more than 3 years of experience and a control group. Results showed that the Tai Chi group had significantly smaller COP excursions in both AP and ML directions than the control group. However, smaller COP excursions may not represent a better postural stability, and examining COP alone cannot fully explain Tai Chi group had a better postural stability and regular practice of Tai Chi could reduce postural sway (Wu, Zhao, Zhou, & Wei, 2002)

2.2 Postural stability

Dynamic postural stability and COG-COP Separation Both COM and COP are vital variables in biomechanics to assess postural stability. COM is the upper equilibrium point and COP reflects the center of distribution of the total force applied to the contact surface. However, sometimes, analyzing COM or COP alone is not sufficient to evaluate dynamic postural stability. Dynamic postural stability refers to the ability to maintain COM within base of support while transitioning from a dynamic to a static state (Wikstrom et al., 2005). Maintaining stability means that the movement of the COP has to vary with the movement of the COM to control the COM over the base of support (BOS) (Corriveau, Hebert, & Raiche, 2000). In most movements, both COM and BOS moves constantly which is different with static stance during which BOS is kept stationary. In this context, to better evaluate balance during locomotion, the combined interpretation of COP and COG, the vertical projection of COM, provides better insight into the assessment of balance than COP and COM taken separately (Corriveau et al., 2000). As a result, several

studies used the distance between COP and COG to evaluate body sway during standing and walking (Winter, 1995; Jian, Winter, & Gilchrist, 1993). “COG-COP” which represents the distance at a given time between COP and COG has been suggested as a good measurement in understanding the postural control system (Yu et al., 2008). To date, there is no study on dynamic postural stability among Tai Chi practitioners using COG-COP as an indicative variable.

Dynamic postural stability and falls Thirty percent of individuals over 65 and 50% of those over 80 fall each year in community dwelling older adults. Fracture is a main result of falling and the most commonly associated age-related fractures are wrist, spine, hip, humerus, pelvis (Todd & Skelton, 2004). As a result, several studies have been carried out in order to identify the risk factors which prevent falls. Maintaining postural stability requires the cooperation of both the musculo-skeletal and sensory systems. Musculo-skeletal components include muscle, joint and body segments. Sensory systems components include vision, vestibular and somatosensory which are involved in balance and stability (Winter, 1995). The dysfunction of musculo-skeletal or sensory systems reflects a poor postural stability and may lead to fall. A good postural stability is important, especially in elderly people, because a high ability to maintain the relative motion and position of the COM with respect to the COP could decrease the risk of falls (Rogers & Mille, 2003). A previous Tai Chi study showed that regularly practicing Tai Chi could improve one’s postural stability (Wu et al., 2002), but the research is limited to the postural stability of static stance. The characteristic of dynamic postural stability among Tai Chi practitioners when perturbation happens remains unexamined.

Obstacle-crossing and Postural Stability Obstacle walking, in daily life, is a challenging locomotion task which has a high demand on postural stability. Among the complex and interactive causes of falls among old adults, tripping over obstacles during locomotion has been reported as a common reason, with about more than 50% of reported falls due to tripping (Blake et al., 1988). As a result, obstacle-crossing behaviors are usually investigated in research to examine both obstacle crossing kinematics and kinetics, which can provide a great insight into locomotor control in populations with fall risk. For example, elderly people and patients with stroke or Parkinson disease usually have impaired balance, motor weakness and decreased walking velocity. As a result, they have higher risk of falls because they cannot respond quickly and appropriately to some daily challenges, such as stairs climbing and obstacle crossing (Simpson, Miller & Eng, 2011; Jaffe, Brown, Pierson-Carey, Buckley & Lew, 2004; Plotnik, Giladi, Dagan & Hausdorff, 2011). Thus, obstacle crossing has been used as a challenging locomotion activity to quantitatively examine gait behaviors so as to get information on fall prediction and prevention (Jaffe et al., 2004; Stegemöller, Buckley, Pitsikoulis, Barthelemy, Roemmich, & Hass, 2012).

During obstacle crossing, the risk of tripping over or falling arises from either: 1) The contact between the obstacle and toe or heel of the swing limb, or 2) The instability caused by the COM being outside of the narrow BOS (Austin, Garrett, & Bohannon, 1999). Variables commonly used for predicting the risk of tripping are vertical heel clearance, vertical toe clearance, pre-horizontal distance, which is the toe-obstacle distance of the trailing limb prior to crossing over the obstacle (Pre-H) and post-horizontal distance which is the heel-obstacle distance of leading limb after crossing over

the obstacle (Post-H). Heel clearance is defined as the distance between heel marker to the obstacle when the heel of the swing limb (trailing or leading limb) is right above the obstacle. Toe clearance is defined as the distance between the toe marker to the obstacle when the toe of swing limb (trailing or leading limb) is right above the obstacle. Pre-horizontal distance (Pre-H) is defined as the distance between toe the marker on the trailing limb and the obstacle prior to crossing. Post-horizontal distance (Post-H) is defined as the distance between the heel marker on the leading foot and the obstacle after crossing. Research has demonstrated that pre or post horizontal distance is related to fall risk due to the distance between toe or heel and obstacle predicts if there is enough space for swing foot to successfully clear (Harley, Wilkie & Wann, 2009). Moreover, the horizontal foot placement before and after the obstacle plays an essential role in determining how high the trailing limb has to be lifted, namely, heel or toe clearance (Chen, Ashton-Miller, Alexander & Schultz, 1991). Chou and Draganich have examined whether the trailing foot placement prior to crossing over an obstacle would influence some related obstacle parameters, such as foot clearance, hip, knee and ankle crossing flexion. It turned out that the closer the trailing limb to the obstacle before crossing, the smaller the foot clearance of the trailing limb (not leading limb) when the toe is above the obstacle. Also, the reduction of toe-obstacle clearance resulted in decreased hip, knee and ankle flexion, which led to decreased foot clearance. Chou and Draganich thought one explanation for this is, when the trailing foot was closer to the obstacle, the time available from toe off of the trailing limb to successfully clear the obstacle was shortened and so the lower limb flexion was decreased in order to move forward. They also found the reduction of pre-horizontal distance led to a greater number of trailing foot contact with

the obstacle, which indicated risk of falling or tripping over (Chou & Draganich, 1998). The variables used to examine the risk of instability are COM velocity, COM displacement and COM-COP separation. COM motion in the frontal plane is important to when examining dynamic stability in the elderly. It has been reported that a fall to the side is one of the independent risk factors for hip fractures among frail elderly nursing home fallers (Greenspan, Myers, Kiel, Parker, Hayes & Resnick, 1998). Therefore, inadequate control of the COM in the frontal plane may lead to a fall to the side. Chou and co-workers (2003) have examined medio-lateral motion of the COM during obstacle crossing in older and young people. They found the range of motion of COM and peak COM velocity in the frontal plane were significantly greater in old participants than those in young participants during obstacle walking. They thought that the increase of COM velocity and ROM in the frontal plane resulted in the difficulty to maintain dynamic stability in the frontal plane, which may be a risk for a fall to the side (Chou, Kaufman, Hahn, & Brey, 2003). Additionally, COM-COP separation, the distance of COM relative to the corresponding COP, is an important measurement in understanding the postural control system (Yu et al., 2008), because it can reflect how the COP moves with the motion of COM. Research has shown that old adults had a smaller maximal COM-COP separation in the sagittal plane than young adults (Hahn & Chou, 2004). This indicates that old adults adopt a conservative strategy when crossing an obstacle. If COM-COP separation increases, the demand for muscle strength of the lower limb will increase because the moment arms for body weight about joints for the supporting limb increase (Hahn & Chou, 2004). So it is reasonable that old adults with a decreased muscle strength would decrease COM-COP separation in order to increase their dynamic stability.

Compared to young adults, crossing over an obstacle successfully is more challenging for old adults who have decreased muscle strength and balance control ability with age increasing. Studies have shown older adults tend to walk slower with smaller steps during obstacle crossing compared with young healthy adults (Galna, Peters, Murphy, & Morris, 2009). Prior to crossing, old adults usually place a foot closer to the obstacle compare with the young (Lu, Chen H, & Chen S, 2006). This may be due to older adults attempting to reduce instability and decrease the risk of tripping through using smaller step length. Also, when the leading foot is over the top of the obstacle, it has been shown that older adults have greater lead hip flexion and less ankle eversion (McFadyen & Prince, 2002; Lu et al., 2006).

A few studies in gait behaviors of obstacle crossing in Tai Chi practitioners were reported. Ramachandran and co-workers (Ramachandran, Rosengren, Yang, & Hsiao-Wecksler, 2006) examined the characteristics of stepping over an obstacle in fifteen middle-aged Tai Chi practitioners and compared the measures with fifteen healthy controls. They found that compared to the control group, Tai Chi practitioners used slower and shorter steps, and spent longer time in single stance when crossing an obstacle, which is similar to walking strategies used by older adults. They proposed this was due to that Tai Chi training emphasizes an awareness of one's surrounding environment and balance limitations. Thus, when challenged by perturbations, middle-aged Tai Chi practitioners tend to use more cautious gait behaviors. Also, during Tai Chi exercise, a lot of Tai Chi movements are performed to lift one leg up and only support with the other leg, which make Tai Chi practitioners comfortable and get used to stand on a single leg. Therefore, this is proposed as another reason for why Tai Chi practitioners utilize a

longer stance time during crossing. Another study examined gait characteristics in older experienced Tai Chi practitioners (over 65 years) and found different gait characteristics during obstacle crossing (Chang, Y., Huang, & Chang, J. 2015). The Tai Chi group had a significantly shorter stride time, longer stride length and faster stride velocity during obstacle crossing (in 3 obstacle height: 10%, 20%, 30% leg length) than the control group. This indicated that the Control group adopted a more cautious strategy, that is: slower stride velocity and smaller steps, to successfully cross over the obstacle. It was also shown in this study that the Tai Chi group flexed the hip more in the crossing leg than the control group, which resulted in a higher vertical clearance of both leading and trailing foot than the control group. They concluded that in order not to trip over, the Tai Chi group and control group adopted different strategies. These findings were supported by a later study which examined the effect of long-term walking and Tai Chi exercise on strategies of stepping over obstacles (Zhang, Mao, Riskowski, & Song, 2011; Chang, Y., Huang, & Chang, J. 2015). In the study, experienced Tai Chi participants (average age: 65.7 years old) crossed over obstacle (Height: 15cm & 23cm) significantly faster with larger crossing step compared to those with experienced walking participants. Also, the Tai Chi group has a larger toe distance of the trailing foot before it stepped over the obstacle and a higher foot clearance of the leading foot when it was above the obstacle. They concluded that the faster crossing speed and larger crossing stride length in Tai Chi practitioners indicated they have a greater balance control and better physical capacity because older adults with insufficient balance control will slow down and utilized a smaller step length during obstacle crossing in order not to fall.

These studies focus on examining the effect of Tai Chi on the obstacle-crossing behavior. They deduced that Tai Chi practitioners have a better dynamic stability only based on some gait parameters. However, dynamic stability, particularly in the mediolateral direction that is associated with fall risk, of old Tai Chi practitioners is still unknown during obstacle crossing, which is very critical for fall prevention. So the distance of COM and its relative COP, which is a good indicator of dynamic postural stability, should be examined.

2.3 Gaps in Literature and Research Focus

The benefits of Tai Chi practice on muscle strength, flexibility, mobility and proprioception have been well demonstrated (Choi et al., 2005; Li et al., 2009). Decreased muscle strength, flexibility, and proprioception are related to poor postural stability which is a major factor that leads to falls (Orr, 2010; Wu et al. 2002; Scarborough, Krebs, & Harris, 1999). Tai Chi was proposed as an exercise which could prevent falls through improving postural stability. Studies need to be done to further examine the benefits of practicing Tai Chi on dynamic postural stability, which will have a significant implication on fall prevention. To date, research on postural stability among Tai Chi practitioners is limited to static stance. However, falls usually happen during walking which is a dynamic task and maintaining dynamic postural stability becomes more challenging. Interestingly, an increasing number of published papers show that postural stability in the medial-lateral direction is strongly associated with past falls (Lord et al., 1999), future fall risks (Maki et al., 1994), and recurrent falling (Stel et al., 2003). Consequently, dynamic postural stability in the medial-lateral direction among Tai Chi

practitioners is the focus of the present study. From this study we will have a better understanding of the relationship between Tai Chi and fall prevention.

Chapter 3: Methodology

3.1 Participants:

A total of 30 participants, both males and females (age: 65-75 years old), were recruited in this study to form two groups: a Tai Chi group and a healthy control group. Both the Tai Chi group and healthy control group recruited were matched for age and physical level. The Tai Chi group was composed of 15 Tai Chi practitioners who had practised Tai Chi 3-4 times a week and 1-2 hours each time for at least a 4-year experience, but were not involved in any other regular physical activity. The group of healthy controls also included 15 participants who had engaged in exercise such as jogging, swimming, bicycling for 3-4 times a week and 1-2 hours each time during the past 4 years or more, but had no Tai Chi experience. The physical activity level was examined and compared between the two groups based on a survey that they were asked to fill out in the participants' preparation section. Participants did not have previous balance impairments, neurological or musculoskeletal disorder.

Participants were recruited through poster and online advertisements, as well as through local community centers and Tai Chi community where Tai Chi programs are offered regularly.

3.2 Instruments

Motion Analysis System

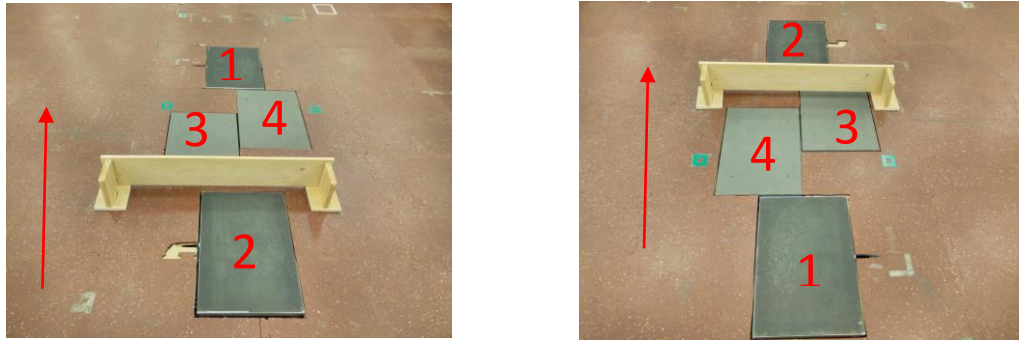
A Vicon Motion Analysis System with ten infra-red, high-speed, optical cameras (Vicon MX-13, Oxford Metrics, Oxford, UK) was used to capture obstacle walking motion 3 dimensions and recorded at 200HZ. All cameras were either hung from the ceiling or mounted on individual tripods.

Force plates & walkway

The ground reaction force generated during obstacle walking was collected using two force plates (models 9286AA, Kistler Instruments Corp, Winterthur, Swtz; FP 4060-08, Bertec Corporation, Columbus, OH, USA) embedded in the floor and recorded at 1000HZ. The arrangement of two force plates allowed participants step on them before and after obstacle-crossing (Figure 3). The walkway was eight meters long and the middle three meters of the walking path was used for data recording.

Obstacle

The obstacle was composed of two upright upholders and one crossing plank which was collapsible and connected with two upholders by magnets. This allowed it to be easily dislodged with any contact and thus prevent participants from falling if they do not clear the obstacle. The obstacle was 20 cm high which is similar to that might be encountered in daily activity. For example, 20 cm is similar in height to most curbs or stairs (Chou et al., 2003). The obstacle was placed in the center of the two force place and will be easily visible to the participants (Figure 3).



a when right leg is dominant

b when left leg is dominant

Figure 3. Illustration of force plates and obstacle placement

3.3 Participation preparation procedure

Participants were given a detailed explanation of the research purpose and data collection process. Then they were provided a written informed consent before testing. Participants were asked to change into a tight black T-shirt and spandex shorts that were provided. Then they were given a survey related to their exercise experience and activity level (Appendix 2). Anthropometric measurements of height (mm), body mass (kg), leg length (mm), knee width (mm) and ankle width (mm) and so on were recorded (Appendix 3). A total of thirty-nine reflective markers were placed over bony landmarks according to the Plug-in-Gait marker system (Appendix 4). Participants were allowed to get familiar with the walkway and the gait test. The starting position was selected by the help of researchers to ensure participants can walk comfortably before encountering the obstacle.

3.4 Testing protocol and Data Collection

The system was calibrated, including two parts, prior to the testing: a dynamic calibration followed by a static calibration. A T-shaped wand (240mm) with three reflective markers was used to perform dynamic calibration recorded at 3000HZ. A static calibration followed using an L-shaped frame (EergoCal, 14mm) placed on the floor in order to establish the origin of the global coordinate system.

Once participants get well prepared, they were asked to do a static trial first. They stood in the center of the testing volume. This was to allow cameras to pick up all the relative markers attached on the body and create the 3D model. The static trial lasted about 5 seconds. Then for the testing procedure, all participants were asked to complete two tasks: normal walking and obstacle-crossing. During level walking, participants walked barefoot along the pathway at their preferred pace. During obstacle-crossing, participants were asked to choose their dominant limb as the supporting limb during crossing. They were asked to step over the 20cm obstacle located in the middle of the two force plates and kept walking until the end of the walk way. If the right leg is dominant, the obstacle would be placed as Figure 3a and the data of force plate 2 and 3 will be used. If the left leg is dominant, the obstacle would be placed as Figure 3b and the data of force plate 4 and 2 would be used. Five successful trials for each condition (walking and obstacle-crossing) were collected for each participant. A successful trial was accepted when participants walked naturally and lost no markers.

3.5 Data processing and Analysis

The present study will analyze the movement in three dimensions when participants cross the obstacle. The crossing stride, which is defined as a gait cycle, of each trial for each participant will be analyzed.

Step velocity, step length and step width; hip, knee and ankle angles; obstacle clearance distance

One successful crossing step is defined by the completion of heel-strike of the trailing limb before stepping over the obstacle to the heel-strike of the leading limb after crossing the obstacle. Heel-strike and toe off moments are determined by visually inspecting the position of the virtual markers on the heel and toe. Crossing step is defined in this study by the completion of heel-strike of the trailing limb before stepping over the obstacle to the heel-strike of the leading limb after crossing the obstacle. Step length, step width and step velocity of the crossing step were calculated from motion capture data (Figure. 4).

Toe or heel clearance for the leading and trailing feet is defined as the minimum vertical distance between the top of the obstacle and the toe or heel at the moment the foot passes over the top of the obstacle (Chen, Ashton-Miller, Alexander, & Schultz, 1994). Heel and toe clearance were calculated as the difference between the markers on the heels/toes and the height of the obstacle in vertical direction. Pre-horizontal clearance is defined as the distance between the toe marker on the trailing leg and the obstacle prior to crossing. Post horizontal clearance is defined as the distance between the heel marker on the leading foot and the obstacle after crossing. Horizontal clearances were calculated

as the distance between heels/toes markers and the marker attached on the obstacle in the AP direction.

Hip, Knee and ankle angles at the moment when the leading toe was above the obstacle in the ML and AP directions were calculated for the leading limb. The kinematics for the hip, knee and ankle were obtained using VICON Nexus (Oxford, UK) and the Plug-in-Gait model (Oxford Metrics, Oxford, UK). The computed lower limb data was exported to Matlab (MathWork, Natick, USA) to calculate and retrieve the hip, knee and ankle angles when the leading toe was above the obstacle of each trial.

COM velocity and displacements, COG-COP separation distance

A crossing stride is defined by the completion from the heel strike of the trailing limb before obstacle-crossing to the heel strike of the trailing limb after obstacle-crossing. The maximal velocity of COM and COM displacements in both AP and ML directions were analyzed during the crossing stride. The kinematics of COM were obtained using VICON Nexus (Oxford, UK) and the Plug-in-Gait model (Oxford Metrics, Oxford, UK). The max COM velocity and max and min COM displacements in both AP and ML directions were computed by VICON Polygon 4.0 (VICON Motion System, Los Angeles, USA). COM ROM was calculated through max & min COM displacements obtained by VICON Polygon in excel. The COP under the stance foot during single leading limb stance phase when participants cross the obstacle was computed based on the measured ground reaction force. Both the trajectory of COP and COM in AP and ML directions of single trailing limb stance phase (from toe-off of leading limb before crossing to heel-strike of leading limb after crossing) were retrieved using Matlab (MathWorks, Natick,

USA) and the distance between COM and corresponding COP in AP and ML directions were calculated based on the Matlab scripts.

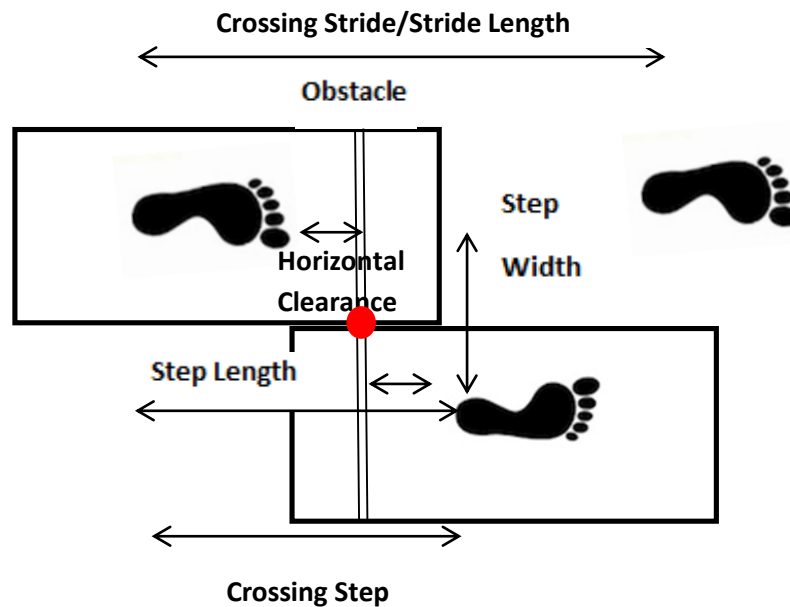


Figure 4. Illustration of gait parameters calculated for the crossing stride

Note: ● a marker that is attached on the obstacle and used to calculate horizontal distances and foot clearance.

3.6 Statistical Analysis

Means and standard deviation were obtained for all variables. Independent-t test was used to examine significant differences in all variables between groups separately in level walking and obstacle crossing. The significant difference level is set at 0.05. All statistical analyses were performed using SPSS (Statistical Package for Social Science) 17.0 software.

Chapter 4: Results

This study aimed to examine the difference in dynamic postural stability between Tai Chi practitioners and healthy seniors who have matched age and physical activity level during obstacle-crossing, especially in the medial-lateral direction. All participants were able to complete the experimental trials without any discomforting. Participants in the Tai Chi group only had Tai Chi experience and were not involved in any other regular physical activity. The group of healthy controls did not have Tai Chi experience, but they practiced other regular exercise. In this study, nine of them engaged in walking, three of them were involved in running and two of them practiced biking. Only one practiced badminton with 5 years' experience. Independent t – test showed that there were no significant differences between groups for age, height, weight, exercise experience or activity level. The details of subject demographics and exercise behaviors are presented in Table 1. All data are reported by mean and standard deviation (SD). The results for the temporospatial parameters and joint motion are given in Tables 2 and 3, respectively. The measurement results for obstacle clearance, COM motion and COM-COP separation are reported in Tables 4, 5 and 6, respectively. The p-values obtained by independent-t test are provided for each variable in the tables.

Table 1. Participants demographics and exercise behaviors (Mean \pm SD)

	Tai Chi (n=15)	Control (n=15)	p-Value*
Male	8	7	-
Female	7	8	-
Mean age (yr)	70.33 \pm 3.35	70.13 \pm 3.77	0.89
Body weight (kg)	65.01 \pm 12.03	68.16 \pm 12.72	0.49
Body height (cm)	164.08 \pm 10.34	165.74 \pm 9.89	0.65
Type of activities			
Walking	-	9	-
Running	-	3	-
Biking	-	2	-
Other	-	1	-
Years of experience	11.4 \pm 5.87	7.4 \pm 9.14	0.16
Activity level			
days/week	3.77 \pm 0.78	4.00 \pm 1.16	0.52
Hours/per time	1.30 \pm 0.49	1.13 \pm 0.29	0.27

4.1 Temporospatial parameters

Table 2. Gait temporospatial measurements for both groups during level walking and obstacle walking (Mean \pm S.D.)

	Level Walking		p-Value	Obstacle Walking		p-Value
	Control	Tai Chi		Control	Tai Chi	
Stride length(LL)	1.37 \pm 0.14	1.45 \pm 0.14	0.15	1.43 \pm 0.08	1.53 \pm 0.15*	0.039
Step length (LL)	0.69 \pm 0.07	0.73 \pm 0.06	0.09	0.76 \pm 0.06	0.79 \pm 0.08	0.25
Step width (LL)	0.12 \pm 0.05	0.12 \pm 0.04	0.98	0.07 \pm 0.05	0.10 \pm 0.06	0.12
Step Velocity (m/s)	1.14 \pm 0.10	1.17 \pm 0.13	0.61	0.96 \pm 0.19	0.99 \pm 0.19	0.56
Trailing single stance time (s)	0.426 \pm 0.03	0.425 \pm 0.03	0.97	0.61 \pm 0.08	0.58 \pm 0.05	0.24

*, $p < 0.05$ vs Control group in obstacle walking. LL: leg length. Stride length, step length and step width were normalized to leg length.

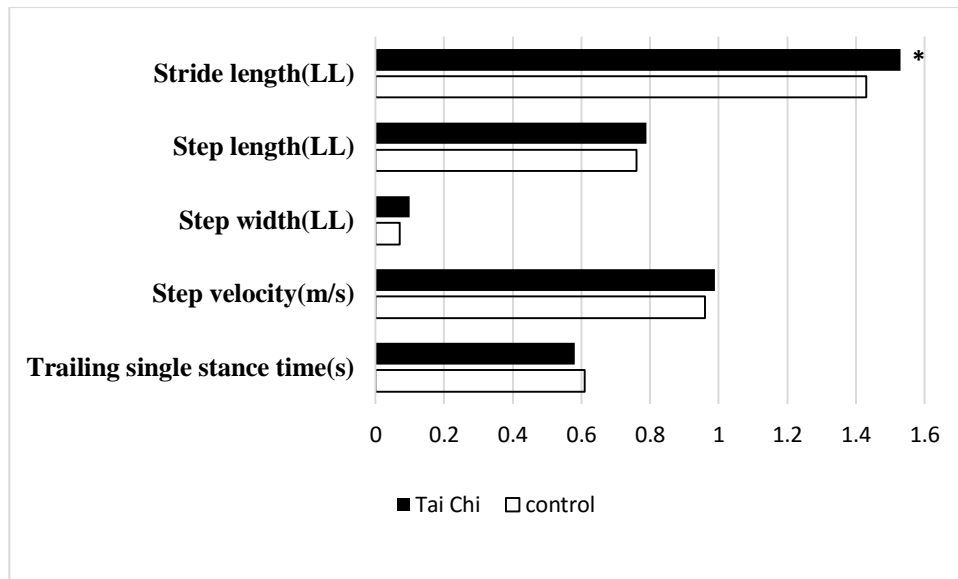


Figure 5. Temporospatial variables for both groups during obstacle walking. *, $p < 0.05$ vs Control group.

No significant difference was found during level walking for temporospatial variables between groups. However, during obstacle walking, crossing stride length was significantly larger for the Tai Chi group than the control group. Also, compared with the control group, when the Tai Chi group crossed the obstacle, step length, step width and step velocity were larger and single limb stance time of the supported limb while the other limb crossing the obstacle was shorter, though magnitude of these differences did not reach a significant level.

4.2 Joint angles

Table 3. Joint angles (degree) of leading limb for both groups when leading toe was directly above the obstacle (Mean \pm SD)

	Control	Tai Chi	p-Value
Hip joint			
Flexion	65.61 \pm 8.48	63.20 \pm 5.71	0.41
abduction	5.07 \pm 8.00	7.65 \pm 6.70	0.36
Knee joint			
Flexion	96.80 \pm 10.06	88.39 \pm 15.79	0.10
Adduction	15.53 \pm 9.35	33.08 \pm 15.35**	0.002
Ankle joint			
Dorsiflexion	21.30 \pm 3.74	13.46 \pm 5.59**	0.00
Inversion	6.62 \pm 4.39	1.85 \pm 3.01**	0.00

** , p<0.01 vs Control group

Table 3 presents the joint angles of the hip, knee and ankle in the frontal and sagittal planes when the leading toe was vertically above the obstacle. Participants in the Tai Chi group exhibited a significantly smaller ankle dorsal flexion and inversion angle than the control group during obstacle-crossing. In terms of hip and knee joint, the control group presented with greater knee flexion and smaller hip abduction than the Tai Chi group when the leading toe was above the obstacle, though the magnitude did not reach statistical significance. Figure 6 illustrate the patters of hip, knee and ankle joint trajectories from the leading foot off before crossing to the leading foot strike after crossing from one of representative participants in the two groups respectively. Time was normalized to 100% stance phase of trailing limb when the leading limb was crossing.

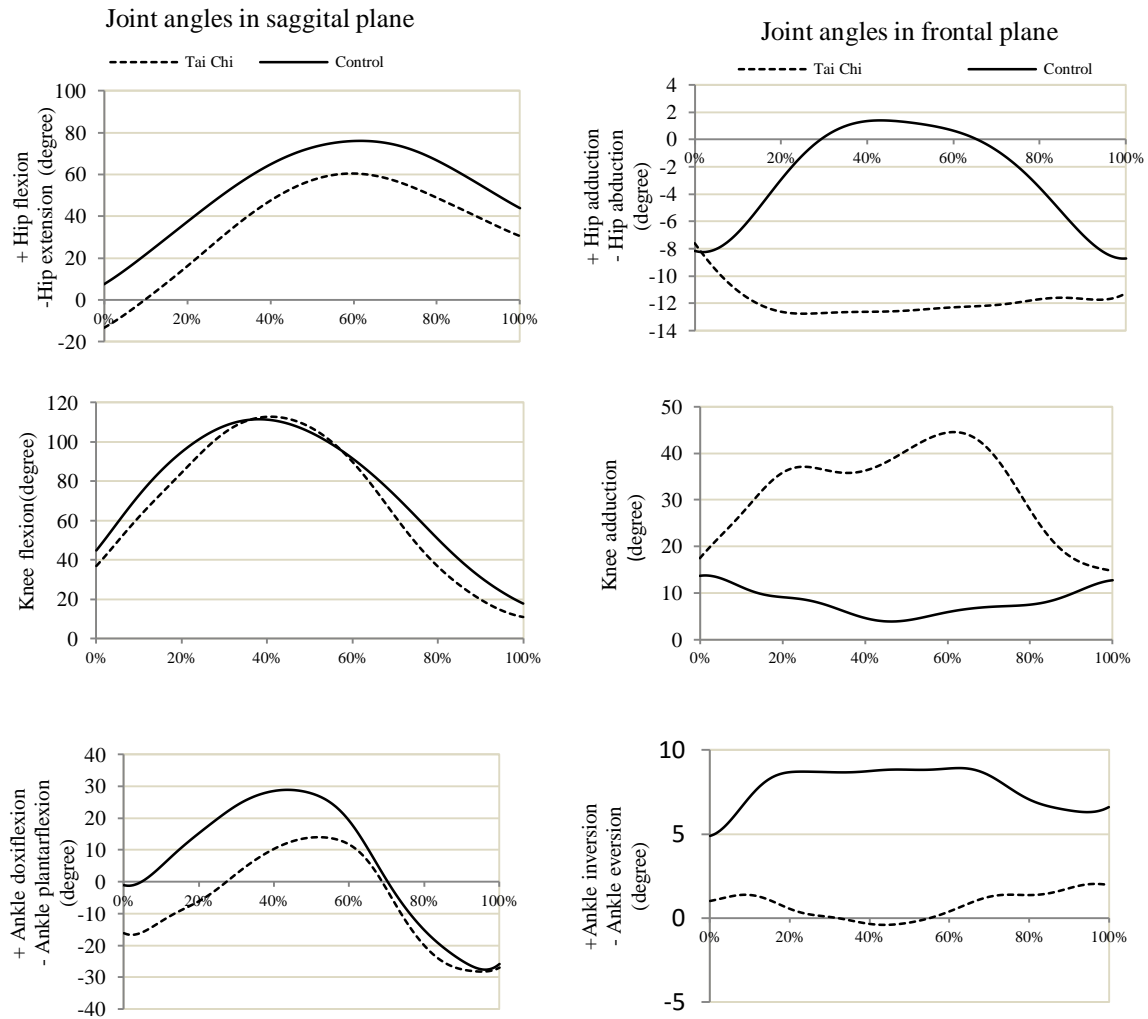


Figure 6. Typical Profiles of leading hip, knee and ankle trajectories in sagittal plane (left) and frontal plane (right) from leading foot off to leading foot strike.

4.3 Obstacle clearance parameters

Table 4. Foot clearance measurements (the absolute and normalized value) for both groups in obstacle walking (Mean±SD)

	Control	Tai Chi	p-Value
Leading heel clearance(cm)	13.45±2.73	9.9±3.89*	0.02
Leading toe clearance(cm)	15.85±2.93	13.91±3.63	0.16
Trailing heel clearance(cm)	32.47±5.10	30.75±5.65	0.44
Trailing toe clearance(cm)	13.17±4.11	12.93±5.10	0.90
Leading heel clearance (LL)	0.16±0.03	0.12±0.05*	0.01
Leading toe clearance(LL)	0.18±0.03	0.16±0.05	0.16
Trailing heel clearance(LL)	0.37±0.05	0.36±0.07	0.52
Trailing toe clearance(LL)	0.15±0.04	0.15±0.07	0.96
Pre horizontal distance(LL)	0.25±0.06	0.30±0.06*	0.05
Post horizontal distance(LL)	0.26±0.04	0.25±0.08	0.63

*, P<0.05 vs Control group in obstacle walking. LL: leg length.

As seen in Table 4, participants in the Tai Chi group exhibited a smaller mean vertical heel clearance height of both the leading and trailing feet, and significance was only found between groups in heel clearance of leading limb. Additionally, participants in the control group placed their trailing foot (supported limb) significantly closer to the obstacle prior to stepping over.

4.4 Dynamic stability parameters

COM motion

Table 5. COM motions for both groups in ML and AP direction during obstacle-crossing stride (Mean ±S.D.)

	Control	Tai Chi	p-Value
COM ROM ML (cm)	4.60±1.76	6.39±2.13*	0.039
COM ROM AP (cm)	125.83±10.01	139.16±1.56*	0.025
Normalized COM ROM ML (BH) ^a	0.028±0.01	0.040±0.01*	0.028
Normalized COM ROM AP (BH) ^a	0.73±0.06	0.84±0.07**	0.001
Max. COM velocity ML (m/s)	0.11±0.04	0.14±0.06	0.219
Max. COM velocity AP (m/s)	1.01±0.30	1.11±0.31	0.462

*, $p < 0.05$ vs Tai Chi group during obstacle-crossing. **, $p < 0.01$ vs Tai Chi group during obstacle-crossing. ^a, COM range in ML and AP directions were normalized to body height.

Table 5 presents COM range of motion and maximal COM velocity for both groups in ML and AP directions during obstacle-crossing stride. One crossing stride, which is defined as a gait cycle in this study, is the completion of heel-strike of the trailing limb before stepping over the obstacle to the heel-strike of trailing limb after crossing the obstacle. The data analysis showed the Tai Chi group had a significantly larger COM range of motion than control group in both ML and AP directions. In addition, after normalizing COM range of motion to body height of participants, significance of COM range of motion for both groups were still found in ML and AP directions. Participants in the Tai Chi group exhibited a larger normalized COM ROM in ML and AP directions. No significant difference was found in maximal COM velocity during obstacle-crossing stride between groups.

COM-COP separation

Table 6. Normalized maximal and minimal COM-COP separation in ML and AP direction for both group during obstacle-crossing (Mean \pm S.D.)

	Control	Tai Chi	p-Value
Max. COM-COP ML	0.046 \pm 0.01	0.064 \pm 0.02**	0.009
Min. COM-COP ML	0.019 \pm 0.01	0.033 \pm 0.12**	0.004
Max. COM-COP AP	0.279 \pm 0.04	0.306 \pm 0.07	0.22
Min. COM-COP AP	0.001 \pm 0.00	0.001 \pm 0.00	0.98

**, $p < 0.01$ vs Control group; The distance between COM and COP in ML and AP directions were normalized to leg length.

Table 6 presents the data analysis results of maximal and minimal COM-COP separation for both groups in the ML and AP directions during the trailing limb single stance phase. It refers to the completion of toe off of leading limb prior to stepping over the obstacle to heel strike of leading limb after stepping over. The Tai Chi group presented a significantly larger max COM-COP separation than the control group in the ML direction, and also a significantly larger min COM-COP separation compared to control group in the ML direction. In the AP direction, a larger maximal COM-COP separation in the Tai Chi group was noticed in comparison to control group, though the magnitude did not reach statistical significance.

Chapter 5: Discussion

The aim of the present study was to examine dynamic postural stability during obstacle crossing in older Tai Chi practitioners with regular Tai Chi practice experience and healthy controls with matched age and exercise experiences, but not Tai Chi. Especially, we wanted to study if there were dynamic stability differences in the ML direction between the groups, and eventually directed into exploring the mechanisms of the effects of Tai Chi practice on fall prevention because Tai Chi has been recommended as an effective exercise to prevent falling by professional bodies (Prevention & Panel, 2001). The findings of this study showed that the Tai Chi and control group demonstrated significant difference in dynamic stability during obstacle-crossing, especially in the ML direction. Compared to the control group, the Tai Chi group showed significantly larger COM range of motion and COM-COP separation in the ML direction, indicating significantly better dynamic stability in this direction. To our knowledge, this is the first study to investigate dynamic stability in the ML direction in Tai Chi practitioners and to

compare with participants who are matched in age and exercise habit. Moreover, we used COM-COP separation as one of the measures of dynamic postural stability that has been suggested as a good measurement in understanding the postural control system (Yu et al., 2008).

5.1 Temporospacial parameters

Data from our study showed that stride length was significantly larger in the Tai Chi group than the control group during obstacle walking, which is in keeping with the result of a previous study (Chang, Huang, & Chang, 2015). Previous published research has found that young people have significantly larger stride length than old people during obstacle crossing (Rosengren, McAuley, & Mihalko, 1998; Galna, Peters, Murphy, & Morris, 2009). Using a short stride strategy among seniors implies their inability to cross the obstacle with long steps. Therefore, shorter stride is an aging-related change and would be a sign of inability. Similarly, reduced stride length during obstacle walking was also found in the patients with imbalance, such as Parkinson and stroke patients (Stegemöller et al., 2012; Said, Goldie, Patla, Culham, Sparrow, & Morris, 1999; Vitória, Pieruccini-Faria, Stella, & Gobbi, 2010). The decreased stride length in patients with balance problem also indicates the difficulty for them to lengthen steps during crossing.

Exercise trainings have some positive impacts in improving gait behavior in older people during obstacle walking. Guadagnin and his co-worker (2015) examined gait behaviors during obstacle crossing among active elderly who were aged 71 ± 8 years and practiced regular exercises 3 times per week, and sedentary counterparts who were aged 63 ± 3 years and without regular physical exercise. They found that, participants who did regular physical exercise displayed a larger crossing stride than the sedentary participants

(Guadagnin, Rocha, Mota, & Carpes, 2015). Furthermore, an exercise intervention study examined the effect of a 12-week aquatic training program on the obstacle-crossing behaviors among older adults aged 77 ± 5 years (Lim & Yoon, 2014). The aquatic exercise program was conducted 3 times per week and 60 minutes per time. The exercise included 10 minutes' warm-up and 10 minutes cool down which were mostly stretching, as well as 40 minutes' main exercise which consisted of running, forward and sidewalks, cross-stepping, and lunge. The results showed old adults used a larger crossing step after the 12-week aquatic training. These studies demonstrated that regular exercise can benefit on the ability to utilize a larger stride length during obstacle crossing.

Given the comparison of crossing stride length in above paragraphs, the larger crossing stride strategy adopted by the Tai Chi group was similar to the strategy used by young adults (Rosengren, McAuley, & Mihalko, 1998; Galna, Peters, Murphy, & Morris, 2009), and active seniors (Guadagnin, Rocha, Mota, & Carpes, 2015). In contrast, the participants with a smaller crossing stride adopted a conservative strategy, which may be caused by their instability during obstacle crossing. Conservative strategy during obstacle crossing is characterized by shorter stride length and step length, reduced stride speed, longer trailing limb single stance time, smaller pre-horizontal distance and higher heel clearance (Stegemöller et al., 2012; Schrodte et al., 2004; Chou, Kaufman, Rabatin, Walker-Brey & Basford, 2004). These characteristics of conservative strategy may be resulted from much cautious attention drawn by participants. It is also associated with several factors, such as instability, fear of falling, weak muscle strength, worse flexibility and proprioception (Harley, Wilkie, & Wann, 2009; Hahn & Chou, 2004; Lu, Chen H, & Chen S, 2006; Stegemöller et al., 2012). The major factor that leads to a conservative

strategy is instability, which is caused by weak muscle strength, limited range of motion and poor proprioception. These factors taken together result in fear of falling among seniors. Thus, they prefer a more conservative and safe way to complete the task. In our study, the Control group adopted a conservative strategy and this is supported by following evidences and reasons. First, individuals in the control group might have a greater concern of safety by slowing down their speed and reducing their crossing stride length because they were fearful to fall. It has been suggested that decreased crossing stride lead to improved balance by decreasing time in the single support phase (Rosengren, McAuley, & Mihalko, 1998). The control group tried to enhance their stability by a shorter crossing stride as the swing time of the leading limb would be decreased. Second, reduction of stride length, step width in the control group may also be related to compensation for instability. It has been shown the decrease in stride length and step width would lead to greater stability in the AP and ML directions, respectively (Stegemöller et al., 2012). The reduced stride length and step width in the control group could help them to confine COM motion in a small range in both AP and ML directions and thus to keep COM in the base of support. At last, participants in the control group might have weaker muscle strength than the Tai Chi group. The moment of arms of body weight about supporting joint during crossing will increase with a larger stride length because the body COM is further from the supporting joint (Hahn & Chou, 2004). More mechanical load is added to the supporting joint by using a larger crossing stride, which have a higher demand on the muscle strength to maintain joints stability. This also indicates that the Tai Chi practitioners have a stronger muscle strength which help them to tolerate the larger mechanical load on supporting joint. In contrast, participants in the

control group reduce their stride length because of the inability to sustain the supporting limb.

All participants recruited either in the Tai Chi group or the control group in our study were active elderly. The participants in the control group and the Tai Chi group had similar exercise background, in terms of exercise intensity, duration and frequency. The major difference between the two groups is exercise types which may be a main reason leading to the different crossing strides between two groups. Based on above explanations, the larger stride length utilized by Tai Chi group is related to the stronger muscle strength and better postural stability. In fact, published study from Xu and co-workers (2006) has already proved that regular Tai Chi practice can not only improve knee and ankle muscle strength and endurance as same as regular jogging in elderly, but also had a significant improvement on the knee extensor endurance and ankle dorsiflexor strength than jogging. Moreover, regular Tai Chi has an effect on improving proprioception in the knee and ankle. Improved muscle strength and proprioception are related to good postural stability, which can decrease fall risks (Orr, 2010; Wu et al.2002; Scarborough, Krebs, & Harris, 1999). Taken together, Tai Chi practitioners with a larger crossing stride had better postural stability and muscle strength of lower limb, as well as more confidence to cross over without tripping.

5.2 Joint motion of lower limb

In the sagittal plane, our data showed that the control group applied a larger hip, knee, and ankle crossing flexion when compared to the Tai Chi group. The same strategy of the larger flexion of lower limb in the sagittal plane was also reported among older adults during crossing, as compared to the young adults (Lu, Chen H, & Chen S, 2006;

Hahn & Chou, 2004). Lu and his colleagues examined crossing joint kinematics among fifteen older adults (72 ± 6 years old) and fifteen young adults (23 ± 3 years old) when they crossed over different heights of obstacles (obstacle heights: 10%, 20%, 30% leg length). They found older adults showed a larger hip and knee flexion in all conditions than young adults. It was proposed that an increased hip, knee, and ankle flexion can contribute to a higher toe clearance, which would decrease the risk of tripping. Also, studies have shown greater hip crossing flexion of the leading foot when the old adults cross the obstacle can make the COM closer to the leading stance foot (Hahn & Chou, 2004). In this way, the COM is closer to the COP, which improves the stability in the sagittal plane.

The larger flexion of lower limb was also found among patients with imbalance. Patients with Parkinson disease preferred to adopt a pelvic hiking strategy to achieve the safe foot clearance (Galna, Murphy, & Morris, 2013). It has been suggested a more flexed hip in AP direction rather than the hip abduction in the ML direction can contribute to the stability during crossing as the flexed hip can draw the COM closer to the base of support (Lu, Chen H, & Chen S, 2006). Similarly, larger hip, knee and ankle flexion will make the COM of the segments (thigh, calf and foot) closer to the base of support, which will make body COM closer to COP. The flexion of lower limb may be a compensate of instability. Based on the above evidences, we think the strategy of large flexion in lower limbs is more often adopted by individuals with imbalance who are more cautious when crossing an obstacle. Tai Chi practitioners in our study with a smaller flexion angle in sagittal plane is considered as individuals with more confidence and better balance.

The effect of exercise on joint kinematic among older adults in obstacle crossing was also reported in a previous study (Lamoureux, Sparrow, Murphy, & Newton, 2003). Sixteen participants in the control group and twenty-nine participants in the experimental group were recruited in their study. Only participants in the experimental group underwent a 24-week progressive resistance-training program targeting five lower body muscle groups which were hip flexion and extension, knee flexion and extension, ankle plantar flexion. They found participants in the experimental group significantly reduced knee and ankle crossing flexion in obstacle crossing after this resistant training program. This may be due to the increase of the muscle strength after training and participants can better control the lower limb during crossing with a greater confidence. A more important reason may be that the targeting training of lower limb improved the proprioception of participants' joints of lower limbs. A better joint proprioception can contribute to a more accurate sensation of joints with a smaller threshold (Xu, Hong, Li, & Chan, 2004), which may lead to a smaller foot clearance caused by the reduced flexion angles among participants. Therefore, a smaller lower flexion of lower limb in the AP direction during crossing is an indicator for a better joint proprioception.

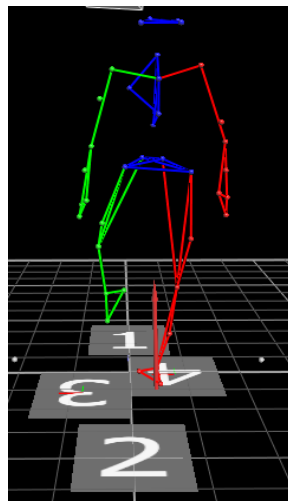
In the frontal plane, participants in the Tai Chi group had a larger hip abduction, knee adduction and smaller ankle inversion than the participants in control group. In order to cross over the obstacle, Tai Chi practitioners were more inclined to alter the joint angles in the ML direction, as presented in Figure 7 below. In the Tai Chi group, the lower limb displayed a greater hip abduction and a greater knee adduction, which is hip was lifted more outward and knee was lifted more inwards. The reason that the Tai Chi practitioners prefer to use a ML strategy might be associated with the characteristics of

some Tai Chi movements. In Tai Chi practice, foot movement patterns are much more complicated than walking because Tai Chi involves many movements and foot placements in different directions. The Tai Chi practitioners often stand on one single leg and some movements are very similar to the pattern shown in Figure 7 (Hong & Li, 2006; Chau & Mao 2006; Wu, Liu, Hitt, & Millon, 2003). For example, stepping sideways is one of the main stepping directions in Tai Chi and the lower joint of the swing leg in this movement displayed exactly the same pattern which is abducted hip and adducted knee (Mao, Hong, & Li, 2006; Chau & Mao 2006). Additionally, it has been proved Tai Chi involves a lot of movements occurring in frontal plane, which are resulted from overall greater lateral motion of hip, knee and ankle (Law & Li, 2014; Jagodinsky, Fox, Decoux, Weimar, & Liu, 2015). Another possible reason that the Tai Chi practitioners were able to have bigger joint motions in ML direction would be related to their greater stability in this direction than the control group. Winter found the activity of hip abductors during swing phase determined the foot placement in the mediolateral direction (Winter, 1995). Hip abductors play an important role to adjust step width and control balance in the frontal plane. The more abducted hip in Tai Chi practitioners made the COM further from COP in ML direction. This makes it possible that COM has a larger range to shift in the ML direction, which implied Tai Chi practitioners has a greater ability to tolerate instability in this direction.

Furthermore, in the previous study that examined joint kinematics among old and young adults in obstacle crossing, older adults were found to use a smaller hip and knee crossing angles in the frontal plane, as compared to the young adults (Lu, Chen H, & Chen S, 2006). Older adults were more comfortable to utilize a flexion strategy in the

sagittal plane. It was also reported that patients with balance problem, such as stroke, demonstrated a significantly limited smaller lower limb range of motion in the frontal plane in comparison with their healthy controls (Lu et, al., 2010). Considering the limited joint motions in the frontal plane, we think instability in the ML direction among elderly people and patients with imbalance is a characteristic of their walking behaviors and this is also a main factor of fall risk (Chou, Kaufman, Hahn, & Brey, 2003; Lord, Rogers, Howland, & Fitzpatrick, 1999; Maki, Holliday, & Topper, 1994). Based on the comparison, we think Tai Chi practitioners showed a similar crossing behavior as young people and healthy adults in frontal plane. In conclusion, participants in Tai Chi group may be more habitual and comfortable to use the ML strategy because they have already simulated and practiced similar movements in Tai Chi exercise. Additionally, the better stability in the ML direction enables them to stabilize hip, knee and ankle in a larger range in the ML direction to keep COM in the new base of support.

Control group



Tai Chi group

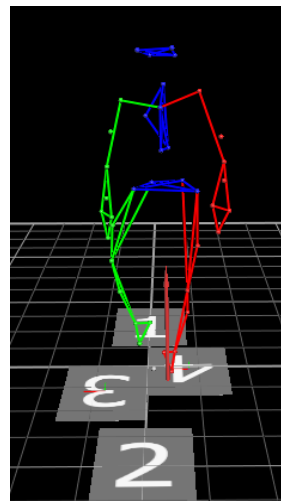


Figure 7. The illustration of lower joint angles of the participants of the control group (left) and Tai Chi group (right) respectively when leading toe was above the obstacle

It is important to point out that significant difference of knee adduction during obstacle crossing were found between the groups. The Tai Chi group presented a larger adduction angle than the control group during obstacle crossing. The large knee adduction has been reported in a Tai Chi movement “Wave-Hand in Cloud” (Law & Li, 2004). The knee adduction angle in this Tai Chi movement was significantly larger than that during level walking. The maximal adduction during the performance of “Wave-Hand in Cloud” reached to 37.17 degree, which was similar to the maximal adduction (33.08 degree) in our study (Law & Li, 2004). Knee adduction was reported to increase with the knee flexion angles because of the coupling between the flexion-extension and adduction - abduction motions of the knee (Yu, Stuart, Kienbacher, Growney, & An, 1997; Grood, Stowers, & Noyes, 1988). Zhang and the co-workers previously investigated the dynamic and static control of the knee in adduction - abduction motion. It was found humans can voluntarily control knee abduction and adduction and knee stiffness can be increased through the contractions of knee adduction - abduction muscles (Zhang, Xu, & Wang, 2001; Zhang & Wang, 2001). It was reported in their study that participants actively contracted adduction - abduction muscles to generate resistive torque to the perturbation in the ML direction, which increased joint stiffness in knee adduction - abduction (Zhang & Wang, 2001). Based on this evidence, the larger adduction in Tai Chi practitioners during crossing might result in the active knee adduction contraction,

which would increase knee stiffness and therefore knee stability in ML direction was improved. Knee adduction and abduction is an important knee motion and plays a vital role to prevent injuries and to perform some functional tasks, such as climbing stairs and crossing over obstacles. Hence, maintaining knee adduction - abduction stability is under the condition that adduction - abduction muscle is strong enough. According to the characteristics of Tai Chi exercise, the large opportunities of shifting knee in the ML direction might contribute to knee stability due to the improvement of adduction - abduction muscle strength (Zhang & Wang, 2001).

5.3 Obstacle clearance parameters

Our results show that the Tai Chi group had a significantly smaller heel clearance and greater pre-horizontal distance than the control group during obstacle-crossing, which supports our third hypothesis. This hypothesis was proposed based on the previous studies which examined obstacle clearance parameters between individuals with imbalance and age-matched controls (Stegemöller et al., 2012; Schrodt et al., 2004; Chou, Kaufman, Rabatin, Walker-Brey & Basford, 2004). In their studies, a shorter pre-horizontal distance and a greater mean foot clearance (heel and toe clearance) were found in individuals with imbalance. We expected that Tai Chi practitioners with a better dynamic stability would display similar obstacle clearance characteristics as their controls. As expected, the results from our Tai Chi group did show a greater pre-horizontal distance and a smaller heel clearance.

Research in examining obstacle crossing between young and old adults revealed that older adults had a shorter horizontal distance and a greater leading heel clearance, as compared to young adults (Lu, et al., 2006). In addition, they found the young group

maintained relatively constant foot clearance with the increase of obstacle height, while older adults increased the foot clearance linearly as the height became higher. It was proposed that the challenging of the task was perceived by the older adults and they tended to increase foot clearance to achieve a safe foot position. The increased heel clearance was directly caused by a greater flexion in lower limb, especially a lifted hip, which also indicated a conservative crossing strategy adopted by older adults. The lower foot clearance in young people was also associated with a better proprioception in young adults than seniors. Proprioception is the perception of joint position and motion as well as the perception of body orientation. During the task of crossing an obstacle, proprioception plays a vital role to determine the distance between foot and the obstacle, especially ankle proprioception. It has been well documented that there is a decline in proprioception with aging (Hurley, Rees, & Newham, 1998; Skinner, Barrack, & Cook, 1984) and ankle proprioception is considerably important because of its essential role in postural control (Ko, Simonsick, Deshpande, & Ferrucci, 2015; Van Deursen, Sanchez, Ulbrecht, & Cavanagh, 1998). A better ankle proprioception in young adult during crossing may lead to a smaller threshold, which reflect on a smaller heel clearance. The result in heel clearance of Tai Chi practitioners in our study is similar to the young adults. It indicates Tai Chi practitioners may have a similar joint proprioception as young adults. This was supported by the research from Xu and co-workers (2004) who demonstrated that regular Tai Chi practitioners had significant better knee and ankle proprioception.

Our results show that the Tai Chi practitioners exhibited a significantly lower heel clearance than the healthy controls. If looking at our data of heel clearance before normalizing, the average value of the Tai Chi group is 9.97cm compared with 13.5cm of

control group. For four Tai Chi practitioners with more than 10 years' experience, their heel clearances were 3.6cm, 4.5cm, 4.8cm, 4.9cm, respectively. They controlled their foot right above the obstacle during crossing without any contact, which showed a great ankle proprioception. However, the lowest value of heel clearance in control group is 8.8 cm. These data values might imply that the good ankle proprioception in Tai Chi practitioners helped them to detect a safe clearance with a smaller threshold. It has been reported that Tai Chi practice has a more significant improvement on ankle dorsal flexors strength than jogging. The significant ankle muscle trainings in the Tai Chi exercise might account for a better ankle proprioception in the Tai Chi practitioners, which indicated that Tai Chi exercise may have a better improvement on ankle proprioception than other exercise. Based on this, the Tai Chi group with a significant lower heel clearance showed a better ankle proprioception than the control group during the task of obstacle crossing.

Several studies documented that regular Tai Chi practice can improve proprioception. Xu and his colleagues measured the knee and ankle proprioception of Tai Chi practitioners by joint kinaesthesia test which is one of the classic method to evaluate joint proprioception (Xu, Hong, Li, & Chan, 2004). Joint kinaesthesia is the sensation of joint movement. They assessed participants' ability to detect the lowest threshold of passive joint motion. In their study, the Tai Chi practitioners showed significantly better proprioception than the other two groups, indicating regular Tai Chi practice made practitioners having a better sense to joint position and motion. The study also demonstrated that Tai Chi exercise has better effects on knee and ankle proprioception training than running and swimming. Significant improvement of knee kinaesthesia was

also found after Tai Chi intervention in more studies (Li, Xu, & Hong, 2008; Jacobson, Cashel, & Guerrero, 1997). Hong, Li and Robinson (2000) examined the ability of postural control through single stance balance test with eyes closed in the Tai Chi practitioners with the average age of 67.5 years and the healthy controls with the average age of 66.2 years. Tai Chi practitioners performed better in this eye-closed standing test and had a significantly longer stance time in both left and right leg, as compared with the healthy controls. Eye-closed balance test examines static postural stability and balance capacity without vision signal input. Postural control with eye-closed relies on vestibular signals, proprioception and neuromuscular control. A better performance of this test indicates a better ability to coordinate vestibular system, neuromuscular analysis and proprioception (Judge, King, Whipple, & Clive, 1995). The longer stance time without vision input in the Tai Chi group in their study might indicate that regular Tai Chi practice has a positive effect to improve these aspects which contribute to sustain postural stability. Plantar pressure distribution in Tai Chi movement was also examined (Li, Hong & Mao, 2006). They found the pressure of first metatarsal head and the great toe were two largest values, which is different with those in normal walking. The large pressure may simulate proprioceptors under plantar foot and increase the sensation of the great toe, which may improve the proprioception of plantar foot. As a result, Tai Chi practitioners with a significant lower heel clearance had a better ankle proprioception. Tai Chi practice can improve knee and ankle proprioception, which will contribute to a better dynamic stability (Orr, 2010; Wu et al., 2002; Scarborough et al., 1999).

5.4 Dynamic stability parameters

For dynamic stability variables, we hypothesised that when Tai Chi participants cross the obstacle, COM velocity and displacement, max COM-COP separation in AP and in ML direction would be smaller than the control group. However, our results deny this hypothesis. Tai Chi participants displayed larger and faster motion of COM, and larger COM-COP separation in the AP and ML directions. This hypothesis was proposed based on previous work by Chou and his colleagues (2003). They examined these variables among patients with traumatic brain injuries and healthy controls during obstacle-crossing. They found that patients with traumatic brain injuries had a greater and faster COM motion, and a larger COM-COP separation in AP and ML direction (Chou et al., 2003). When we proposed the hypothesis, we thought Tai Chi practitioners should display a slower COM motion and a smaller COM-COP separation as the findings of healthy controls in their study. We neglected one main difference between our studies which is that we examined different populations. The participants in Chou's studies are healthy controls and patients with traumatic brain injuries who complained of "imbalance" and "unsteadiness" while walking, who apparently suffered balance problem and had a larger body sway due to brain injuries. In our study, both control group and Tai Chi group are composed of healthy and active adults. All of them probably have a better body condition than age-matched sedentary old adults. When asked a daily living locomotion task, crossing over a 20 cm obstacle, they would not display any great perturbation of their balance. What can be observed is different strategies they adopted in order not to trip over, which will imply their ability to tolerate interference.

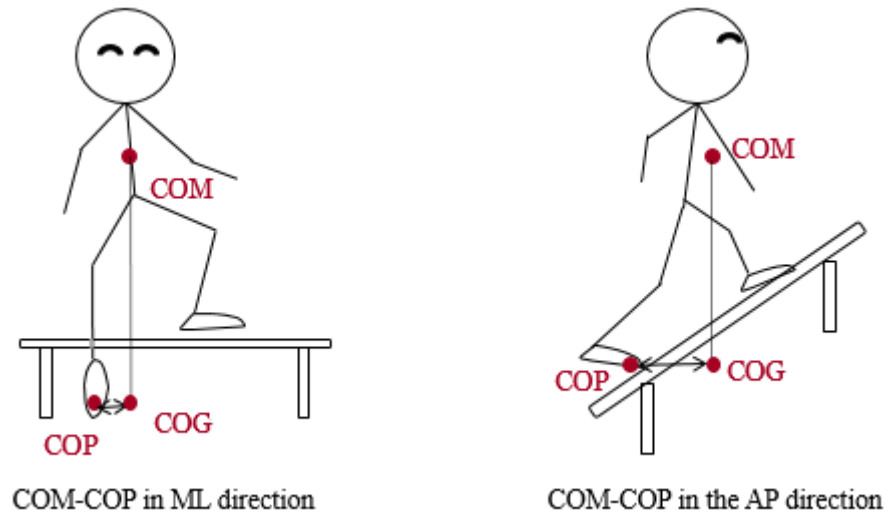


Figure 8. The illustration of COM-COP separation in ML and AP directions during crossing

In the sagittal plane, our results show that COM ROM and max COM-COP separation in the AP direction in the control group were smaller than the Tai Chi group, and the difference of COM ROM between the two groups reached to the statistical significance. The larger flexion angles of lower limb in sagittal plane in control group we talked above, as well as their adoption of a significantly shorter stride length contributed to this result as COM was closer to the base of support when hip, knee and ankle were lifted higher and closer to the body. Thus, the COM ROM and the distance between COM and COP in the AP direction become smaller. That the Tai Chi group had a larger COM ROM and COM-COP separation is due to the great flexibility in the leading hip and longer crossing stride. The longer stride made the body COM further from the base of support, which lead to a larger COM-COP separation in the AP direction. In the frontal plane, the Tai Chi group also had a significantly larger COM ROM and COM-COP separation than the control group. Similarly, the abducted hip in the Tai Chi group during

obstacle-crossing made COM move laterally, which lead to larger range of motion of COM and max COM-COP separation in the ML direction.

The age-related difference in dynamic postural stability between young and elderly adults has been examined in obstacle crossing by Chou and his colleagues (2004). Thirteen young (25.7 ± 3.6 years) and thirteen old adults (72.8 ± 6.0 years) have been recruited in their study. The results revealed that there were significant age-dependent reductions in COM ROM, COM velocity and COM-COP separation in the AP direction. They thought that older adults adopted a conservative strategy with decreased forward COM velocity and distance between COM and COP due to the reduced ability to maintain dynamic stability in older adults. Using a larger COM-COP is difficult for them because it will cause larger moment arms for the body weight about the joint of the supporting limb, which needs strong muscles to support. If looking at the data values, COM ROM in the AP direction for the condition of 10% body height (obstacle height in our study is about 12% body height) of their results is 151.4 cm and 136.1cm for young and older adults, respectively, compared to the values in our study is 125.8 cm and 139.1cm for the control and the Tai Chi group. Furthermore, the maximal COM velocity in the AP direction of their results is 1.52 m/s and 1.36 m/s for young and older adults, respectively, compared to the values in our study is 1.01m/s and 1.11m/s for the control and the Tai Chi group. The data in two studies are similar but also vary in a reasonable range because of different obstacle heights.

To our knowledge, this is the first study to investigate COM-COP separation, an important variable to evaluate dynamic postural stability, among Tai Chi practitioners in obstacle crossing. Tai Chi exercise was reported to significantly enhance balance

responses and increased COM path, max COM-COP separation in the AP direction for seniors (Gatts, Woollacott, 2007). They proposed the improvement was possibly due to the increase of COM flexibility in the AP direction after Tai Chi training and the participants had a less cautious gait and greater confidence to avoid a fall. Importantly, Chang and Kerbs suggested that the distance between COM-COP implied the individual's ability to tolerate unsteadiness (Chang, & Kerbs, 1999). The maximal COM-COP separation indicates how far the COM can deviate from the COP, which shows the ability of one's dynamic postural stability (Hwa-ann, & Krebs, 1999). In our study, the Tai Chi group had a larger COM ROM and a larger max COM-COP separation in both AP and ML directions, which benefit from Tai Chi practice. It has been well documented practicing Tai Chi can improve joint flexibility, muscle strength and proprioception (Choi et al., 2005; Li et al., 2009; Hong et al., 2000). The flexibility provides them a larger range of motion which lead to a larger COM-COP separation. The great muscle strength supports the larger moment arms about joints caused by the larger COM-COP. Larger COM-COP indicates the tolerant capacity of unsteadiness or perturbation is improved. In other words, the distance between COM and COP is larger, the feasible range of movement during which the dynamic stability can be maintained is larger. It has been reported that dynamic stability in the frontal plane is very important among seniors and most falls occurred due to the instability in this plane (Chou, Kaufman, Hahn, & Brey, 2003). In our study, the Tai Chi group had a significantly larger range COM-COP in the ML direction, which indicates that if perturbations occur, they can flexibly shift COM to confine COM in the base of support which is important to prevent a sideway-fall. To sum up, Tai Chi practitioners demonstrated a larger COM-COP separation in both AP and ML

directions, which indicates they have a larger potential range during which preventing COM moves out of base of support.

5.5 Limitation

Several limitations exist with our research. Due to we only set one height of the obstacle in this study, the feedback from the participants of the Tai Chi group is “too easy”. Therefore, raising the height of the obstacle may give more challenge for crossing the obstacle and may provide more information about the postural stability in both groups. Future study should consider to raise the obstacle height which enables us to understand more about the dynamic stability and effects of exercise on it.

Another possible limitation which existed in our study was that we asked participants to walk with barefoot. We at first considered that toe marker is important to calculate pre-horizontal distance and thus the position of toe marker need to be very accurate, which should be placed over the second metatarsal head, on the min-foot side of the equines break between fore-foot and mid-foot. Wearing shoes would make some difficulty for us to place this maker. However, some participants complained of uncomfortable when they walked with barefoot even with warm-ups before testing. This may influence their crossing strategy during data collection. A possible solution to use in future study is to provide different sizes and same brand sport shoes for participants. Place the heel markers on these shoes in advance with accurate measurement.

Chapter 6 Conclusion

Falling among seniors cannot be ignored due to the related injuries, expensive cost and some other negative consequences. Tai Chi has been suggested as an effective intervention to decrease the incidence of falls because its beneficial effects on balance and postural stability through improving muscle strength and endurance, flexibility, and proprioception and neuromuscular control. In order to add understanding to the scientific basis of regular Tai Chi's beneficial effect on postural stability, specifically in the medial-lateral direction because this is one of most sensitive indicators of fall risk, we examined the effect of regular Tai Chi practice on dynamic postural stability during obstacle walking. Our findings have answered our research question which is the dynamic stability is different between regular Tai Chi practitioners and their active health controls, and Tai Chi practitioners have a better ability to control their dynamic stability in obstacle crossing. The larger COM-COP separation performed by Tai Chi practitioners in the AP and ML directions indicates regular Tai Chi practice can improve dynamic postural stability in both directions. Therefore, Tai Chi practice is recommended to seniors who might have a decline in dynamic postural stability and might have some fall risks. Tai Chi training is also recommended as a proper intervention in rehabilitation clinic for seniors, in order to improve the capability in controlling dynamic stability. In conclusion, Tai Chi practice can improve seniors' flexibility through Tai Chi movements with large range of motion, can enhance proprioception by repeating specific position of joints, and can increase muscle strength and endurance in order to achieve large range of motions that are encountered in Tai Chi movements. All of these benefits contribute to a better ability to control dynamic postural stability in Tai Chi practitioners.

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Appendix 1: Summary of Tai Chi biomechanics

	Author	N	Sex	Age(year)	Years of experience	Tai chi style/ # of movements	Outcome variables
Kinematic study	Chan et al. (2005)	1	M 1	49	22	Yang / 1	COG; ROM of trunk, hip, knee and ankle.
	Chau(2006)	10	M6F4	26.80±4.05	13.2±5.77	Yang / 42	Time of whole set Tai chi, double limb support time/percentage, single limb support time/percentage, time of each foot work
	Mao, Hong and Li(2006)	16	M8F8	23.07±5.53	8.09±5.72	Yang / 42	Total duration/ percentage(of the whole set of Tai chi)of each support pattern and step direction
	Law and Li(2013)	15	M15F0	65.5±8.9	14.3±10.6	Yang or Wu/ 2	COM displacement, maximum and minimum hip, knee, ankle joint angles in 3 direction, single and double support time, step length, stride length/width/time
	Xu, Li and Hong(2003)	6	M3F3	22.8±3.4	at least 5 years	?/ brush knees and twist steps of 42 form	Displacements velocity and acceleration of the COG in 3 dimensional direction; ROM of knee, and ankle.
	Wu (2003)	10	M5F5	27±4	not familiar with Tai	? / Tai chi gait(TCG)	Average speed of TCG, TCG duration, stance/swing ratio, stride length, ROM of hip, knee, ankle.

					chi except for 1 (6 years experien ce)		
Kinetic study	Mao, Li and Hong (2006)	16	M8F8	23.1±5.5	8.1±5.7	Yang/5	Center of pressure(COP), ground reaction force(GRF)
	Chang et al.	10	?	29.90±7.87	> 4 years	Yang/1	GRF
	Wang, Lo and Su (2012)	7/8	M8F?	T: 62.9±12.6 C: 23.3±1.0	T:6.0±4.8 C: 0	?	GRF
	Wu and Hitt(2004)	10	M5F5	27±4	0	Yang/TCG	COP and GRF
Musculoskeletal study	Wu, Zhao, Zhou et al., (2002)	T2 0 C1 9	?	T:>55 C:>55	T:21 C:0	?	Muscle strength of knee extensors and flexors
	Lan, Lai and Chen et al., (2000)	32	M15F17	61.1±9.8	0	Yang/?	Muscle strength of knee extensors
	Li, Xu and Hong (2009)	T:2 2 C:1 8	T:M11 F11 C:M9 F9	>60	0	24-form	Muscle strength of knee flexors and extensors ankle plantarflexors and dorsiflexors
	Choi	T:2	?	Mean:77.8	0	Sun	Muscle strength of knee flexors and extensors

Moon and Song (2005)	9						ankle plantarflexors and dorsiflexors
Chan et al. (2005)	C:3 0						
Xu, Li and Hong(2003)	1	M 1	49	22	Yang / 1	EMG activity of lumbar erector spinae, rectus femoris, medial hamstrings and medial head of gastrocnemius;	
	6	M3F3	22.8±3.4	at least 5 years	?/ brush knees and twist steps of 42 form	EMG activity of rectus femoris, semitendinosus and gastrocnemius and anterior tibialis;	
Wu (2003)	10	M5F5	27±4	not familiar with Tai chi except for 1 (6 years experience)	? / Tai chi gait(TCG)	EMG activity level of tibialis anterior, soleus, peroneus, and tensor fasciae latae(The peak and root-mean-square value of each muscle)	

Note: N, sample size; M, male; F, female; N, numbers of participants; ?, unknown T: Tai Chi group; C: control group.

Appendix 2: Survey

Title of the study: DYNAMIC POSTURAL STABILITY OF OLD TAI CHI PRACTITIONERS DURING OBSTACLE CROSSING

1. **Name:** _____
 2. **Age:** _____
 3. **Email:** _____
 4. **Telephone (optional):** _____
 5. **Do you practice Tai Chi? (If “No” go to “Question 9”)** _____
 6. **Which style of Tai Chi do you practice? (Indicate what it is if you choose D)**
 A Yang B Chen C Wu D Other _____
 7. **How many years’ experience in Tai Chi do you have?** _____
 8. **In the past year, how many times per week do you practice Tai Chi?**

 9. **What kind of other regular exercise do you have in the past few years?**
 (Indicate what exercise it is if you choose D)
 A Jogging B Speed Walking C Running D Other _____
 10. **How long have you been practicing this exercise?** _____
 11. **In the past year, how many times per week do you practice this exercise?**

 12. **Do you need to use an assistive device when you are walking?** _____
 13. **Have you had any sprains or bone fractures in the past 6 months or any other neurological or physical impairment that may affect your postural stability in this study?**

 14. **Have you had any neuromuscular disorders, such as Parkinson, Stroke, or vestibular disorders, such as Concussion?** _____
 15. **Comments/Notes/Questions:** _____

-

Appendix 3: Anthropometric measurements

LABTAOTARY DATA

Leg dominants:

Kicking Leg	<input type="checkbox"/>	Left	<input type="checkbox"/>	Right
Balance Recovery	<input type="checkbox"/>	Left	<input type="checkbox"/>	Right
Supporting leg when crossing an obstacle	<input type="checkbox"/>	Left	<input type="checkbox"/>	Right

Anthropometric Measurements:

Height: _____ mm

Weight: _____ mm

Shoulder offset: _____ mm

Left Side

Leg Length _____ mm

Knee Width _____ mm

Ankle Width _____ mm

Wrist width _____ mm

Hand thickness _____ mm

Right Side

Leg Length _____ mm

Knee Width _____ mm

Ankle Width _____ mm

Wrist width _____ mm

Hand thickness _____ mm

Appendix 4: Plug-in-Gait marker set

