

**KINETICS AND KINEMATICS OF THE LOWER EXTREMITY
DURING PERFORMANCE OF TWO TYPICAL TAI CHI
MOVEMENTS BY THE ELDERS**

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“You can't catch a cub without going into the tiger's den.”

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Abstract

Reduced mobility is a growing problem among the aging population in Canada. Joint limitations along with natural decline in strength and endurance of muscles make engagement in aerobic and vigorous exercises difficult for the elders. Tai Chi Chuan is a safe alternative for those who wish to improve balance and physical wellbeing. Long-term Tai Chi practice has numerous positive benefits towards health that have been well-documented. Its popularity continues to grow as more scientific evidence is being accumulated from a growing body of research aimed towards improving the health of a sedentary elderly population. To date, the literature on Tai Chi biomechanics remains limited to a few studies on the after-effects of Tai Chi training. Future studies have yet to examine the features and characteristics of individual Tai Chi movements. The aim of this study was to examine the biomechanical features of the lower extremity during performance of two Tai Chi movements, the “Repulse Monkey (RM)” and “Wave-hands in clouds (WHIC).” The study’s parameters included quantitative measures of the temporospatial, kinematic, kinetic characteristics and muscle activity of the lower extremities. Fifteen male Tai Chi participants with more than 4 years of Tai Chi experience were recruited. Three-dimensional (3-D) kinematic and kinetic data was collected using VICON motion analysis system with 10 infrared cameras and 4 force plates. The following variables were examined: stride width, step length, step width, single- and double-support times, centre of mass (COM) displacement, peak joint angles, range of motion, peak joint moments, time to peak moment, and ground reaction force (GRF). The differences in the measurements of the two Tai Chi movements were compared with walking using two-way ANOVA. The main findings are summarized and grouped into the following three categories:

1. *Temporospatial*: RM and WHIC demonstrated a shorter stride length while WHIC demonstrated a larger stride width than walking. Single-support duration was shorter for WHIC and RM while RM demonstrated a longer double-support time than walking. Both movements had larger mediolateral and vertical COM displacement.
2. *Kinematics*: For maximal dynamic hip mobility, RM had higher peak flexion, adduction, abduction, total sagittal and frontal ROM while WHIC had increased peak flexion, abduction and frontal ROM, as well as smaller peak adduction and sagittal ROM than walking. For the knee, RM had increased flexion, varus, sagittal and frontal ROM while WHIC had decreased flexion, varus, valgus and sagittal and frontal ROM. For the ankle joint, RM demonstrated increased plantar- and dorsiflexion, inversion, sagittal and frontal ROM than walking. For WHIC, joint angles were larger for dorsiflexion, inversion, sagittal and frontal ROM while smaller for plantarflexion, and eversion.
3. *Kinetics*: Both RM and WHIC demonstrated lower mediolateral and vertical GRF. RM had a larger anterior force while WHIC had a larger posterior force than walking. At the hip joint, greater extension and adduction moments were seen for RM and WHIC and less flexion and abduction moments. At the knee joint, a greater extension moment was seen for RM and WHIC as well as varus moment for RM. At the ankle, RM and WHIC had smaller plantar-/dorsiflexion and a larger eversion moments than walking. Time to peak moment was longer for RM and WHIC at the hip and knee compared to walking.

The quantitative evidence from the current study would help in the development of effective fall-prevention strategies for the elders through future Tai Chi interventions. Overall, the rehabilitative potential of Tai Chi is promising since these two typical Tai Chi movements can easily be taught to elders and adapted to their slow-paced lifestyle.

CHAPTER I: INTRODUCTION

1.1 Background

Tai Chi Chuan, or *taijiquan*, is a slow, graceful, and rhythmic traditional Chinese exercise that encourages the muscles to let go of tension, the mind to let go of worry, and the heart to let go of angst. The word *Tai Chi* translates to “supreme ultimate” or “global optimal” while *Chuan* translates to “fist” (Lee & Johnstone, 1989). Tai Chi is primarily used as an exercise to help work out the mind and body. Following the Taoist principles where it is derived from, Tai Chi is seen as a useful tool to help improve health by balancing the *chi* or life’s energy that’s following within us (Lee & Johnstone, 1989; McKenna, 2001).

The historical development of the different style of Tai Chi can be traced back to the original Chen style (Kurland, 1998). Each style of Tai Chi has its own unique traits, ranging from the fast, brisk movements of the Chen style to the more graceful, tranquil Yang style. Nonetheless, the principle and teaching of each school has remained the same. The most popular form of Tai Chi is the Yang style, which has been taught in China and abroad for over four generations. The Yang style is separated into a set of short and long forms. The simplified 24 forms Tai Chi can be performed in seven to ten minutes while the long form consists of 108 forms that can be performed in twenty minutes. From then on, the Yang style has spawned additional style such as the Wu and Sun. The popularity of Tai Chi is growing because it is an exercise that can be practiced anyplace and anytime by both the young and elderly.

Mobility is commonly reduced in the elders who are physically inactive or suffering from chronic diseases. Muscle mass decline 30% to 50% between the ages of 30 to 80 years, which accounts for much of the loss of muscle strength (Daley & Spinks, 2000). The number of slow twitch or type II muscle fibers starts to decline around the age of 25 years and continues to

decline 39% by the age of 80 years (Daley & Spinks, 2000). With the reduced muscle endurance and muscle strength, the risk of falling among the elderly is increased, particularly among those who are physically inactive with functional impairments. There are notable changes during forward walking in the elders who tend to use flatter-foot landing and less plantarflexor muscles to push the toes off the ground (Gatts & Woollacott, 2007). Furthermore, weakness in the muscles means that the elderly need to be more cautious of where they step, which alter their walking gait patterns (Judge et al., 1996; Mecagni et al., 2000; Bassey et al., 1992; Wolfson et al., 1995; McGibbons, 2003; Kerrigan et al., 1998).

A literature review by Tai Chi by Li, Hong, & Chan (2001) revealed that Tai Chi has many beneficial effects on cardiorespiratory and musculoskeletal function, posture control, and reducing the risks falling among the elderly (See article for more details). Tai Chi is also said to ward off illness by calming the body and mind. This exercise can improve balance, deep and slow breathing, posture, digestion, blood circulation, and functioning of the internal organs (Man-Ch'ing & Smith, 1978). Experiences of relief from neurasthenia, high blood pressure, hypertension, heart problems, anaemia, tuberculosis, and other maladies have also been documented (Yang, 2010; Cheng Man-Ch'ing & Smith, 1978). Recently, the American Geriatric Society and British Geriatric Society have recommended Tai Chi as an effective intervention to reduce the number of falls among the elderly (American Geriatric Society, 2011). According to Liu & Frank (2010), Tai Chi can help improve awareness of the body's position by focusing on the proper placement of the foot, maintaining the trunk and head in an upright position, and moving the body attentively to the different Tai Chi postures. Daily physically activity can help maintain functional mobility while long-term Tai Chi practice has been shown to help improve muscle strength and joint flexibility (Tsang, Hui-Chan, 2005; Hong, Li, Robinson, 2000).

1.2 Research Question

The purpose of this study is to compare the biomechanical features of two typical Tai Chi movements, “Wave-hand in Cloud (WHIC)” and Repulse Monkey (RM)”, with normal walking gait. The primary research question that the study aims to address is whether there is a difference in the biomechanics of the hip, knee, and ankle joint during Tai Chi performance and normative gait. The three-dimensional (3-D) kinematic and kinetic data of the hip, knee, and ankle will be measured along with the electromyography (EMG) activity of muscle in the lower limb. A group of experienced Tai Chi practitioners between the ages of 65 to 75 will be recruited. By comparing and analyzing the participants’ measurements, the results will shed light as to whether there is a difference in the joint biomechanics during Tai Chi performance and normative gait.

To the author’s knowledge, only a few studies have examined the movement characteristics of individual Tai Chi forms. The following variables have been examined: the characteristics temporospatial variables and EMG activity of the lower limb muscles has been examined for “Brush-knee-twist step” (Xu, Li, & Hong, 2003); temporospatial and joint kinematics as well as EMG activity of the lower limb muscles for “Parting the Wild Horse’s Mane” (Wu, Liu, Hitt, & Millon, 2004); joint moments of the lower limbs and ground contact characteristics for Tai Chi Gait (Wu & Millon, 2008; Wu & Hitt, 2005). Furthermore, the foot movement characteristics of 42-form Tai Chi (Mao, Hong, & Li, 2006a; Mao Hong & Li, 2006b) have been examined. The Tai Chi support and stepping pattern of the WHIC and RM has been examined in past studies (Mao et al., 2006b), but the 3-D joint kinematics and kinetics of the lower limb and ground reaction forces during foot contact on the ground remain unknown. In order to get better understanding to Tai Chi movement, it is necessary to study the biomechanical characteristics of typical Tai Chi movements. WHIC and RM are selected mainly because they are two typical Tai Chi movements that have rehabilitative potential for the elderly practitioners.

1.3 Variables

Movement of study

The two Tai Chi movements shown in Figure 1, “Wave-hand in Cloud” and “Repulse Monkey”, are studied and compared with normal walking. They are part of the 13 basic or classical Tai Chi movements that were derived from the Chen style and share common biomechanical features with other Tai Chi movements such as “Brush-knees and Twist Step” and “Parting the Wild Horses’ Mane” (Please view Appendix III for illustration).

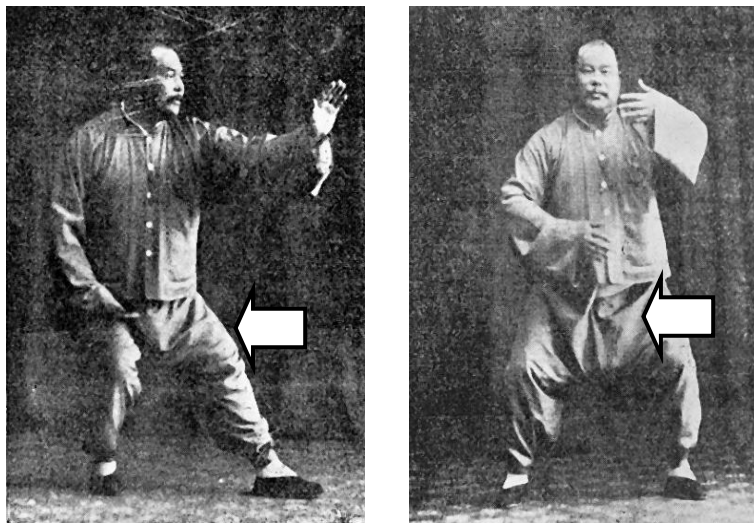


Figure 1. Side-view of Repulse Monkey (*left*) and front-view of Wave-hand-in-Cloud (*right*). The arrows illustrate the direction of the movement.

Variables to be studied

a) Temporospatial Parameters

The temporospatial parameter consisted of stride length (m), stride width (m), stride time (ms), double and single stance time (s). The step length and stride width provided the dimensions to determine the base of support. Stability and balance is determined by the displacement of the centre of gravity (COG) away from the base of support. The effects of balance training are accessed by the smoothness of the displacement of the COG along the mediolateral plane and the duration of double-support (Xu et al., 2003; Wu et al., 2004).

b) Kinematics variables

The kinematic parameters included three dimensional (3-D) joint angles of the knee, ankle, and hip. The mean values of the peak angle are acquired at instances where the heel or toe contacts the ground during movement. Similarly, the mean values of the peak angle are recorded where the heel or toe takes off the ground in the two directions. The maximum displacement of the centre of mass (COM) along the sagittal, frontal, and transverse planes are used to assess stability. The angular deviation of the COM provided insight into the central nervous system (CNS) and vestibular functions (Eng & Winter, 1995). Comparisons are made with the study by Wu and colleagues (2004).

c) Kinetic variables

The kinetic parameter consisted of ground reaction forces during heel-strike and toe-off, peak moment force (Nm), and time to peak moment force (% of one gait cycle) for each joint of the lower extremity. The data is compared with past studies on Tai Chi gait (Wu & Millon, 2008; Wu & Hitt, 2005).

Table 1. Variables

VARIABLES	
Category	Description (unit)
Temporospatial Parameters	Stride Length (cm)
	Stride Width (cm)
	Stride Time (s)
	Single and Double Stance Time (s)
Kinematics	Peak joint angle (°)
	Range of motion (°)
	COM displacement (mm)
Kinetics	Ground reaction force of the foot during touch down and take off of the movements (%BW)
	Peak hip moment force (Nm/Kg)
	Peak knee moment force (Nm/Kg)
	Peak ankle moment force (Nm/Kg)
	Time to peak hip moment force (% gait cycle)
	Time to peak knee moment force (% gait cycle)
	Time peak ankle moment force (% gait cycle)

1.4 Hypothesis

It is hypothesized that the kinetic, kinematic, and EMG activity of the participants' lower extremity would be different from that in forward walking when performing the two typical Tai Chi movements ("Repulse Monkey" and "Wave-hand in Cloud"). Based on the results from a pilot study (n=2) conducted by Law, Law, & Li (2011), the following tentative hypotheses are tested in the present study.

In comparison with the forward walking, when asked to perform "Repulse Monkey",

- a) Stride length will decrease;
- b) Stride width will increase;
- c) Joint angle in the lower extremity will increase especially along the sagittal plane;
- d) Posterior displacement of COM will be larger along the transverse plane;
- e) And peak moment of the lower extremity will be increase.

In comparison with forward walking, when asked to perform "Wave-hand in Cloud",

- f) Stride length will be altered;
- g) Stride width will increase;
- h) Joint angle in the lower extremity will decrease along the sagittal plane;
- i) Lateral displacement of COM will be larger along the frontal plane;
- j) And peak moment of the lower extremity will increase.

1.5 Rationale

The “Repulse Monkey” and “Wave-hand in Cloud” movements contain many defining features common to previous biomechanical studies on Tai Chi Chuan. Semi-deep squatting, greater joints angles ROM, and coordinated movement patterns have come to define Tai Chi movements (Xu, Li, & Hong, 2003; Chua & Mao, 2006; Wu, 2008a, 2008b). These elements are necessary to prevent falls by building muscle strength and improving joint proprioception. It can further be implied that “Repulse Monkey” and “Wave-hand in Cloud” express similar beneficial effects in contrast to daily tasks such as forward and backward locomotion. For comparative purposes, it is assumed that normal gait share similar qualities with the two Tai Chi movements.

The two movements are described differently in Tai Chi Chuan books, yet they contain similar elements, namely counteracting movements of the arms and legs (Yang, 2010; Cheng Man-Ch’ing & Smith, 1978). Both movements involve circular movements of the hand in the forward and backward directions for “repulse monkey” and sideways for “wave-hand in cloud”. In the meantime, the practitioners are required to step backward and sideways for “repulse monkey” and “wave-hands in cloud”, respectively. The weight of the body is transferred between the legs while stepping backwards or sideways. The timely movement of the upper and lower limbs require a high degree of coordination to keep the body upright.

“Repulse Monkey” contains elements of backward walking which have been used in rehabilitative studies involving patients with Parkinson Disease or stroke (Hackney & Earhart, 2009; Yang, Yen, Wang, Yen, & Lieu, 2005). Studies comparing forward and backward walking reported that the same muscle activation patterns can be used for either direction, although EMG activities of the lower extremities are typically greater during backward walking (Grasso, Bianchi, Lacquaniti, 1998; Winter, Pluck, & Yang, 1989). During “Repulse Monkey”, the foot

step diagonally as the left leg is retracted. The practitioners are cognitively aware of the placement of the toes, which must contact the ground first and point straight ahead. The right leg that's in front slowly turns inward so that the feet are parallel and the weight is shifted back on to the left foot (Man-Ch'ing & Smith, 1978). The "four-six stance" is commonly applied in "Repulse Monkey" and requires 60 percent of the body weight to be supported by the rear leg and 40 percent in front leg (Yang, 2010). The rear leg is slightly bent at the knees and the toes and knees are turned inward, while the front leg is held loose, slightly bent and relaxed. This defensive stance encourage greater joint loading in both the rear and front leg than normal gait.

Similar to other Tai Chi movements, "Wave-hand in cloud" movement requires greater coordination of the upper and lower extremity than normal walking. During "Wave-hand in cloud", the weight of the body is transferred side-to-side as the practitioners sidestep in the lateral direction. The twisting actions at the hip during "Wave-hand in cloud" help to loosen the waist and spine, and to direct power from the legs to hands with a rotation motion (Yang, 2010). The "horse stance" is found in "Wave-hand in clouds" where the feet are parallel and shoulder width apart (Yang, 2010). The knees are slightly bent between the rear thighs and calf. The body weight is transferred from the left leg to the right stance leg during sidestepping. The complexity of shifting of the COG along the mediolateral plane while maintain a linear step progression would require additional proprioceptive feedback. When stepping from side-stepping during "Wave-hand in cloud", it can also be expected that additional muscle activity will be seen in the lower extremity as the weight of the body shifts from one side to another. Lateral instability is the culprit for falls to the side, which is why this type of movement has been recommended as an activity for elders to build the capacity to side-step over obstacles (Maki & McIlory, 1997). The mediolateral stability of the ankle joint is of important interest in this movement.

1.6 Terms and definitions

1. Centre of mass (COM): a point equivalent to the total body mass in the global reference system that is the weighted average of COM of each body segment in 3D space (Winter, 1995).
2. Centre of gravity (COG): the vertical projection of COM onto the ground (Winter, 1995).
3. Centre of pressure (COP): the location of the vertical ground reaction force vector. This is the vector force representing the weight average of all the pressure over the surface of area that is in contact with the ground.
4. Gait cycle: a cyclical movement pattern that is used for bipedal locomotion in humans
5. Stride length: the distance travelled by a person over one cycle from initial heel strike to the next heel strike.
6. Stride width (walking base): the side to side distance between the feet measured between the right and left ankle joint centers (Perry, 1992).

1.7 List of Relevant Acronyms

WHIC	=	Wave-hand in Cloud, movement
RM	=	Repulse Monkey, movement
BKTS	=	Brush-knee and Twist Step, movement
TCG	=	Tai Chi gait
COM	=	centre of mass
BOS	=	base of support
ROM	=	range of motion
GRF	=	ground reaction force
EMG	=	electromyography

CHAPTER II: REVIEW OF LITERATURE

2.1 Introduction

Tai Chi is a popular traditional Chinese physical exercise characterized by circular, slow, and even movements that can be performed by adult practitioners of all ages. Derived from Qi Gong over 1200 years ago, Tai Chi was first introduced to China by a Buddhist monk named Batuo from India in A.D. 464 (Yang, 2010). Qi Gong, translated into English, means “breath work” or “energy exercise.” Traditionally, Tai Chi was used to improve the self-defence and spiritual wellbeing of Taoist monks (Cheng Man-Ch’ing & Smith, 1978). Their health was deteriorating due to the prolong time spent in deep meditation. These monks were unable to defend their temples and were at risk of being attacked and robbed by bandits. To stop this trend, *Muscle/Tendon Changing Classic* and *Marrow/Brain Washing Classic* were published by an Indian monk named Da Mo Sardili (A.D.483- ?). His work taught the importance of strengthening the body as well as the mind through Taoist principles which has lead to the development of Tai Chi into a more accessible form of physical exercise.

Tai Chi’s prominence in the West did not rise until the turn of the 20th century. Like many other types of Chinese martial arts, Tai Chi Chuan was kept in secret from foreigners and shared only between grand masters and their disciples. Tai Chi was first revealed to the public in 1926 by Yang, Chen-fu at the Nanking Central Guoshu Institute. Due to government regulations, masters like Cheng, Man-Ch’ing was not officially given the liberty to leave China and teach Tai Chi overseas until the 1960s (Yang, 2010). Fuelled by new diplomatic changes following Nixon’s 1973 visit to China and the overseas success and popularity of *kung fu* motion pictures by Bruce Lee’s, interest in the Chinese culture has gradually gained in the West (Yang, 2010).

The scientific literature of Tai Chi has grown substantial, yet there is still much to gain from future studies in this area. Past research has suggested that long-term Tai Chi training can elicit beneficial effects on health. These effects gained from long-term Tai Chi participation are not equivalent to swimming or running. In study by Xu and colleagues (2004), proprioceptive functions of the ankle and knee joints were better in the Tai Chi group than their sedentary control while ankle kinaesthesia of the Tai Chi group was also better than their swimmers and runners counterpart. In another study, Tai Chi practitioners had similar ankle dorsiflexor strength as runners, suggesting that the physical demands of these exercises are similar or equal (Xu et al., 2008). Furthermore, the slowness and control movements of Tai Chi help to reduce the amount of stress in joints and connective tissues (McKenna, 2001). This especially for the important for elderly practitioners, who require a safe mean to enhance joint flexibility and stability while maintain the vigorous demands similar to other physical activity.

Long-term Tai Chi practice can also help to improve muscle strength, cardiovascular functioning, and balance (Li, Hong, & Chan, 2001). Although several studies have suggested Tai Chi practice may help to reduce the risk of falling among the elderly (Gatts & Woollacott, 2007; Wu, 2008b), this literature is still limited to the biomechanical effects after Tai Chi training. Hong's (2011) review of the literature on Tai Chi and fall prevention found substantial evidence that Tai Chi training can help to improve balance test scores and neuromuscular control. Again, the studies examined in the review were post-Tai Chi interventions and did not address the unique biomechanical features during Tai Chi practice. The types of fall prevention strategies used by elderly Tai Chi practitioners remain a mystery, mainly because the scientific understanding of Tai Chi forms is still lacking (Leung & Tsang, 2008; Xu, Li, & Hong, 2003).

Although the practice of Tai Chi can lead to the improvement of one's health, the biomechanical analysis of Tai Chi movements remain limited. Wu, Liu, Hitt, & Million (2004) state that biomechanical analysis of Tai Chi is challenging because of the variation in styles (eg. Yang, Wu or Chen), movements (ranging from 24 to 94), and duration of movements (ranging from 5 min to 40 min). A better understanding of the different Tai Chi movements would allow for a more accurate recommendation of the suitable types of fall prevention training exercises for the elderly (Hong, 2011).

This literature review will aim to provide an overview of the current published literature for biomechanical studies in Tai Chi and address any research gaps, which will help to find the research direction and define the research purpose and objectives in this Tai Chi biomechanics study. This literature review is structured as the following sections:

- (a) Kinematical characteristics of Tai Chi,
- (b) Kinetic characteristics of Tai Chi.

2.2 Kinematic characteristics of Tai Chi

Tai Chi practitioners are constantly shifting their body weight and holding different stances during consecutive movement sequences. It is important to analyse the displacement of the centre of mass (COM) during Tai Chi movements because the angular deviation of COM away from the base of support (BOS) can be used to assess patient's balance control capacities (Lugade, Lin, Chou, 2011; Roger & Mille, 2003; Winter, 1995). The circular motion of the arms and hands would cause greater displacement of COM during performance of the two Tai Chi movements.

Bipedal locomotion, such as walking and Tai Chi movements, provides additional challenges for the central nervous system (CNS) in comparison to quiet standing. As noted by Alum & Carpenter (2005), it is important to examine COM displacement during translation since falls most often occur during movement, rather than when the individual is standing stationary. Compared to standing stationary, the COM is no longer positioned within the limits of the base of support (BOS). The act of walking forward shifts the BOS from two foot to one foot, namely from double-support stance to single-support stance. The BOS is defined by the supporting limb's foot width, ankle width, and foot length during single-limb support and proportions of the foot in contact with ground and the area between the feet for double-limb support (Lugade et al., 2011). During forward locomotion, shifting of the COM is used to initiate or terminate gait, which can be away from, or towards, the base of support (Winter, 1995). The displacement of COM away from the BOS can be used to assess the efficiency of the CNS in maintaining postural stability and balance across dynamic tasks.

Quantitative studies on the COM displacement during Tai Chi practice are limited; only one study has examined the kinetic characteristics and COM displacement during "Brush Knee and Twist Steps" (BKTS), a typical Tai Chi movement found in all Tai Chi schools and 42-form Tai Chi used for international competition (Xu, Li, Hong, & Chan, 2003). Six elite Tai Chi masters (mean age of 23) were recruited and their movements were video-recorded and analyzed. During the performance of BKTS, the direction of motion frequently changed but the pace of the motion was slower. Slow changes to the movement pattern make this type of exercise appropriate for the elderly to participate. Controlled and deliberate shifting of the COM would help to improve mediolateral stability (Xu et al., 2003), but these findings have yet to be applied to an older population. Physiological changes may affect performance characteristics of the

young and old, which means that the collected data for the young subjects would not apply to older participants (Wang, Flanagan, Song, Greendale, & Salem, 2003). The types and amount of physical activity engagement by the Tai Chi masters was not specified. Although the sample size fairly small, statistical analysis or baseline control values (for normative gait) have not been provided, the study is first to quantify the kinematic data of BKTS for comparison with other Tai Chi movements.

Wu and colleagues (2004) examined the kinematical characteristics of “Tai Chi Gait” (TCG) among a group of young health subjects ($n=10$). TCG is a cyclical movement with characteristics similar gait characteristics as forward walking (Wu, Liu, Hitt, & Millon, 2004; Wu, 2008b). Compared to normal gait (NG), TCG had longer cycle duration (11.9 ± 2.4 vs. 1.3 ± 0.2 s) and longer duration of single-leg stance time (1.8 ± 0.6 vs. 0.4 ± 0.05 s). During the performance TCG, the direction of motion frequently changed but the stride length was shorter and the pace was slower than normal gait (Wu et al., 2004). Furthermore, the ROM of the foot-ankle, knee, and hip were much larger during TCG than NG. The findings suggest that Tai Chi can help improve joint flexibility and stability. However, these claims are based on test young subjects (mean age 27), which may account for their longer single-leg stance time. The data collected may not be reliable for two other reasons. First, only one Tai Chi instructor (with more than 6 years of experience) participated in the study while the rest of the subjects had one week to learn TCG. Secondly, the researchers acknowledge that TCG was performed in isolation of the simultaneous arm movements, which may introduce biases in the results. It would be important to consider the feasibility of a movement prior to testing in order to ensure that the subjects are comfortable and the collected data is reliable.

To our knowledge, two studies have reported the kinematical features of 42-form Tai Chi movement in its entirety, once in a group of ten Tai Chi masters (Chua & Mao, 2006) and the other time in a group of sixteen experienced Tai Chi practitioners (Mao et al., 2006a). The step stance (support pattern) and footwork (step directions) was recorded using two video cameras. In comparison to normal walking, double-limb support was found to be most frequently used during the set of Tai Chi movement while single-limb support was shorter, but the duration of both double- and single-limb support phases were longer. These results are consistent with the study by Wu and colleagues (2004). Spending more time in double-limb support is necessary for the maintenance of balance, which is why Tai Chi is safe for individuals with functional impairments.

Tai Chi movements involve complex footwork in multiple stepping directions. The percentage of total duration of forward, sideward and backward stepping was 19.99, 13.94 and 4.84, respectively (Mao et al., 2006a). Grinding footwork occurred at extreme range of motion (ROM) of the ankle which could help to improve ankle proprioception and build muscle strength (Chua & Mao, 2006). Sideway footwork is another type of motion in Tai Chi that involves utilizing the hip abductor and adductor muscles. Although backward footwork occurs less frequent during Tai Chi, it places less stress on the patellofemoral joint than forward gait but enough stress to help strengthen the quadriceps muscle (Chua & Mao, 2006). The strength of the first study (Chua & Mao, 2006) is its' methodology section, which clearly outlined the types of step stance and footwork. For both studies, only Tai Chi practitioners with more than 7 years of experience are recruited. It would appear that the practitioners would be knowledgeable in Tai Chi, but it is questionable whether they are familiar with the 42-form Tai Chi sequence, given that each Tai Chi style follows a difference movement sequence. The subject's performance

would be affected by the current style that he or she is learning. Another limitation of the two studies is the use of video recording, which the researchers acknowledge that there were difficulties with identifying the initial points of touch down and take off (Mao et al., 2006a). From the above studies, it would appear that future research should compare the footwork and step stance of experienced and novice Tai Chi practitioners in order to further study the beneficial effects of Tai Chi training for those with functional limitations.

The study conducted by Wu (2008b), examined a group of young ($n = 6$) and old ($n = 6$) Tai Chi practitioners who have been practicing Yang-style Tai Chi for at least 3 times a week for at least 4 months before the study. The purpose of the study was to compare the temporal and spatial features of Tai Chi gait performed by a group of healthy young adults (21 to 45 years) and elders (61-85 years) to normative gait performed by the elders. The spatial and temporal variables examined include single-stance time, along with knee and hip flexion angles. The subjects were asked to perform “Parting the Wild Horse’s Mane”, a common Tai Chi movement containing elements of Tai Chi gait, at a self-determined speed and normative gait at slow speed.

The performance characteristics of the elders and young are notably different in the above study, suggesting that there are possible effects of aging. Swing phase, single-stance, and overall duration of TCG was shorter among the elders compared to the young. The elders also spent significantly longer time in double-support stance and swing phase during TCG than NG. The elders had a shorter stride length but wider stride width in TCG than NG. These findings are consistent with other studies analyzing normal gait (Roger & Mille, 2003; Maki, 1997) that suggest a wider stride width demonstrates a greater fear of falling backwards or sideways among the elders, namely because of poor mediolateral stability. The elders had less knee and hip flexion than the young during TCG, suggesting that the elders assume a higher stance posture

(Wu, 2008b). The level of experience between the two groups is the same, which means the limitation in this study could be associated with the elder's reduced joint flexibility. It is unclear whether the 4-month training period is sufficient to see a significant change in joint flexibility among an older group of participants. Furthermore, the findings may not be representative for the two age groups. To minimize the possibility of confounding effects, the young and elder groups should be appropriately defined within a more narrow age range.

Based on the reviewed literature, only a few studies have examined the movement of interest for the present study: “Repulse Monkey” and “Wave Hand in Cloud.” However other similar Tai Chi movements like “Brush-knee and Twist Step” and “Parting the Wild Horse's Mane” are available for biomechanical comparison. Wu and colleagues (2004) quantified the movement patterns of TCG and found similarities between Tai Chi and normal walking gait. Unlike NG, lowering COG and shifting of the body weight during Tai Chi practice helps to build balance and stability (Xu et al., 2003; Wu, 2008b). The authors acknowledged that TCG may not represent all forms of Tai Chi and the findings may be limited for that particular movement (Wu, 2008a). In a larger scope, Tai Chi movements can involve additional shifting of the body's position backward and sideways. For each Tai Chi form, there is a possible of 8 different types of Tai Chi stances that are incorporated differently into the 42-Tai Chi forms Yang style. Notably, “Repulse Monkey” and “Wave-hand in Cloud” incorporate the “four-six stance” and “horse stance”, respectively. The temporospatial and kinematic characteristics may be altered since each Tai Chi movement can have its own unique stance and sequence.

2.3 Kinetic aspects of Tai Chi

The displacement of centre of pressure (COP) has been used to examine the effects of aging on equilibrium, both in static conditions such as quiet standing (Melzer, Benjuya, & Kaplanski, 2003) and forward platform translation (Nakamura, Tsuchida, & Mano, 2001). In double-support stance of forward translation, the COP is somewhere between both feet. COP then shifts between the swing and stance foot before moving forward with the stance foot as the toe leaves the ground of the swing limb (Perry & Burnfield, 2010).

The magnitude of the COP displacement can be used to study the stability of the ankle joint. Hoogvliet, Duyl, Bakker, & Mulder (1997) demonstrated that ankle displacement & COP migration are highly related. The lateral and medial displacement of the COP is a good indicator of the tilting motion of the foot observed during a one-leg standing test. The horizontal force is doubled and ankle joint reaction force is 4× higher during extreme medial lateral ankle displacement than non-extreme displacement (King & Zatsiorsky, 2002). Furthermore, the location of COP under the foot directly reflects the neural control of the ankle muscles (Winter, 1995). The ankle muscles cannot help to avert falls once in motion, rather to fine tuning the anteroposterior or mediolateral acceleration of the body's COG (Winter, 1995). Falls are averted through the safe placement of swing foot once every step.

In the study by Nakamura et al., (2001), the researchers found that increasing displacement of COP not only increased the electromyography activity, but also the number of muscles that are used in the lower extremities. In Nakamura's study, the displacement of COP increased with initiation of forward translation onto a force plate. Tai Chi movements incorporate both side-stepping and turning movements that can occur along multi-axial directions. It can be expected that the COP displacement and neuromuscular effects would be

much higher during Tai Chi practice than normal gait (Mao, Li, & Hong, 2006b), yet the kinetic studies on Tai Chi movements remain limited. Of the available kinetic studies, COP displacement has been examined during performance of stationary (standing or sitting) Tai Chi forms or quiet standing balance test (Leung & Tsang, 2008; Tsang & Hui-Chan, 2003; Wu, Zhao, Zhou, Wei, 2002). Few studies have examined the COP displacement during dynamic TC movement (Mao et al., 2006b, 2006c). Other than the findings provided by Wu & Millon (2008), no study has reported the joint moment and forces during Tai Chi practice.

Mao and colleagues (2006b) examined the plantar pressure distribution characteristics in the five typical Tai Chi movements. Sixteen Tai Chi masters (mean age 23 ± 5) participated in the study. The masters were asked to perform brush knee and twist steps, step back to repulse monkey, wave hand in cloud, kick heel to right, and grasping the bird's tail which include stepping forward, backward, sideways, up-down, and fixing movement, respectively. The displacement of COP during these movements was significantly larger in the anterior and posterior directions at end and initial foot contact, respectively, compared with walking. Displacement of the COP was significantly wider in the mediolateral direction in the forward, backward, and sideways during the Tai Chi movements. The amplitude of the ground reaction forces for the Tai Chi movements was much lower than normal gait. It would appear that a larger ROM of the joints and controlled placement of the contact foot during Tai Chi practice would help to improve balance control and muscle strength (Mao et al., 2006b). The findings would be helpful for future studies, however care should be taken when applying or comparing the data to an older and less experienced target population.

Single-leg stance can pose a challenge for those with postural instability. Mao, Li, & Hong (2006c) recruited sixteen gender-matched long term Tai Chi practitioners with average of

eight year of Tai Chi experience. The participants were asked to performed the whole set of 42-form Tai Chi along a 15-m pathway at a self-selected speed. The purpose of the study was to quantify the displacement of COP and plantar loading during one-leg stance in Tai Chi. One-leg stance was defined as the interval spent standing on one foot when ground reaction force of the other foot is below two Newton. Medial-lateral displacement of COP was significantly greater during one-leg stance in Tai Chi movements than normal walking. The authors suggest movements in Tai Chi induces greater ankle torque and horizontal forces as the practitioners attempted to restore the centre of gravity to a more balance position (Mao et al., 2006c). This would further imply that mediolateral stability could be improved with more Tai Chi training; however the findings are limited to a young group of experienced Tai Chi practitioners. The stability of the ankle joints among these subjects (aged 23.07 ± 5.5) would be superior in comparison to an older demographic. The lack of ankle stability with aging has been documented (Nakamura et al., 2001), which means Tai Chi training would be more noticeable among the elders. Future studies have yet to examine the mediolateral displacement of the COP among the elders during Tai Chi practice.

Wu & Hitt (2005) examined the foot contact characteristics of TCG performed by a group of young individuals ($n = 10$). TCG had significantly higher peak medial force and smaller peak anterior-posterior (AP) and vertical forces. In comparison to TCG, higher rate of loading was seen for slow walking during double stance phase (Wu & Hitt, 2005). TCG involves low initial foot contact force with the ground, which has been attributed to better coordination of the muscles in the lower extremities (Wu & Hitt, 2005). The specific joint forces and moments characteristics during Tai Chi practice have not been examined extensively. Wu & Millon (2008) examined the intersegmental joint loading force and moment patterns, computed using the

inverse dynamic approach. The kinematical and kinetic features of in the lower extremities were characterized during TCG, and compared to NG in a group of young ($n = 6$) and old ($n = 6$) subjects with 15 weeks of Tai Chi practice prior to testing. Along the frontal and sagittal plane, peak moment at the hip and knee was significantly larger for TCG than NG, except for the ankle plantar flexion moment (Wu & Millon, 2008). During TCG, increased shear force was recorded at the knee and ankle along the medial-lateral direction (Wu & Millon, 2008). Peak shear force was highest at the knee when the knees are flexed, but compressive force was less with more torque in the sagittal plane (Wu & Millon, 2008). Higher knee extensor torque was recorded during TCG when compared to normal walking gait (Wu & Million, 2008). As well, higher hip abduction torque and lower plantar flexion torque was recorded during TCG in comparison with normal walking gait (Wu & Millon, 2008). It is questionable whether a 15-week of Tai Chi practice session is sufficient for subjects to become familiar with TCG. Selecting a group of participants with more Tai Chi experience would help strengthen study's finding.

To recap, the kinetic features of Tai Chi have not been reported in a number of studies, which limits the understanding of the demands of the different movements. The displacement of COP is not equivalent during static and dynamic movements (Nakamura et al., 2001). Wider mediolateral displacement of COP during forward, backward, and sideways Tai Chi movements suggest that ankle stability is improved in the Tai Chi practitioners (Mao et al., 20006b, 2006c). Some Tai Chi movements, like “Repulse Monkey” and “Wave-hand in Cloud”, require a lot of twisting movement that may pose some interesting ground reaction force results. Furthermore, when stepping backward and sideways, the slow nature of the two movements and the gentle placement of the toes (rather than the heel) will help to minimize the applied downward force of the foot. More research is needed in this area of Tai Chi study.

2.5 Gaps in Literature and Research Focus

Few studies have examined a group of older subjects during Tai Chi practice (Xu et al., 2005; Wu et al., 2002; Cristou et al., 2003; Lan et al., 2000; Xu et al., 2008, Wu, 2008a). These studies all use different classification for the participants' age. If the findings of the study are to be applied to an older target population, the age of participants would need to be controlled. Lan and colleagues (2000) examined the effects of a 6-month Tai Chi training program on knee extensor muscular strength for the elderly. The mean age of the study group was 61.1 ± 9.8 years. Similarly, Wu (2008a) examined the knee extensor strength and muscle action pattern of older Tai Chi practitioners (mean age 72.6 ± 8.7) during performance of "Parting the Wild Horse Mane." In both studies, the researchers failed to properly define the study's targeted age range, which would not account for the variable rate at which muscles atrophy with age. Hence, the age range of the participants should be narrowed when recruiting participants for our study so that any effects of aging are minimized.

The EMG studies mentioned above have primarily focused on the neuromuscular control of the ankle, and the strength and endurance of the knee extensors of the elderly. This would suggest that the effects of Tai Chi training on the lower extremity muscles are significant for the elders. The relationship between joint loading and muscle activity for Repulse Monkey and Wave-hand-in-Cloud has not been examined. Backward movements in Tai Chi would be less stressful on the patellofemoral joint but enough to help strengthen the quadriceps (Chua & Mao, 2006). Only the muscle activation patterns for Brush-Knee-Twist Step and Parting the Wild Horse's Mane have been studied so far (Xu et al., 2003; Wu, 2008a). It would be beneficial for future studies to examine the muscle activation patterns of the lower extremities in order to better understand their role in maintaining the stability of joints during Tai Chi practice.

The muscles of the hip joint have not been extensively examined in the literature reviewed. Sideway movements in Tai Chi would help to strengthen the muscles used for hip abductor and adduction (Chua & Mao, 2006). The problem for older subjects is that these muscles surrounding the hip joint would be difficult to locate, especially if adipose tissues is increased and muscle tone is reduced. The elderly may be uncomfortable having EMG electrodes placed on their gluteus and TFL muscles. Improper identification of these muscles would limit the quality of the EMG signals and make data processing difficult. Studies on the kinematics and kinetics of Tai Chi practice is still limited a group of young, experienced practitioners (Xu et al., 2003; Wu et al., 2004; Mao et al., 2006a, Mao et al., 2006b; Mao et al., 2006c; Wu & Hitt, 2005). The joint loading and forces of the lower extremities has been compared between young and old Tai Chi practitioners (Wu & Millon, 2008). It would be interesting to compare these values with Repulse Monkey and Wave-hand-in-Clouds. The plantar distribution characteristics for Repulse Monkey and Wave-hand-in-Cloud have been examined. The researchers reported a wider displacement of COP for forward, backward, and sideway Tai Chi movements than NG (Chua & Mao, 2006b). Backward and sideway Tai Chi movements would involve unique loading patterns on the joints of the lower extremities, but more evidence is needed.

To recap, the focus of this study is to examine the biomechanical features of two typical Tai Chi movements performed by a group of elderly practitioners. The neuromuscular effects of pre- and post- Tai Chi training will not be examined, nor will the changes between Tai Chi movements during practice be measured. The level of performance of the practitioners will not be enhanced through participation in this study. Rather, the data collected will simply help to address the need for a better understanding of the Biomechanics of Tai Chi movements.

CHAPTER III: METHODOLOGY

3.1 Participants

Community-based adults, between the ages of 65 to 75 years, were recruited. For the purpose of this study, a total of 15 male Tai Chi practitioners with more than 4 years of Tai Chi experience were required. Participants had practiced either the Yang- or Wu-styles of Tai Chi. Both experienced Tai Chi Masters and students were eligible to participate. Participants were excluded from this study if they reported any of the following conditions: cardiovascular disease or did suffer from stroke; impaired mobility; dementia; symptoms of cardiovascular disease during moderate exercise; and use of specific medications known to impair balance. Participants were recruited through poster advertisement as well as through Tai Chi classes offered at local community centers in the Ottawa region. The outlined protocol has been approved by the University of Ottawa Health Science and Science Research Ethics Board.

3.2 Instruments

Force Plates & Walkway

The ground reaction force data was recorded using four force plates (models 9286AA, Kistler Instruments Corp, Winterthur, Switz; FP 4060-08, Bertec Corporation, Columbus, OH, USA) at 1000 Hz. The force plates are fastened to a metal track which is fixed to the concrete floor, and built into the walkway. The arrangement of the force plates allowed the participants to step on each plate without alteration of their gait patterns. The walkway is approximately 8m long. Of the length of the walkway, only approximately 3m of the walkway was used in the calibration of the testing volume used for data collection. The concrete floor of the walkway is covered with a rubber material to provide for a cushioning effect. Please refer to appendix B for illustrations of the manner in which the two Tai Chi movements are performed and collected.

Motion Analysis System

The temporospatial and kinematic data was obtained from Vicon Motion Analysis System. Ten VICON MX-13 cameras (Oxford Metrics, Oxford, UK) were used for motion recording at 100 Hz. All cameras hanged from the ceiling or mounted on individual tripods that were placed around the testing area (Figure 2). The cameras are arranged so that all the reflective markers on the subjects can be detected during data collection. All cameras are synchronized to capture and generate the 3-D movements of interest.

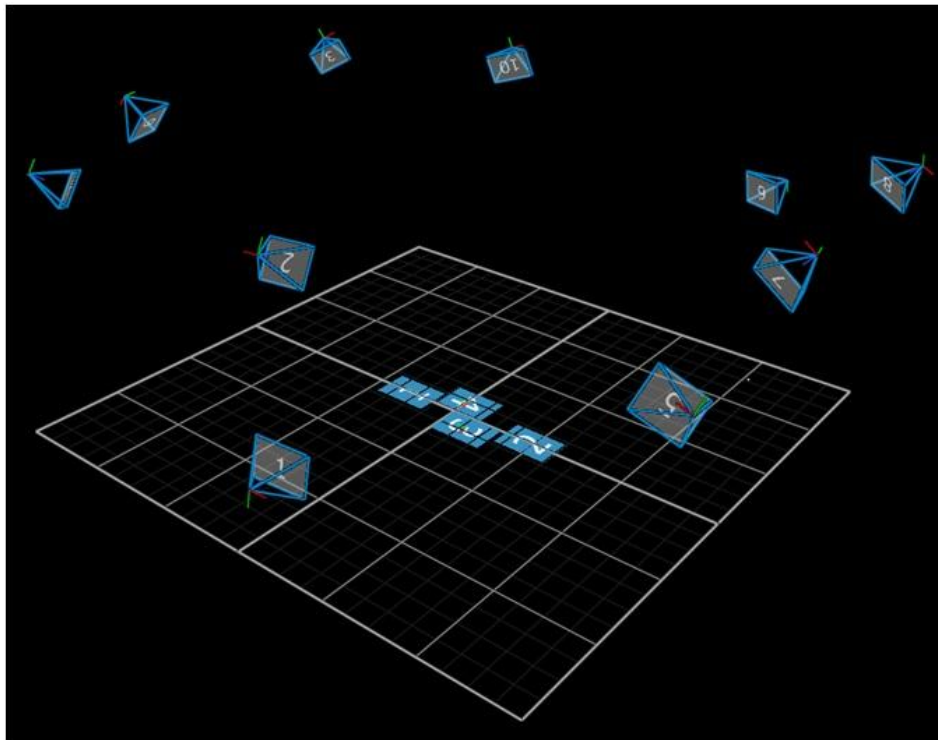


Figure 2: Three dimensional illustration of the testing area with a total of ten infrared cameras and four force plates (1: models 9286AA, Kistler Instruments Corp, Winterthur, Switz; 3 & 4: FP, 4060-08, Bertec Corporation, Columbus, OH, USA).

Synchronization of the cameras involved two types of calibration: static and dynamic. Static calibration involved using an L-shaped frame (ErgoCal, 14mm) to identify the origin of the capture volume. The X, Y, and Z axes were set in accordance to the anterior-posterior, medial-lateral, and vertical upward directions, respectively. Dynamic calibration was performed using a T-shaped wand (240mm) to calculate the relative position and orientation of the cameras. The total volume that was statically and dynamically calibrated is 12 m³ (3.5 x 2.4 x 2.1m).

Electromyography (EMG)

Surface electromyography was used to study the muscle activities of the lower extremity. EMG data was collected simultaneously with kinematics and kinetics data with sixteen-channel EMG system (DS-B04, BagnoliTM-16 Desktop EMG system Delsys Inc., Boston, MA) at 1000 Hz. Bipolar single differential surface electrodes (SP-E04, De 2.1, Delsys Inc., Boston, MA) were used. As suggested by Winter (1991), the following muscles on both the right and left leg were recorded during each Tai Chi and walking trials: rectus femoris, semitendinosus, anterior tibialis, lateral gastrocnemius, vastus medialis, vastus lateralis, bicep femoris, and peroneus longus. The surface electrodes were connected to a portable unit (SP-N05, Bagnoli-8, DelSys Inc., Boston, MA) which was worn by the participant on a belt. This unit was attached to the main amplifier (SP-B08, Bagnoli-16, DelSys Inc., Boston, MA) that fed the analog EMG signals to the VICON acquisition board via ac/dc convert for the synchronization with the kinetic and kinematic data.

3.3 Participant Preparation Procedures

The study was conducted at the University of Ottawa's Human Movement Biomechanics Laboratory (200 Lees Avenue, E Building). Prior to testing, a briefing period was used to address any questions or concerns of the participants. To ensure that the participants understood the

nature and design of the study, a signed consent form was obtained. If requested, the participant assumed anonymity and given the liberty to withdraw from the test if their concerns are not properly addressed.

The participants' accessories were removed prior to testing. The participants were outfitted with a black skin-tight suit of varying sizes (large, medium, and small) or a tight-fitted short and T-shirt of choice. Movements were performed in the comfort of the shoes that they had on that day. Participants were asked to practice walking forward and backward for two to three minutes along the testing path to become familiarize with the experiment settings. Similarly, time was allocated for the participant to practice the two Tai Chi movements. More time was given at the request of the participant.

Reflective markers were attached on the skin or over clothing with double-sided adhesive tape. In accordance to the Plug-in-Gait marker set, 39 reflective markers (14mm in diameter) were placed on body landmarks as modified from original Helen Hayes marker set (Figure 3). Anatomical landmarks were located through palpation. Markers were asymmetrically placed on the left and right side to clearly distinguish the different sides of the body. Sixteen surface EMG electrodes were attached to the skin of the overlying muscle belly. Palpation by the researcher helped to identify the proper location and placement of the electrodes. No skin preparation was needed for the application of these electrodes (DelSys Inc., Boston, MA). The reference or ground electrode was placed on the patella. Maximum Voluntary Contraction (MVC) for each muscle was recorded prior to commencing the walking trials.

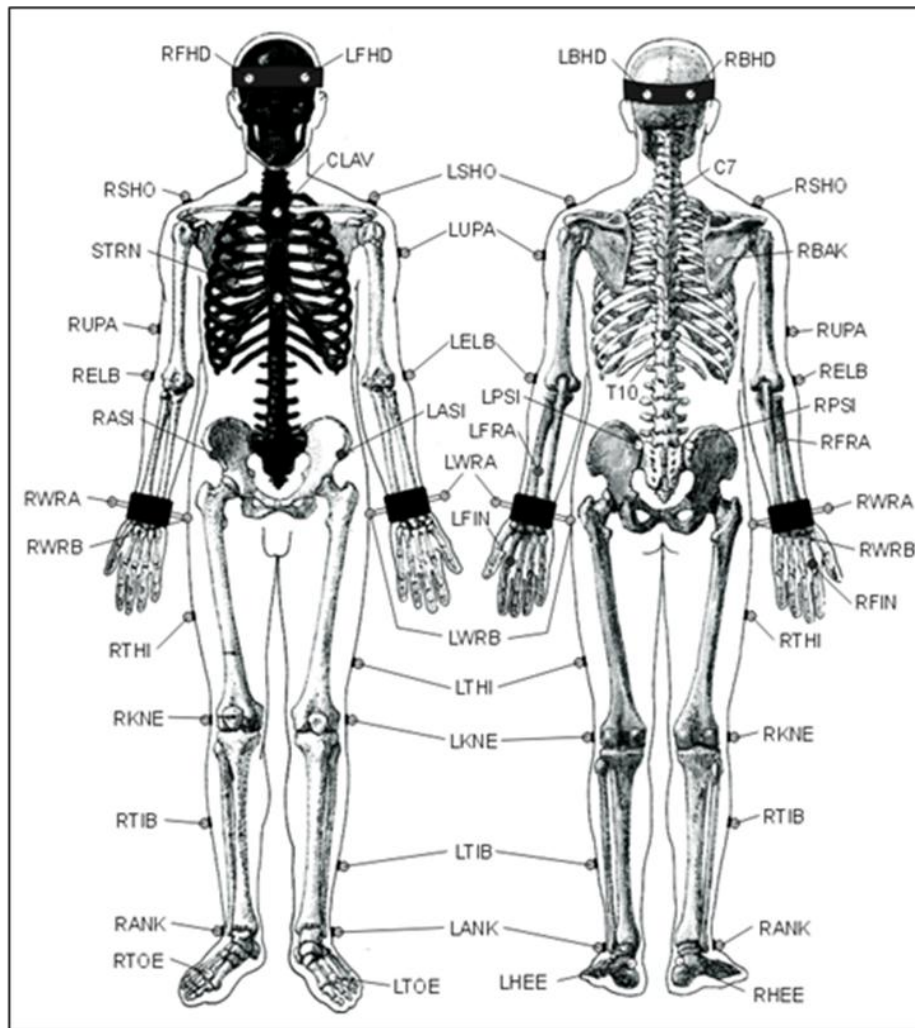


Figure 3. Anatomical landmarks of Plug-in-Gait marker set for the motion capture during data collection.

3.4 Testing Protocol and Data Collection

The data collection session consisted of a preliminary screening questionnaire, gathering of anthropometric data, and 3-D motion capture. Body height (cm), body masses (kg), and anthropometric dimensions (leg length (cm), knee width (cm), and ankle width (cm)) were recorded once the participants wore the black experiment suit.

Measure of Maximal Voluntary Contraction (MVC)

Based on the recommendations provided by Seniam.org (2011), MVC was obtained while the participants are seated, standing, or lying face down. The participant was asked to resist an external force that will be manually applied against the action of the muscle for 5 seconds. A total of MVC 3 trials were obtained with 2 minutes of rest period in between. The highest measurement that was obtained will be used in this study.

MVC was obtained for the following group of muscles. (1) For the vastus medialis, the participants sat with the knees in slight flexion and the upper body slight bent backward. They were asked to extend their knee without rotating the thigh while an external pressure was applied against the leg above the ankle in the direction of flexion. (2) For the rectus femoris and (3) vastus lateralis, the same procedures as vastus medialis were used. (4) For the long head of the biceps femoris, the participants were lying face down with the thigh down on the table and the knee slightly flexed. They were asked to flex their knee while an external pressure was applied against the leg proximal to the ankle in the direction of knee extension. (5) For the semitendinosus, the participants were lying face down with the thigh down, with the leg medially rotated with respect to the thigh. The knee was flexed less than 90 degrees. They were asked to flex their knee while an external pressure was applied against the leg proximal to the ankle in the direction of knee extension. (6) For the tibialis anterior, the participants was sitting or supine while the leg supported just above the ankle joint with the ankle joint in dorsiflexion and the foot in inversion without extension of the great toe. Pressure was applied against the medial side, dorsal surface of the foot in the direction of plantar flexion of the ankle joint and eversion of the foot. (7) For the peroneus longus, the participants sat with their leg medially rotated and supported above the ankle joint. They were asked to everse their foot with plantar flexion of the

ankle while pressure was applied against the lateral border and sole of the foot in the direction of inversion of the foot and dorsiflexion of the ankle joint. (8) For the lateral head of the gastrocnemius, the participants attempted to stand on the tips of their toes while an external pressure was applied downward onto the shoulders.

Tai Chi Movement Instructions (please see Figure 4 for illustration)

To perform “Repulse Monkey”, the left hand is first drawn backward, palm up while the right palm is pushed forward, palm down. Here, the right foot should be turned slightly inward at 45-degree angle. The left hand continues to be drawn backward past the left ear as the right knee is raised. To begin the next segment, the right palm is first turned upwards. The left hand continues to push forward as the right hand is pulled backwards. The retraction of the right hand occurs in synchronization with the right leg, which is retracted backwards. The right toes touch the ground first and are pointing straight ahead. At this point, 60% of the body weight is shifted onto the right leg while 40% of the body weight is on the left. The same sequence is repeated for the opposite side for a total of four complete cycles. To perform “Wave-hand in Clouds”, the movement begins with the simulation of holding a ball at the left side with the left hand, palm down, on top and the right hand, palm up, below. The weight of the body should be concentrated on the left foot (Man-Ch’ing, 1978). As the body turns to the right, the left hand, palm in, moves along under the right arm toward the naval while the right hand, palm in, moves toward the throat. The right hand press down while the left arm is lifted up to the chest height just as the left leg steps to the side of the right leg (Yang, 2010). The body weight is transferred from the left leg to the right stance leg. The movement continues with the turning of the body back to the left, follow by the right leg stepping to the right side as the hands are switched. This sequence is repeated 3 times to complete the series of Wave-hand-in-cloud movement.

Static and Dynamic Motion Capture

Static and dynamic calibration of the Vicon system was completed before the arrival of the participant to the laboratory. One static trial was collected to ensure all reflective markers are picked up by the camera so that a 3-D model of the participant could be generated. All extraneous variables were properly controlled during collection.

Data from a static, standing trial with the arms at the side and feet approximately shoulder-width apart (load evenly distributed on both legs) was collected. Next, the dynamic trials were collected. The participants were asked to perform two types of Tai Chi movement, “Repulse Monkey” and “Wave-hand-in-Cloud”, and forward walking trials. The participants were allowed to take a break anytime during the experiment. The first part of the data collection involved forward walking in the forward direction across the walkway at a self-selected speed. The participants were advised to walk naturally as if they were not being recorded or watched. It was ensured that the participants stepped on the force plates consecutive and did not look down as they walked. Five successive trials of forward walking were collected. The second part of the testing involved the performance of the two Tai Chi movements, Repulse monkey and Wave-hand-in-cloud. These two movements are included in various Tai Chi styles, such as Yang, Chen, Sun and Wu, and are thought the most representative movements of Tai Chi (Mark, 1979). These movements include basic Tai Chi support and stepping pattern that have been examined in a previous study (Mao et al., 2006b). The participants were instructed to perform Tai Chi movements at their natural speed without any reference to the force platforms imbedded in the middle of the testing space for the testing trials. At least five successful trials were recorded for each participant and each task for subsequent analyses.

3.5 Important Considerations in Data Processing

Classification of Tai Chi movement

The stepping characteristics of “Repulse Monkey” and “Wave-hand in Cloud” are illustrated in Figures 4. The two Tai Chi movements have cyclical gait characteristics. Similar to gait analysis, the two movements can be broken into stance phase and swing phase for the left-foot contact from consecutive left heel off and left toe-strike. One cycle time was defined as the duration from two consecutive foot strikes, which can be determined either by the ground reaction force from the force platform or motion analysis. During “Repulse Monkey”, one stride length was defined as the anterior-posterior distance between the left toe-strike to the second left-toe strike. On the other hand, one stride width of “Wave-hand in Cloud” was the lateral distance from left foot-strike to the second left foot-strike.

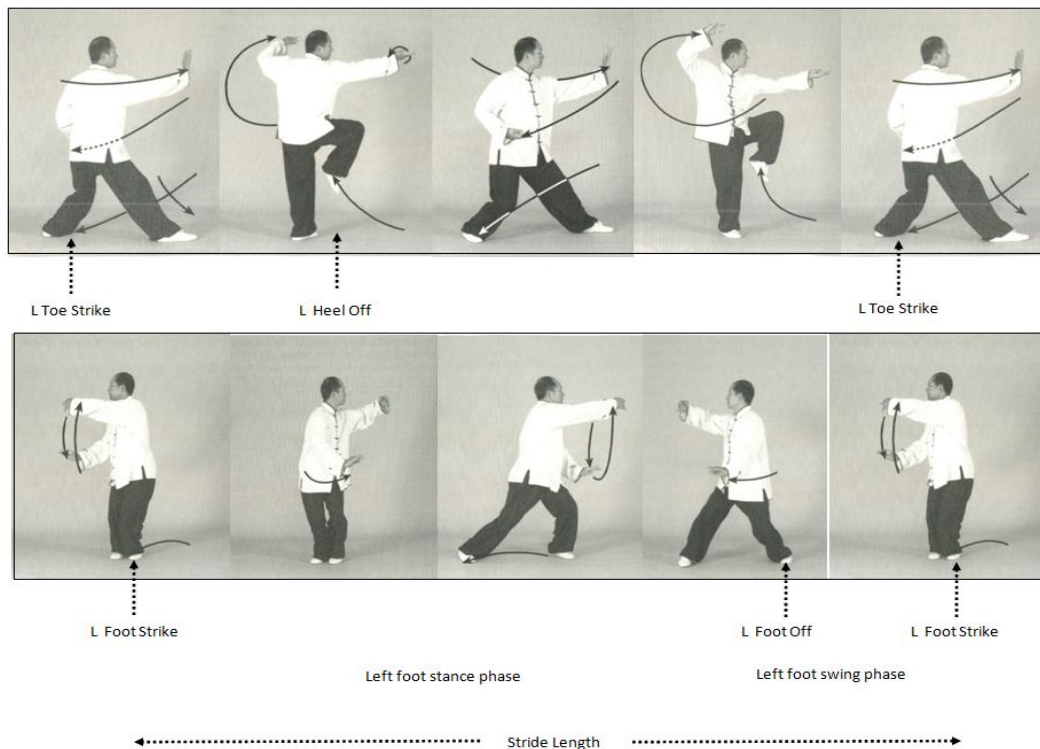


Figure 4. Illustration of a complete gait cycle of the movements “Repulse Monkey” (top) and “Wave-hand in Cloud” (bottom). Gait events have been labelled. One stride length is defined from toe strike to toe-strike (or foot-strike to foot-strike).

Age of Participant

There were notable differences between young and old Tai Chi practitioners (Wu, 2008; Wu & Millon, 2008; Wu & Ren, 2009; Wu, 2008b). To minimize the effects of aging, selection of the participants were based on criteria set forth in previously published review papers. Past studies in on Tai Chi selected participants from one age cohort (Wu, 2008a; Xu et al., 2005; Cristou et al., 2003). Based on the reviewed literature, our study recruited community-based participants between the ages of 65 to 75 years. Inconsistencies in the data were attributed to possible intrinsic characteristics of the participants.

Normalization of Data

Changes to stride length could alter muscle activity (Winter & Yang, 1985; Nilsson, Thorstensson, Halbertsma, 1985), such that an increase in cadence would also lead to an increase in muscle activation. If cadence alone was to be controlled, then the EMG amplitude would remain the same and thus result in similar or shorter stride (Winter & Yang (2005). Stride length and cadence speed should be normalized for all participants. In this study, the participants were advised to perform at a slow and comfortable pace to limit the effects of performance speed. For each trial, all movements were therefore controlled and smooth. Any increased muscle activities were attributed solely to the property of Tai Chi practice. Postural height had an effect on duration and magnitude of leg muscle activation, as shown in both the young and older groups (Wu & Ren, 2009). In a study by Wu & Millon (2008), this effect was controlled by normalizing all joint forces by the subject's body weight & the subject's joint moments were normalized by body weight (% of BM, which product body weight & body height). Normalization of the data was performed if there is any significant inter-subject variability due to age. Any confounding effects of age were limited by selecting the Tai Chi participants from a fixed age-range.

3.6 Data Processing and Analysis

Data was analyzed using Vicon Nexus software (v1.3), Bodybuilder software (v3.6), and MATLAB (v7.1 Release 2006a) programs to obtain kinematic and kinetic joint data. All calculations were derived from Plug-in-gait model (Vicon Oxford Metrics, Oxford, UK) that predicts joint centers of the hip, knee, and ankle originally from Davis model and provides kinematic and kinetics data.

For each successful trial, the gait events were visually inspected on the Vicon Nexus software (v1.3) and properly defined. Each movement was normalized to 100% or one full gait cycle. Raw ground reaction force data from the force plates will be filtered with 2nd-order Butterworth lowpass filter at 6Hz and combined with the data from the camera system to calculate the joint moment at each joint. The amplitudes of the ground reaction forces and moments of force were normalized according to body mass for each participant. These values were calculated by the software using the inverse dynamics approach. The profiles of the five successful normalized Tai Chi movements and walking trials were averaged to obtain a mean for each participant. The mean profiles of each participant were averaged and then combined for the group in order to obtain the standard errors of the mean. Raw EMG of all muscles was collected, but not been processed in this study.

3.7 Statistical Analysis

Prior to performing any statistical analysis, the participants' data was checked for outlier values due to measurement errors such as hidden markers. Descriptive statistics, including means and standard deviations, were obtained for all variables. A two-way ANOVA was used for this study. The two independent variables were Tai-Chi movements (2 levels: Repulse Monkey & Wave-hand in Cloud) and walking condition (1 level: forward walking). The dependent variables that were described include the temporospatial, kinematics, and kinetics parameters for the lower extremities. These variables are summarized in Table 1 (See section 1.3: Variables). When required, a Bonferroni correction was performed to adjust the alpha value to account for multiple comparisons. All statistical analyses were performed using Statistical Package for Social Science (SPSS) version 17.0 software (SPSS Inc., Chicago, IL, USA) for Windows with a significance level of 0.05.

Articles

The Temporospatial and Kinematic Characteristics of Typical Tai Chi Movements: Repulse Monkey and Wave-hand in Cloud

Short Title: The Kinematics and Temporospatial Features of Tai Chi

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Abstract

“Repulse Monkey” and “Wave-hand in Cloud” are two typical Tai Chi movements which share similar kinematic and temporospatial features as normal walking. These slow and graceful movements can be isolated or performed in series with other Tai Chi forms during practice. However, the understanding of the biomechanical characteristics of the two Tai Chi movements is limited. The purpose of the study was to examine and to compare the temporospatial and kinematic features of two typical Tai Chi movements with forward walking. A group of experienced male Tai Chi practitioners ($n = 15$) between the ages of 65 to 75, performed “Repulse Monkey (RM)”, “Wave-hand in Cloud (WHIC)”, and forward walking. The three-dimensional angles of hip, knee, and ankle joints; range of motion (ROM) of the joints, and temporospatial parameters were measured during performance and analyzed. Compared to walking, “Repulse Monkey” was characterized by: shorter stride length, step length, and stride width; longer double support duration; larger mediolateral and vertical displacement of COM; larger minimal knee flexion and extension angles; larger minimal varus and valgus angles; and larger plantar- and dorsiflexion ROM. For “Wave-hand in Cloud”, the movement was characterized by: shorter stride length and step length; longer stride width; shorter single- and double-support duration; larger mediolateral and vertical displacement of COM; larger maximal extension and adduction angles at the hip; larger minimal knee flexion angles; and larger maximal ankle plantar- and dorsiflexion angles. The slow, gentle stepping-action and fluidity of two Tai Chi movements have unique biomechanical features that may result in special training to postural control capacity.

INTRODUCTION

Tai Chi is a traditional Chinese exercise that has been practiced for over 1200 years.¹ Originated from 13 basic postures, different variation of Tai Chi styles emerged with distinct yet repeatable movement patterns.¹ Regular Tai Chi practice can help to maintain or improve balance, posture, breathing, muscle strength, digestion, cardiovascular and circulatory functions.^{1,2,3,4} Recently, the American Geriatric Society and British Geriatric Society have recommended Tai Chi as an effective intervention to reduce the number of falls among the elderly.⁵ As the popularity of Tai Chi continues to grow, more scientific research is needed to better understand and support these promising health claims.

Maintaining functional mobility is a major concern for the elders. Limited mobility may lead to increase hip fractures and fall-related injuries later in life.⁶ Joint flexibility and movement restrictions hinder the elders' ability to carry out daily living activities.⁹ Furthermore, notable gait changes can be seen among the elders who use flatter-foot landing and less plantarflexion to initiate push-off with the toes.⁷ Tai Chi is an appropriate and safe exercise for the elderly. The Tai Chi movements are performed at a slower pace with longer periods of double- and single-support times than normal walking gait.¹² The displacement of the COM showed large directional and positional changes during Tai Chi performance, which suggests regular practice would help to train balance and postural stability.^{11,8} Large changes to the range of motion (ROM) of the ankle and knee joints would also help to improve postural control and joint flexibility.^{12,6,9,10} These beneficial effects would not only be reflected in the elders' performance of daily living tasks but also in their overall quality of life.

There are few studies that have examined the joint kinematics and displacement of the body's centre of mass (COM) during Tai Chi performance. Of the available Biomechanics literature on Tai Chi, the kinematics and temporospatial characteristics of Tai Chi movements have been studied for movements like "Push Hand", "Brush-knee Twist Step (BKTS)" and "Parting-the-Wild-Horse's Mane (PWHM)".^{11,12,13,14,15} No studies have examined the dynamic displacement of COM during dynamic backwards and sideways Tai Chi movements. More research in backward and sideways locomotion would benefit those in the field of preventative care and rehabilitation science. A similar study by Wu and colleagues¹² suggest that normal gait can be chosen as a control variable because this movement is an essential balance activity that is used daily by the elderly. Engagement in Tai Chi at home or recreational Tai Chi programs offered in the local recreational centres is a safe and practical way for the elders to maintain their physical wellbeing and to build strong support networks.

The purpose and objectives in this study were to examine the temporospatial and kinematic characteristics of two Tai Chi movements, "Repulse Monkey" (RM) and "Wave-hand in Cloud" (WHIC), and to compare the temporospatial and kinematic features of these two Tai Chi movements with walking. In accordance with the past Tai Chi literature, it is hypothesized that flexion/extension, adduction/abduction, and internal/external rotation at the hip, knee, and ankle joints will be altered during performance of RM and WHIC. The slow and calm nature of these Tai Chi movements will help to increase the stance time and stride dimensions. Vertical displacement of the body's COM will be larger than walking during RM and WHIC while mediolateral displacement of the COM will be larger than walking during WHIC.

MATERIALS AND METHODS

Participants

Fifteen male Tai Chi participants with more than 4 years of Tai Chi experience were recruited. Participants for this study were between the ages of 65 and 75. Participants should have practiced either the Yang- or Wu-styles of Tai Chi. Both experienced Tai Chi Masters and students were eligible to participate. Recruitment of the subjects was from two local community centers in the Ottawa region where Tai Chi was taught and practiced in a large group, twice a week. Each session was approximately 1.5-2 hours long with one fifteen-minute break in between.

The participants' physical conditioning and health was screened prior to data collection. Self-reported surveys indicated that all subjects were in good health. The exclusion criteria for the study included any of the following past medical conditions: cardiovascular disease or did suffer from stroke; impaired mobility; dementia; symptoms of cardiovascular disease during moderate exercise; and use of specific medications known to impair balance. All participants signed an informed written consent prior to participating. This study has been approved by approved by the University of Ottawa Health Science and Science Research Ethics Board.

Table A 1. Participants' Demographic Data, and Year(s) of Experience in Tai Chi Practice (n = 15)

	Mean $\pm$ SD
Age (yr)	65.5 $\pm$ 8.9
Body weight (kg)	70.0 $\pm$ 8.8
Height (cm)	166.7 $\pm$ 7.8
Body Mass Index (kg/m ²)	25.2 $\pm$ 2.6
Years of experience in practicing Tai Chi (yr)	14.3 $\pm$ 10.6

Instrumentation and studied Tai Chi movements

The movements were recorded at 100Hz by the VICON Motion Analysis System (Vicon MX-13, Oxford Metrics, Oxford, UK) using ten VICON MX-13 cameras (Oxford Metrics, Oxford, UK). Three metal force plates (models 9286AA, Kistler Instruments Corp, Winterthur, Swt; FP 4060-08, Bertec Corporation, Columbus, OH, USA) were used to define the instances of heel-strike and toe-off. These force plates were imbedded into an 8m long walkway.

“Repulse Monkey” is a typical Tai Chi movement that involves backward stepping while pushing the palms forward. “Wave-hand in Cloud” is the other typical Tai Chi movement involving waving of the hands and lateral stepping. Both forward walking and backwards “Repulse Monkey” were performed in-line but opposite directions while “Wave-hand in Cloud” was performed in the direction perpendicular to forward walking (Figure 1). These two Tai Chi movements were chosen for analysis because they are typical movements included in each style of Tai Chi and represent the typical Tai Chi side- and backward stepping patterns.

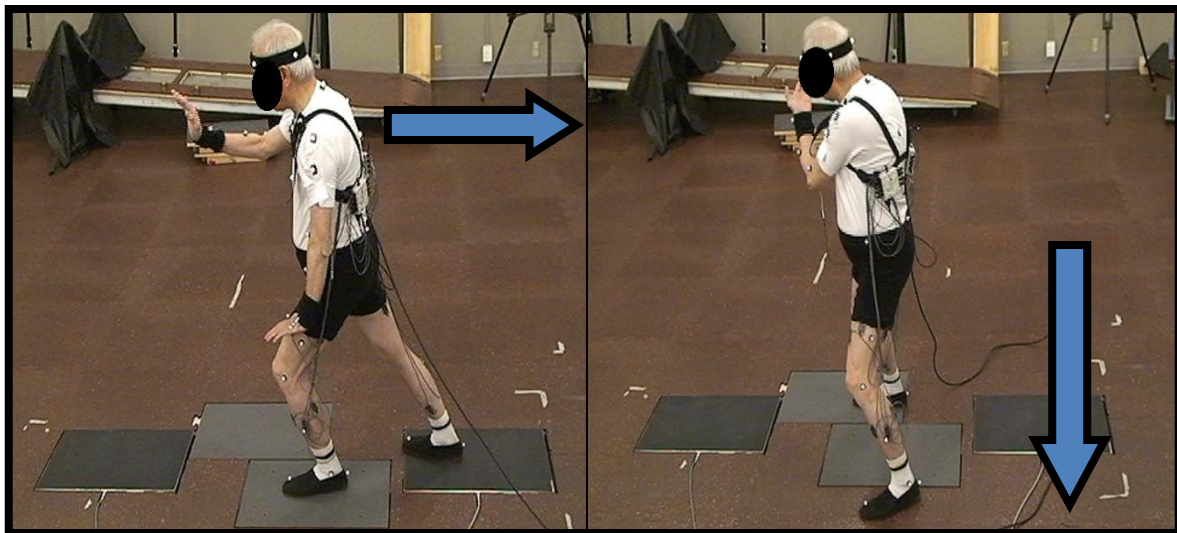


Figure A 1. Side-view of Repulse Monkey (*left*) and Wave-hand-in-Cloud (*right*). The large arrow indicates the direction of the movement.

Procedure

The participants' anthropometric measures were recorded prior to being outfitted with a tight-fitting spandex suit. 39-reflective makers were attached on the skin or over clothing with double-adhesive tape to indicate the body's anatomical landmarks in accordance with the Plug-in-Gait marker set (Oxford Metrics, Oxford, UK), as modified from the Helen-Hayes marker-set.¹⁶ The movements were performed in the comfort of their own shoes that they had on that day. Prior to data collection, the participants were given two to three minutes to practice the Tai Chi movements and become familiarized with the experiment setting. A minimum of five trials each for the two Tai Chi movements and forward walking were recorded. For the two Tai Chi movements, the participants were instructed to perform at their comfortable speed and to contact the force plate with only one foot at a time. Similarly, the participants were asked to maintain a comfortable stride and walking speed during the forward walking trials.

Data Processing and Analysis

One successful gait cycle was defined by the completion of heel-strike to heel-strike for the same foot. Heel-strike and toe-off was defined by the software readings when the foot contacts and leaves the force plates and by visually inspecting the position of the virtual markers on the heel and toe. Two consecutive gait cycles for the left and right leg were analyzed for the temporospatial and kinematic parameters, and the data was normalized to one gait cycle for further analysis. The 3-D kinematics for the lower extremities and the displacement of the body's centre of mass (COM) were calculated using VICON Nexus (Oxford Metrics, Oxford, UK) and the Plug-in-Gait model (Oxford Metrics, Oxford, UK). The trajectory of COM was calculated by VICON Nexus software and exported to Excel (Microsoft, Washington, USA) in order to find

COM displacement in three-dimensional space. The computed joints data were exported to Matlab (MathWorks, Natick, USA) to average and calculate the total maximum and minimum angles of each trial of movement using a custom-built graphic user interface (GUI) output.

The kinematic variables included the displacement of the COM along the medio-lateral (X), superior-inferior (Y), and anterior-posterior (Z) directions; and the maximal or minimal hip and knee joint angles along the frontal axis (flexion-extension in the sagittal plane), sagittal axis (adduction-abduction in the frontal plane), and vertical axis (internal-external rotation in the transverse plane).¹⁷ Following a similar method as suggested in the study by Xu, Li, & Hong¹¹, the minimal position of the COM marker was subtracted from its maximal position in order to determine the total range that the COM displacement. For the ankle joint, angles will be obtained along the transverse (plantar- and dorsiflexion in the sagittal plane), anteroposterior (inversion and eversion in the frontal plane), and longitudinal axes (horizontal adduction-abduction in the transverse plane).^{11,18} Single- and double-support time, step length, and stride length was obtained from VICON Polygon 4.0 (VICON Motion Systems, Los Angeles, USA).

The temporospatial parameters included the support times during each movement. For RM and WHIC, left single-support was defined from the instance when the right-leg leaves and touches the ground while the left leg is in stance. In RM, double-support phase was examined for the time from the left foot (trailing foot) contacts to the instance when the right foot (leading foot) leaves the ground. Similarly, double-support phase during WHIC was defined from the instance the left foot (leading foot) contacts to the instance when the right foot (trailing foot) leaves the ground. In order to compare between the three movements, single- and double-support times were normalized to the time of one stride cycle. Single- and double-support times were reported as a percent of the total time for one stride.

Step length is defined as the distance from the point of contact on one foot to the same point of contact on the other foot.^{9,19,20} Hence, stride length is the distance from initial contact of one foot to the next contact point of the same foot.¹⁹ Stride width (or the base of support) is the side to side distance between the feet measured between the right and left ankle joint centers.^{9,19} Stride width was not available as an output in VICON Polygon, therefore the position of the foot markers was determined by inspecting the raw data. Following the Plug-in-gait model, the left and right ankle markers were placed on the lateral malleolus. The magnitude between the distance of the left and right ankle markers were used to determine stride width. The peak distance between the two markers was found at left-toe off for walking and RM and right-toe for WHIC when stepping off the force plate (Figure 2).

“Repulse Monkey” and “Wave-hand-in-Cloud” was performed symmetrically and continuously for both the right and left sides. Given the symmetry of the movements, only the results for the left limb (trailing limb) has been reported. The participants were asked to perform five trials of two Tai Chi movements under conditions similar to their weekly practice. The

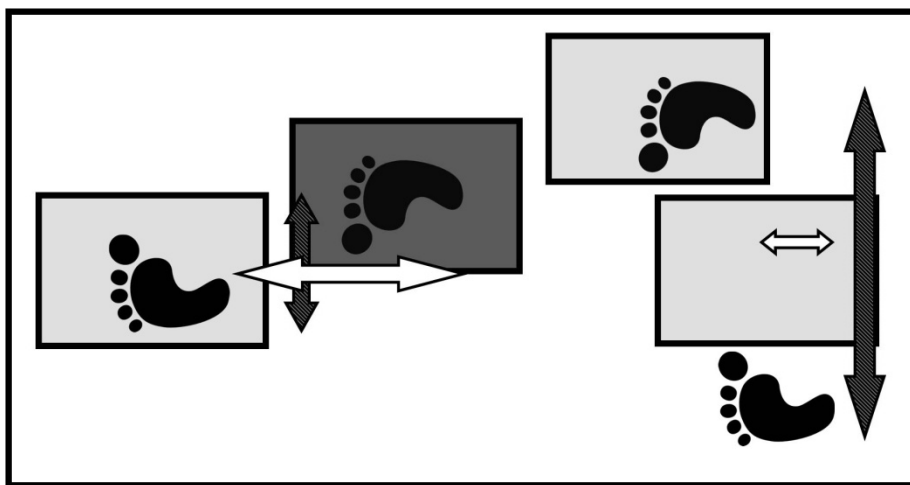


Figure A 2. Two-dimensional view of the stepping pattern of “Repulse Monkey” (*left*) and “Wave-hand in Cloud” (*right*) Tai Chi movements. The vertical striped arrow (*blue*) indicates stride width while the horizontal solid arrow (*gold*) indicates step length.

walking trials were not altered and the subjects were asked to walk at their normal pace. The COM displacement along the X, Y, Z directions was averaged for each participant. The ensemble averages were obtained for each of the two movements of all participants and then separately compared with those ensemble averages for normal walking. Similarly, the two peak angular displacement values of each joint were averaged in order to obtain the maximal and minimal joint angles for each participant. These values were then ensemble averaged for each of the two Tai Chi movements of all participants and separately compared with the ensemble average for normal walking.

Statistical Analysis

All five trials of three movements were average for each participant. The data was initially inspected to ensure that any outlier values were properly accounted for and that subsequent errors in the data were properly removed prior to analysis. Descriptive statistics were reported for the temporospatial parameters and peak values of the kinematic data using Statistical Package for Social Sciences (SPSS) version20 software for Windows (SPSS Science, Chicago, Illinois). Two-way ANOVA (Repulse Monkey $\times$ walking; Wave-hand in Cloud $\times$ walking) was used to compare average 3-dimensional COM displacement, joint angles and ROM. Independent t-test was performed for the following single dependent variables: stride length, step length, stride width, single- and double-support times. Tukey's post-hoc analysis was used if any main effects or significant interaction were found. Significance level was set at 0.05.

RESULT

The data for the temporospatial parameters and COM displacement are reported in Tables 2 and 3, respectively. Mean and standard deviation of the maximal and minimal angles for the

hip, knee, and ankle are presented in Tables 4, 5, 6, respectively. The p-values are provided beside each value for the two Tai Chi movements as a comparison with the baseline walking.

Temporospatial Parameters and COM displacement

Table A 2. Mean and standard deviation for temporospatial parameters for the left limb during the two Tai Chi and walking conditions (n=15). Single- and double-support times were normalized by total stride time.

Parameter	Movement						
	Walking	Repulse Monkey	p-value	% diff	Wave-hand	p-value	% diff
Stride Length (m)	1.48 ± 0.06	1.12 ± 0.08*	0.000	0.24	0.40 ± 0.07*	0.000	0.73
Step Length (m)	0.72 ± 0.04	0.62 ± 0.03*	0.000	0.14	0.69 ± 0.06**	0.048	0.04
Stride Width (m)	0.65 ± 0.03	0.54 ± 0.04*	0.000	0.17	0.67 ± 0.04*	0.000	0.03
Stride Time (s)	1.34 ± 0.15	9.40 ± 2.77*	0.000	6.01	5.77 ± 3.01*	0.000	3.31
Single Support, SS, Time (s)	0.51 ± 0.03	1.30 ± 0.60*	0.000	1.55	0.55 ± 0.17	0.212	0.08
Double Support, DS, Time (s)	0.31 ± 0.06	6.49 ± 2.40*	0.000	19.94	3.87 ± 2.24*	0.000	11.48
Norm. SS Time (%)	38 ± 2	14 ± 5*	0.000	0.63	12 ± 6*	0.000	0.68
Norm DS Time (%)	23 ± 3	69 ± 11*	0.000	2.00	21 ± 13*	0.000	0.09

* p < 0.001 vs. Walking

** p < 0.05 vs. Walking

From Table 2, “Repulse Monkey” (RM) was performed much slower than walking with smaller backward steps. Step length and stride time were 1.12m and 9.40s for RM. Stride width was significantly smaller for RM than normal walking (0.54m vs. 0.65m, p = 0.000). On the other hand, “Wave-hand in Clouds” (WHIC) was a slow side-stepping exercise that involved significantly wider lateral steps in close session. Stride width was 0.67m vs. 0.65m for WHIC and walking, however there was minimal significant difference between the lateral and forward step lengths. For comparative purposes, single- and double-support times were reported as a

percent of stride time. RM had significantly shorter normalized single-support times and longer normalized double-support times (14% and 69%, respectively). In contrast, WHIC had shorter normalized single- and double-support support times (12% and 21%, respectively). The data shows that 61% of one gait cycle is spent in stance phase during the walking trial. For RM and WHIC, stance phase accounts for 83% and 33% of one complete gait cycle, respectively.

Table A 3. Mean and standard deviation for total COM displacement range and maximal COM displacement during the two Tai Chi and walking conditions (n=15)

Direction	Movement				
	Walking	Wave-hand	p-value	Repulse Monkey	p-value
Mediolateral (m)	0.09 ± 0.03	1.02 ± 0.09*	0.000	0.30 ± 0.07*	0.000
Anteroposterior (m)	2.58 ± 0.13	0.10 ± 0.03*	0.000	1.35 ± 0.54*	0.000
Vertical (m)	0.05 ± 0.00	0.06 ± 0.01	0.073	0.07 ± 0.03**	0.019
Max-Mediolateral(m)	0.12 ± 0.04	0.55 ± 0.06*	0.000	0.17 ± 0.05	0.544
Max-Anteroposterior(m)	1.45 ± 0.09	0.18 ± 0.06*	0.000	0.40 ± 0.16*	0.000
Max-Vertical (m)	0.96 ± 0.06	0.95 ± 0.06	0.211	0.97 ± 0.07	0.445

* p < 0.001 vs. Walking

** p < 0.05 vs. Walking

The data in table 3 shows that compared to walking, horizontal displacement range of the COM was larger when performing RM. Displacement of the COM during RM was 1.35m compared 2.58 m for walking. On the other hand, WHIC involves notably larger mediolateral displacement of the COM than walking; the mediolateral position of the COM for WHIC and walking were 1.02m compared to 0.09m, respectively. The maximal mediolateral COM displacement for WHIC was 0.55m, compared to 0.12m for walking. Anteroposterior displacement of the COM was small during WHIC (0.10m) since the movement was sideways. Vertical displacement of the COM was larger for both RM (0.07m) and WHIC (0.06m)

compared with normal walking (0.05m). RM had a significantly larger vertical displacement of the COM than normal walking.

Kinematics of the left limb

Table A 4. Mean and standard deviation of the maximal and minimal hip angles (degrees) on the left limb in the two Tai Chi movements and walking (n=15; ROM = Range of Motion)

Angle (°)	Movement				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Maximal Flexion	32.58 ± 5.57	54.89 ± 14.98**	0.002	37.50 ± 3.42	0.381
Minimal Flexion	-	48.37 ± 5.77	-	28.50 ± 9.88	-
Maximal Extension	-15.83 ± 8.82	-1.17 ± 6.94**	0.007	13.12 ± 10.12*	0.001
Minimal Extension	-	32.69 ± 6.34	-	21.55 ± 4.47	-
ROM (flexion/extension)	49.09 ± 6.94	60.03 ± 11.06	0.078	21.54 ± 1.97*	0.000
Maximal Adduction	3.95 ± 3.10	7.62 ± 4.99	0.259	3.31 ± 7.29	0.489
Minimal Adduction	0.19 ± 1.27	5.32 ± 5.47	0.055	-	-
Maximal Abduction	-9.59 ± 3.68	-17.54 ± 11.98**	0.037	-25.93 ± 4.49*	0.000
Minimal Abduction	-1.89 ± 3.06	0.34 ± 6.78	0.850	-	-
ROM (adduction/abduction)	14.11 ± 2.06	28.92 ± 10.90	0.138	26.98 ± 5.31**	0.003

* p < 0.001 vs. Walking

** p < 0.05 vs. Walking

As seen in Table 4, the hip flexion angle was largest for RM than walking (54.89° vs. 32.58°, p = 0.002). The left leg was slightly extended (-1.17°) after stepping backwards. As the trunk was propelled backward, the practitioner sat back and flexed the left hip (48.37°). Minimal extension of the left hip (32.69°) was seen when the contralateral limb was raised. Abduction (-17.54°) of the hip flexion was largest at toe-off. For WHIC, the left hip is extended maximally

(13.12°, $p = 0.001$ vs. walking) as the left leg extends out to the side. Slight extension (21.55°) occurred when the trunk turned in the direction opposite (right) of the movement. ROM of flexion/extension of the hip for WHIC was significantly smaller than walking ($p = 0.000$). The hip maximal abduction angle was larger during WHIC than walking ($p = 0.000$). ROM of adduction/abduction of the knee for WHIC was significantly larger than walking ($p = 0.003$).

Table A 5. Mean and standard deviation of the maximal and minimal knee angles (degrees) on the left limb in the two Tai Chi and walking conditions (n=15; ROM = Range of Motion)

Angle (°)	Movement				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Maximal Flexion	51.35 ± 13.82	67.52 ± 6.76	0.060	41.83 ± 14.87	0.113
Minimal Flexion	11.05 ± 11.99	38.96 ± 16.58**	0.012	24.22 ± 14.11**	0.027
ROM (flexion/extension)	55.25 ± 6.37	75.00 ± 17.00	0.084	37.93 ± 8.62**	0.004
Maximal Varus	37.59 ± 11.40	51.48 ± 13.39**	0.022	37.17 ± 13.61	0.744
Minimal Varus	12.59 ± 7.32	38.0 ± 11.62*	0.000	25.58 ± 14.84	0.070
Maximal Valgus	4.20 ± 5.07	6.86 ± 4.93	0.331	11.08 ± 8.05	0.065
Minimal Valgus	0.16 ± 3.91	22.45 ± 6.80*	0.000	-	-
ROM (varus/valgus)	37.65 ± 11.23	43.99 ± 12.22	0.061	14.65 ± 5.31**	0.016

* $p < 0.001$ vs. Walking

** $p < 0.05$ vs. Walking

Table 5 shows the angles and ROM of the knee. During RM, the knee remains flexed as indicated by the minimal flexion values (38.96°). The minimal and maximal varus angles are larger for RM than walking, suggesting that the segment below the knee is bent more inwards. Minimal valgus angle was significantly larger for RM than walking (22.45° vs. 0.16°, $p = 0.000$).

During WHIC, maximal flexion angle was larger than walking (24.22° vs. 38.96°). ROM of flexion/extension and varus/valgus were smaller for WHIC ($p < 0.05$ vs. walking).

In Table 6, the left ankle's dorsiflexion angle for RM was 35.03° compared with 15.56° for walking ($p = 0.000$). Furthermore, maximal plantarflexion angle for RM was -26.34° compared with -13.25° for walking ($p = 0.000$). The larger plantarflexion of ankle occurred because the left toes remain pointed and in contact with the floor until they leave the ground. ROM of dorsiflexion/plantarflexion and inversion/eversion were greater RM than walking ($p < 0.05$). During WHIC, significantly higher maximal dorsiflexion and plantarflexion angles were seen ($p < 0.001$). Maximal plantarflexion angle for WHIC was more positive than walking (15.76° vs. -26.34, respectively).

Table A 6. Mean and standard deviation of the maximal and minimal ankle angle (degrees) on the left limb in the two Tai Chi and walking conditions (n=15; ROM = Range of Motion)

Angle (°)	Movement				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Maximal Dorsi-flexion	15.56 ±1.60	35.03 ± 4.53*	0.000	24.63 ± 5.86*	0.001
Maximal Plantar-flexion	-13.25 ± 3.50	-26.34 ± 8.40*	0.000	15.76 ± 7.89*	0.000
ROM (dorsi-/plantarflexion)	28.83 ± 2.78	61.52 ± 4.43*	0.000	36.63 ± 15.06	0.684
Maximal Inversion	4.55 ± 3.13	6.83 ± 3.42	0.274	6.24 ± 3.36	0.494
Minimal Inversion	4.16 ± 2.67	4.81 ± 2.98	0.687	5.23 ± 2.81	0.653
Maximal Eversion	1.46 ± 2.85	2.35 ± 2.85	0.510	2.76 ± 2.94	0.551
Minimal Eversion	1.08 ± 2.60	2.76 ± 2.86	0.326	4.31 ± 2.89	0.086
ROM (inversion/eversion)	4.11 ± 1.22	6.16 ± 1.17**	0.019	4.19 ± 1.74	0.966

* $p < 0.001$ vs. Walking

** $p < 0.05$ vs. Walking

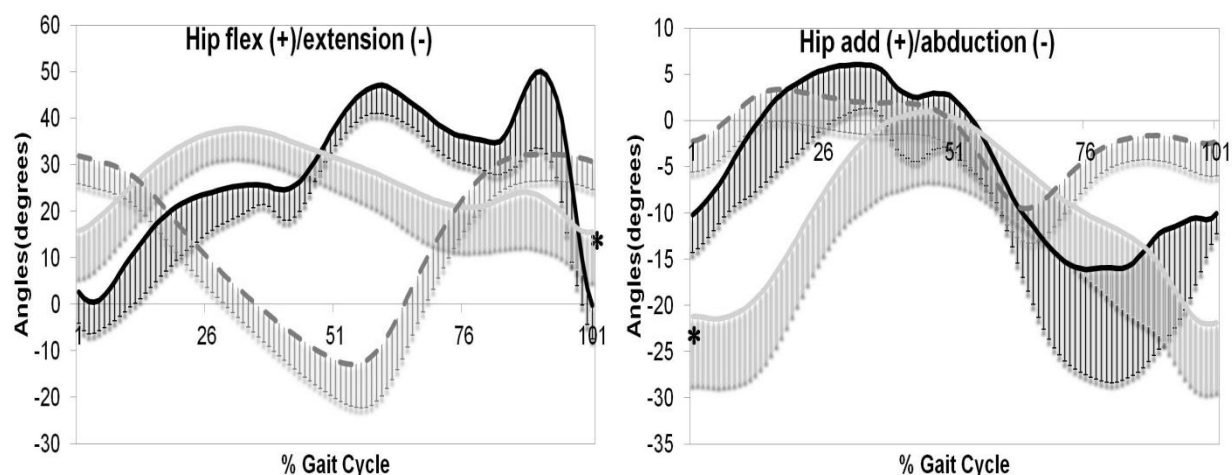


Figure A 3. Hip joint angles in sagittal and frontal planes during Repulse Monkey (*black*), Wave-hand in Cloud (*gray*), and walking (*dotted-line*) during one gait cycle (N = 15). * signify $p < 0.001$.

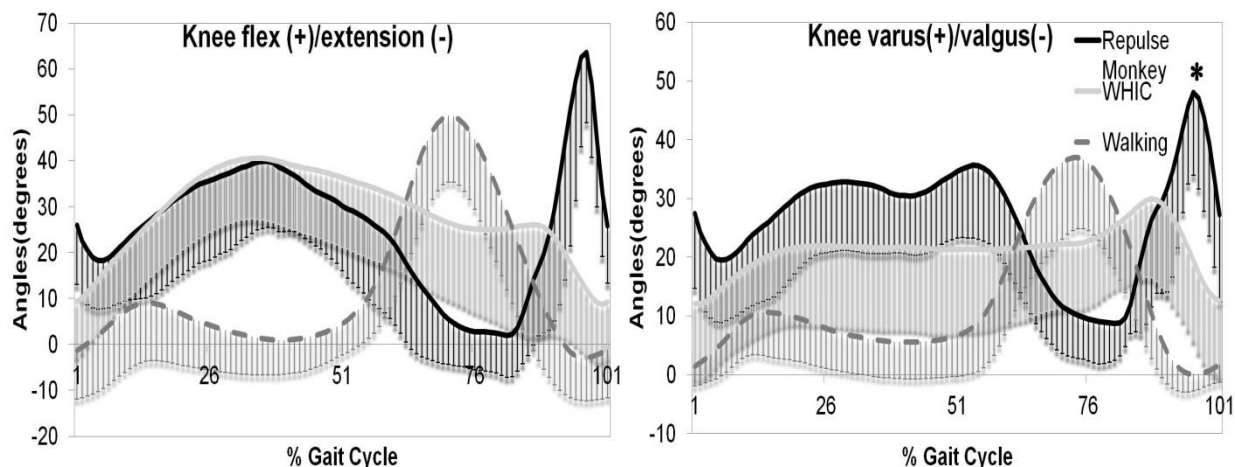


Figure A 4. Knee joint angles in sagittal and frontal planes during Repulse Monkey (*black*), Wave-hand in Cloud (*gray*), and walking (*dotted-line*) during one gait cycle (N = 15). * signify $p < 0.001$.

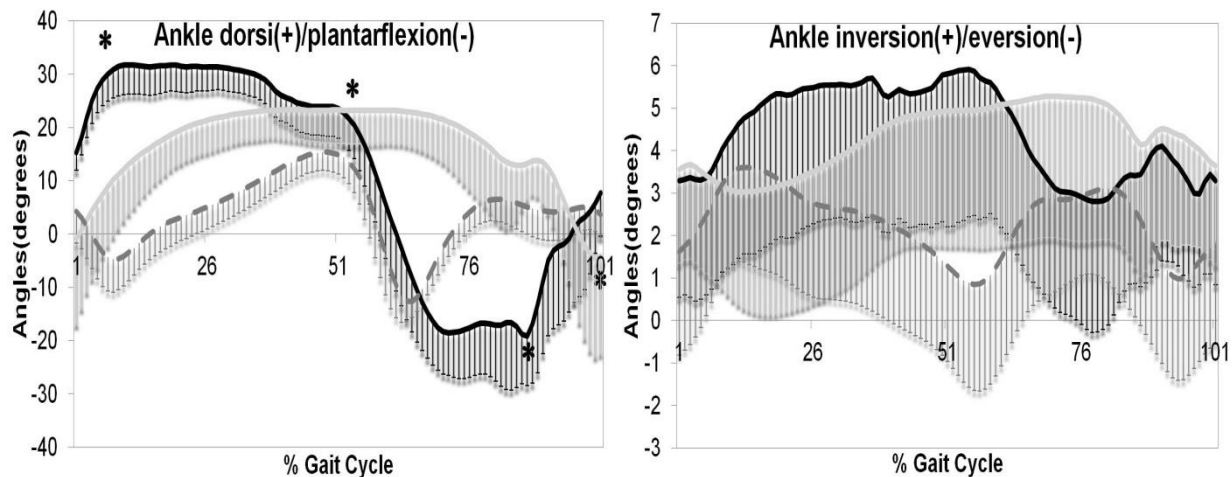


Figure A 5. Ankle joint angles in sagittal and frontal planes during Repulse Monkey (*black*), Wave-hand in Cloud (*gray*), and walking (*dotted-line*) during one gait cycle (N = 15). * signify $p < 0.001$.

DISCUSSION

The purpose of this study was to examine the joint kinematics of the lower extremity during performance of “Repulse Monkey” and “Wave-hand in Cloud” Tai Chi movements. The results showed that the two Tai Chi movements had unique temporospatial and kinematics characteristics when compared to walking. This was the first study to examine the joint dynamics and COM displacement of backward and sideway Tai Chi movements. These findings would add to the understanding of Tai Chi and its mechanisms in which physical capacity and postural control can be improved.

Temporospatial Parameters. Data from our study showed that step length proportionally decrease as the task becomes more challenging. Step length was 0.807m, 0.583m, and 0.713m respectively for forward, backward, and sideward Tai Chi movements.⁹ The values mentioned in the study by Xu, Hong, Li¹⁰ is comparable as “Repulse Monkey” demonstrated a smaller step length similar other backward Tai Chi movements in the set of 42-form Tai Chi. For the three types of movement, stride width was smaller than the step length values. During the set of 42-form Tai Chi, stride width was 0.697m, 0.447m, and 0.755m respectively for forward, backward, and sideway Tai Chi movements. The reported results and findings of this study are comparable, as the “Repulse Monkey” had the smallest stride width and “WHIC” had the largest value.

The base of support (BOS) is increased during WHIC, indicating that Tai Chi is a safe exercise for the elders. Our data showed that forward walking had a smaller stride width. Hospitalized fallers consistently demonstrated a narrower stride width in their gait.^{21,22} Research supports that longer single-support place more attention to balance because the base-of-support is smaller.²³ Moreover, narrowing the BOS is a challenge because the mediolateral displacement of

COM must be tightly controlled in order for the frontal plane stability to be maintained.^{24,25}

During RM, stepping backwards in a straight line can be difficult because the visual perception is limited. This is especially true when the BOS is reduced for RM compared to walking. Even so, RM share similar characteristics with backward walking which have been applied safely in rehabilitative studies involving patients with Parkinson Disease or stroke.^{26,27} Backward walking has shown decreased stride length, gait velocity, and swing phase along with increased double-support phase.^{28,29,30} Based on the study evidences in backward stepping, movements like RM would be good exercises for the elders to improve proprioceptive feedback.

Performance speeds of the movements were variable; after normalizing double-support time by stride time, RM had a longer duration than walking. One study in Tai Chi reported that the duration of left single-support were 2.81s, while double-support with left and right leg forward were 5.3s and 5.32s, respectively for BKTS.¹¹ These results mentioned are consistent with the data from this study. Compared to double-support (with left leg forward) of BKTS, double-support time was significantly longer during RM and shorter during WHIC. Stance phase was 83% for RM, compared to 61% of a gait cycle for walking. The results mentioned are also consistent with those found in the studies by Chua & Mao¹³, Mao, Hong, & Li³⁵, who also reported longer duration of double-support stance during the set of 42-form Tai Chi. Researchers found that slower speeds during level-walking has been attributed to increasing the risk of falling.^{31,32} Furthermore, slower movements have been shown to increase the risk of falling by increasing the time spent in single-support.^{23,28} These Tai Chi movements require good balance capacity and increased muscle activation, making this a challenging yet safe activity for the elders.^{13,35} Practicing these Tai Chi movements may attribute to the improvement of balance capacity.

The movement of Centre of Mass (COM). This is the first study to examine the COM displacement during backward and sideway Tai Chi movements. During forward BKTS, the anterior-posterior, medial-lateral, and superior-inferior COM displacements were 0.54, 0.18, and 1.22m, respectively.¹¹ These published data are comparable with the values obtained for the two Tai Chi movements and walking trials, except for the vertical COM displacement along the Z-axis. In our study, RM and WHIC elicit large changes to the backward and sideways displacement of the COM, respectively. However, the BKTS movement mentioned in the previous study had larger vertical COM displacement than walking, RM, and WHIC.

In some Tai Chi Movements like “Push-hand”, the position of the COM is required to be upright and stable when moving from one position to another.¹⁴ The optimal position of COM can therefore be changed depending on type of the Tai Chi movement. However, it is also important to note that “Push-hand” is a stationary Tai Chi exercise that is performed while standing. It would be difficult to compare our results found for our two dynamic Tai Chi movements. Differences in the COM displacement can also be attributed to the performers’ inexperience or unfamiliarity with the movement.²⁵ For the RM movement, performers could have altered their gait by taking larger steps backward. In doing so, the hip is bent forward in order to compensate for the loss of balance as the COM is moved further away from BOS. This would not only alter the vertical displacement of COM but also the COM displacement in the anteroposterior direction.

Balance is maintained if the COM is within the BOS.^{11,6,21} If COM is moved away from the BOS, then this may lead to instability or loss of balance.¹³ Falls in the frontal usually occur when the COM exceeds a certain temporospatial limit with respect to the BOS.³³ Research

demonstrated that static balance training is not enough to help maintain balance in later life; the elders need to engage in different types of physical activities because poor lateral COM displacement abilities are the culprits for falling and slipping.^{13,21} The data for lateral COM displacement and stride width were $1.02 \pm 0.089\text{m}$ and $0.67 \pm 0.04\text{m}$, respectively for WHIC. This would be a safe movement for the elders because the lateral displacement of the COM is large but over an equally large BOS. Furthermore, side-stepping is a preferable technique over cross-over in the event of a fall.²¹ Practicing side-stepping exercises such as WHIC would therefore help in the prevention of falls.

Kinematics of the Lower extremity. ROM of the lower extremity had been examined for 5 typical Tai Chi movements and Tai Chi gait.^{12,9} Studies in lateral step-up elicit large knee flexion and ankle dorsiflexion angles compared to forward step-up.³⁴ It is suggested that these types of forward and lateral stepping exercises could help to improve muscle joint specific functions for the elders.³⁴ The data gathered in this study supports this finding since the full ROM of the joints in the lower extremity is maximized during Tai Chi practice. A deep squatting posture would encourage that the joint be flexible in order for practitioners to push and maximize the full capacity of their joints. RM, like backward walking, elicits large changes to the ROM.^{28,29,30} This can be used to develop and build balance and joint proprioception.

For RM, the hip is significantly flexed to drive the leg upward. As the practitioner steps back, the hip is slightly extended (-1.17°), a value much smaller than walking (-15.83°). At the knee joint, there is no significant difference for the maximal flexion and extension angles, however the minimal flexion and extension angles were larger than walking. The large maximal and minimal varus angle suggests that the distal portion of the lower segment is bent inward as

the lateral side of the knee is being loaded. This was due to the lateral shifting of the COM as the practitioner turned sideways to push the palm forward. RM had a significantly more dorsiflexion angle and more maximal plantarflexion angles than walking. In our study, flexion/extension ROM at the hip, knee, and ankle for RM were 50.0°, 75.0°, and 61.5°, respectively. These values were consistently larger than the values obtained during walking. ROM was significantly larger for flexion/extension and adduction/abduction during RM than walking at the ankle joint. The results are consistent with a study by Wu and colleagues¹² who reported larger ROM ankle, knee, and hip joints for Tai Chi gait (TCG) than normal gait (NG). RM had noticeably larger changes to the ankle's ROM than even TCG. These large ROM changes suggest that RM has high demands for muscle activity and joint flexibility which are important in postural stability.

A less vigorous movement for the elders would be WHIC because smaller ROM changes were seen at each joint in the lower extremity. In our study, the flexion/extension ROM at the hip, knee, and ankle for WHIC was 21.5°, 37.9°, and 36.6°, respectively. Compared to walking, ROM during WHIC was significantly smaller for hip flexion/extension, knee flexion/extension, and knee varus/valgus. The gentle stepping-action and fluidity movement sideways would help to minimize the stress on the knee joints, but hip abductors and adductors had to work harder. Valgus and varus angles were not significantly different when compared with walking. The knee joint remained flexed during WHIC. Significant difference was seen at the ankle joint between WHIC and walking; the ankle joint remained dorsiflexed for a majority of gait of the cycle in WHIC. At the hip joint the minimal flexion angle was 13.12° during WHIC since the hip joint remained flexed. The maximal adduction angle was small given that the hip remained largely abducted as the practitioners raised the leg to the side during stepping. The maximal abduction angle for WHIC was significantly larger than walking.

In the study by Mao, Hong, Li¹⁰, the ROM in the sagittal plane of the ankle and knee was found to be 62.2° and 72.1°, respectively, during backward Tai Chi movements. The ROM of ankle and knee was 37.9° and 37.2°, respectively, for the sideway Tai Chi movement. The values for sideway Tai Chi movement reported by the other researchers were very similar to WHIC, which supports the validity of our findings. Similarly, the values for backward Tai Chi movement were larger for knee and ankle ROM but very similar to the values obtained for RM.¹⁰ From our study, ROM (flexion/extension) for the hip, knee, and ankle during walking were 49.0, 55.3, and 28.8 respectively. The values obtained during RM were much larger than walking. The same conclusion can be made as Mao, Hong, Li, who suggest that these large ROM changes at the knee and ankle complex would help to improve muscle strength and balance.¹⁰

One limitation of our study was whether the directionality of the movement. During Tai Chi practice, the practitioner was moving backwards for RM and sideways for WHIC. It is not clear whether the effects of the movements' directionality affected the mediolateral or anteroposterior displacement of the COM. Although the participants were instructed to strike one force plate at a time, differences in leg length could affect the stride length and stride width when stepping onto or off the metal force plates. As seen, the results were comparable with other studies which have examined the sideway and backward Tai Chi movements. The findings in this study cannot be generalized as there other Tai Chi movements which have yet to be examined with their own unique features and properties. The turning and grinding footwork can alter the joint kinematics about ankle complex³⁵, which remains unknown unless the proper modeling tools and instruments are developed.

CONCLUSION

Tai Chi practice has been found to help remedy the deficiency of physical activity among those leading a sedentary lifestyle. The findings outlined in this study demonstrate that the two Tai Chi movements had unique biomechanical characteristics compared to walking. The elders would benefit from performing “Repulse Monkey” and “Wave-hand in Cloud” because these are typical Tai Chi movements that elicit gentle and fluid changes to position of the upper body mass and the joints in the lower extremity. First, RM and WHIC are safe alternative exercise because less time is spent in single-limb support and more in double-limb support. RM is slow backward-stepping exercise characterized by deep squatting and large changes to the body’s centre of mass. Both RM and WHIC had large mediolateral displacement of the centre of mass which could be used to improve balance and joint proprioception. In terms of joint kinematics, the knee remained flexed throughout RM and WHIC. Unlike WHIC and walking, RM had larger abduction and adduction angles at the knee joints. Moreover, the side-stepping action during WHIC would be less stressful on the knee joint. This type of exercise would be ideal for those suffering with knee pains due to osteoarthritis. The large plantar- and dorsiflexion ROM during performance of RM can help to improve the stability of ankle joint. Overall, engaging in these types of Tai Chi is a safe way for the elders to improve balance, physical capacity, muscle and joint flexibility.

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Articles

The Stepping-pattern and Kinetic Characteristics of Typical Tai Chi Movements: Repulse Monkey and Wave-hand in Cloud

Short Title: The Stepping and Kinetic of Tai Chi Movement

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Abstract

Tai Chi is a traditional Chinese exercise that has help many practitioners maintain their physical conditioning and improve their mental acuity. Regular Tai Chi practice has been shown to be beneficial in promoting joint health and postural stability, yet the effects of Tai Chi training are not well understood. The purpose of this study was to examine the three-dimensional kinetic features of the hip, knee, and ankle during performance of two typical Tai Chi movements, “Repulse Monkey” and “Wave-hand in Cloud.” A group of experienced male Tai Chi practitioners (n=15) with at least 4 years regular Tai Chi practice and training participated in the study and their two Tai Chi movements and walking trials were recorded using motion analysis system. The ground reaction force was measured during performance to determine the amount of contact force, and the moment of force of the hip, knee and ankle joints were analyzed. The results showed that compare to walking, “Repulse Monkey” had significantly smaller vertical ground reaction force ($p = 0.000$); smaller hip flexion ($p = 0.008$) and abduction moments ($p = 0.001$); longer peak hip extension and adduction moment generation time ($p < 0.001$); larger varus ($p = 0.000$) and valgus moments ($p = 0.007$); longer peak knee extension, flexion, and abduction moment generation time ($p < 0.001$); and a larger ankle dorsiflexion moment ($p = 0.000$). For “Wave-hand in Cloud”, when compared with walking, vertical ground reaction force was significantly larger ($p = 0.002$); hip adduction moments was larger ($p = 0.02$); moment during internal rotation of the knee was larger ($p = 0.02$); longer peak moment generation time at hip and knee joints; and ankle dorsiflexion and plantarflexion moments were smaller ($p = 0.001$). The comparisons with walking demonstrated that these two Tai Chi movements are slow and gentle which reduce the amount of stress placed on the lower extremities joints. These types of low-intensity exercises are suitable for those with knee osteoarthritis or knee pains.

INTRODUCTION

Tai Chi has long been practice for improvement of one's physical and mental wellbeing. Originated in Buddhist temples over 200 years ago, this form of conditioning exercise was used by Taoist monks to maintain their physical fitness and to balance the amount of time that they were spending in deep meditation.¹ The beneficial health effects of regular Tai Chi practice has become apparent as many individuals report relief of joint pains and stiffness, neurasthenia, high blood pressure, hypertension, heart problems, anaemia, tuberculosis, and other maladies.^{1,2,3,4,5} Recently, the American Geriatric Society and British Geriatric Society have recommended Tai Chi as an effective intervention to reduce the number of falls among the elderly.⁶ Tai Chi continues to become more popular because the natural flow of the movements makes this type of exercise accessible to practitioners of different ages.

The capacity to engage physical activity is reduced with age. The Centre of Disease Control and American Heart Association strongly encourage elders to participate in aerobic and resistance training exercises to help improve cardiovascular functions, muscle strength and endurance.^{7,8} Even so, it is unclear as to whether these types of weight-bearing exercises are safe in terms of the impact force and loading on the joints in the lower extremity. Notable differences can be seen in the movement patterns of the lower extremities between the elders and young when running.⁹ High impact exercises such as jogging and weight-training are necessary to help increase bone mineral density, however individuals with osteoporosis or osteoarthritis cannot safely or fully engage in such activities.^{10,11} The elders risk injuring themselves or overextending beyond their functional capacity when performing exercises that are strenuous or high-intensity.¹² Individuals with limited functional capacity are unable to accumulate the necessary stimulus for maintenance of their bone's strength and mass.¹⁰

As the problem of inactivity grows among the aging in North America, more studies into the effects of low- and high-impact exercises would benefit the elders. Low-impact exercises such as Tai Chi is a suitable for the elders because performance is slow and joint loading on the knees and ankles is low.^{3,5} The biomechanical understanding of different Tai Chi movements is lacking because there is a limited number of studies into the joint kinetics and stepping-pattern during Tai Chi performance. The joint moment and loading force of the lower extremity has been examined for the elderly and young Tai Chi practitioners during performance of normal walking and Tai Chi gait.¹³ One study has examined the ground reaction force during performance of Tai Chi gait¹⁴, and only a few studies have examined the plantar pressure distribution during Tai Chi practice^{15,16} and gait initiation after Tai Chi training.¹⁷

The purpose of the study is to examine the amount of joint loading at the hip, knee, and ankle joint during performing two typical Tai Chi movements, “Repulse Monkey” (RM) and “Wave-hand in Cloud” (WHIC). The stepping and ground contact characteristics will be examined for the two Tai Chi movements, and later contrasted with forward walking. Based on the research evidences in Tai Chi biomechanics from published studies, it was hypothesized that joint moments of flexion/extension, adduction/abduction, and internal/external rotation at the hip, knee, and ankle during performance of RM and WHIC would be different from that in walking. Specifically, RM would have a larger hip extension moment when stepping backwards while WHIC would have a larger hip abduction moment when stepping to the side. For ground reaction force, the vertical component of the reaction force would be less for RM at foot-contact and would be altered during side-stepping WHIC compared to walking. This study will hopefully clarify whether there are noticeable changes to joint moment and stepping force between Tai Chi performance and everyday walking.

MATERIALS AND METHODS

Participants

Fifteen male Tai Chi participants with more than 4 years of Tai Chi experience were recruited. Participants for this study were between the ages of 65 and 75. Participants should have practiced either the Yang- or Wu-styles of Tai Chi. Both experienced Tai Chi Masters and students were eligible to participate. Recruitment of the subjects was from two local community centers in the Ottawa region where Tai Chi was taught and practiced in a large group, twice a week. Each session was approximately 1.5-2 hours long with one fifteen-minute break in between.

The participants' physical conditioning and health was screened prior to data collection. Self-reported surveys indicated that all subjects were in good health. The exclusion criteria for the study included any of the following past medical conditions: cardiovascular disease or did suffer from stroke; impaired mobility; dementia; symptoms of cardiovascular disease during moderate exercise; and use of specific medications known to impair balance. All participants signed an informed written consent prior to participating. This study has been approved by approved by the University of Ottawa Health Science and Science Research Ethics Board.

Table B 2. Participants' Demographic Data, and Year(s) of Experience in Tai Chi Practice (n = 15)

	Mean $\pm$ SD
Age (yr)	65.5 $\pm$ 8.9
Body weight (kg)	70.0 $\pm$ 8.8
Height (cm)	166.7 $\pm$ 7.8
Body Mass Index (kg/m ²)	25.2 $\pm$ 2.6
Years of experience in practicing Tai Chi (yr)	14.3 $\pm$ 10.6

Instrumentation and studied Tai Chi movements

Three-dimensional kinetic and ground reaction force data was obtained using ten VICON MX-13 cameras (Oxford Metrics, Oxford, UK) recorded at 1000Hz, and four metal force plates (models 9286AA, Kistler Instruments Corp, Winterthur, Switzerland; FP 4060-08, Bertec Corporation, Columbus, OH, USA). The instance of heel-strike and toe-off were determined by these force plates which were imbedded into the middle of the ground of an 8m long walkway.

“Repulse Monkey” is a Tai Chi movement that involves backward stepping while pushing the palms forward. “Wave-hand in Cloud” is the other Tai Chi movement involving waving of the hands and lateral stepping. Both forward walking and backwards “Repulse Monkey” were performed in-line but opposite directions while “Wave-hand in Cloud” was performed in the direction perpendicular to forward walking (Figure 1). These two Tai Chi movements were chosen for analysis because they are typical movements included in each style of Tai Chi and represent the typical Tai Chi side- and backward stepping patterns.

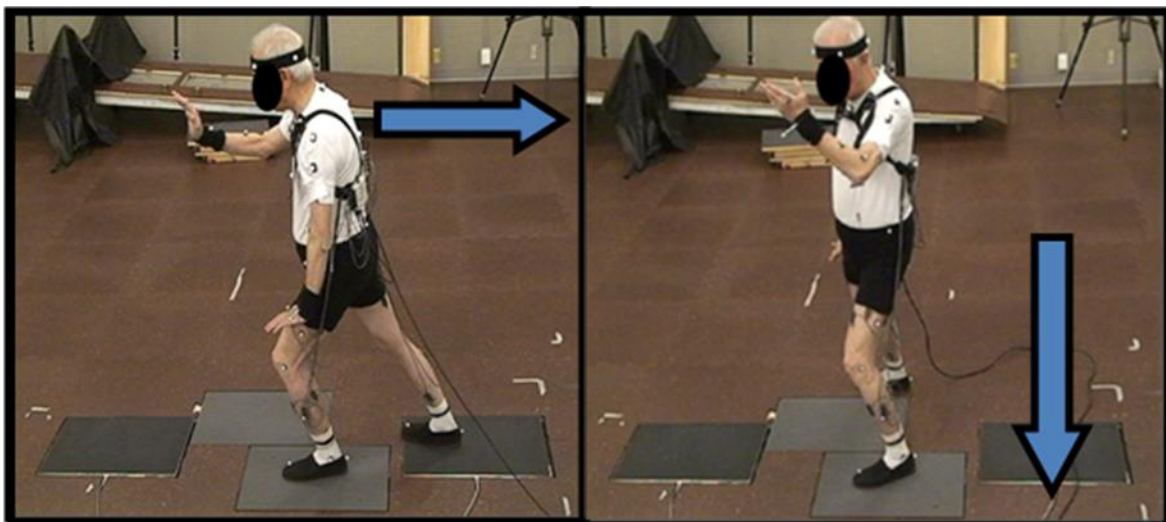


Figure B 1. Side-view of Repulse Monkey (left) and Wave-hand-in-Cloud (right). The large arrow indicates the direction of the movement.

Procedure

The participants' anthropometric measures were recorded prior to being outfitted with a tight-fitting spandex suit. 39-reflective makers were attached on the skin or over clothing with double-adhesive tape to indicate the body's anatomical landmarks in accordance with the Plug-in-Gait marker set (Oxford Metrics, Oxford, UK), as modified from the Helen-Hayes marker-set. The movements were performed in the comfort of their own shoes that they had on that day. Prior to data collection, the participants were given two to three minutes to practice the Tai Chi movements and become familiarized with the experiment setting. A minimum of five trials each for the two Tai Chi movements forward walking was recorded. For the two Tai Chi movements, the participants were instructed to perform at their comfortable speed and to contact the force plate with only one foot at a time. Similarly, the participants were asked to maintain a comfortable stride and speed during the walking trials.

Data Processing and Analysis

One successful gait cycle was defined by the completion of heel-strike to heel-strike for the same foot. Heel-strike and toe-off was defined by the software readings when the foot contacts and leaves the force plates and by visually inspecting the position of the virtual markers on the heel and toe. Two consecutive gait cycles for the left and right leg were analyzed for the kinetic parameters, and the data was normalized to one gait cycle for further analysis. The 3-D joint moment for the lower extremities and maximal ground reaction force at foot-strike were found using VICON Nexus (Oxford Metrics, Oxford, UK) and the Plug-in-Gait model (Oxford Metrics, Oxford, UK). These raw data values were exported to Excel (Microsoft, Washington, USA) for further analysis. The computed joint kinetic data was exported to Matlab (MathWorks,

Natick, USA) to average and calculate the total maximum and minimum joint moments for each movement using a custom-built graphic user interface (GUI) output.

The kinetic variable included the joint moment in the lower extremity along the frontal (flexion-extension in the sagittal plane), sagittal (abduction-adduction in the frontal plane), and vertical axis (internal-external rotation in the transverse plane).¹⁸ For the ankle joint, the moment values were obtained along the frontal (plantar- and dorsiflexion in the sagittal plane), sagittal (inversion and eversion in the frontal plane), and vertical axis (horizontal abduction-adduction in the transverse plane).¹⁹ The maximal ground reaction force was obtained from the force plate readings. For “Repulse Monkey”, the reading was taken from the instance of foot-strike, which was the point at which the toes contacted the force plate. For “Wave-hand in Cloud”, the instance of foot-strike was when the lateral metatarsal of the foot contacted the force plate. Lastly, for walking, foot-strike was equivalent to the time of heel contacting the floor (Figure 2).

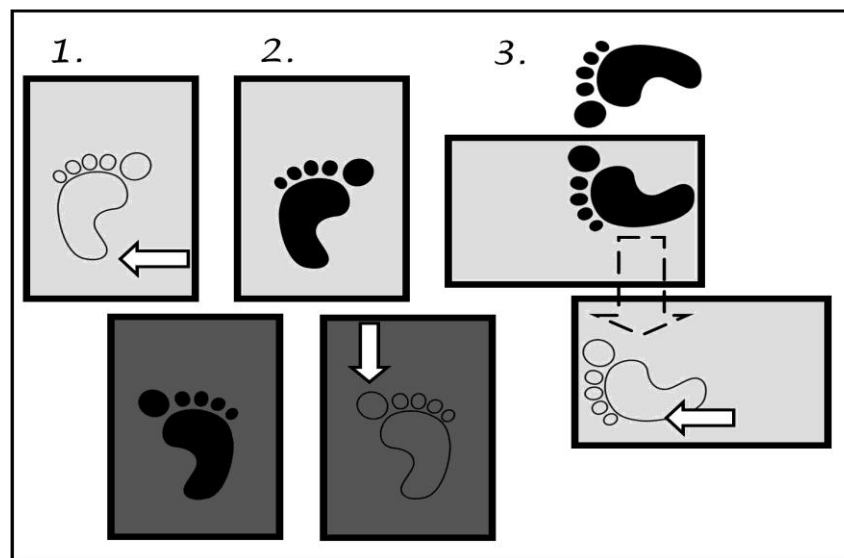


Figure B 2. Two-dimensional view of types of foot contact for walking (1), “Repulse Monkey” (2) and “Wave-hand in Cloud” (3). The contact-foot is hollow (*black outline*). Going left to right, the white arrows illustrate heel-contact, toe-contact, and lateral-metatarsal for the respective movements.

“Repulse Monkey” and “Wave-hand-in-Cloud” was performed symmetrically and continuously for both the right and left sides, therefore only the left lower extremity was selected for analysis. The participants were asked to perform five trials of two Tai Chi movements under conditions similar to their weekly practice. The walking trials were not altered and the subjects were asked to walk at their normal pace. The maximal ground reaction force (N) at foot-strike was averaged for each participant. The ground reaction forces were normalized to body weight of the subject ($\text{Nm}/(\text{kg}(\text{ms}^{-2}))$) and reported as a percentage for comparison between movements.¹⁴ This value was normalized to multiples of body weight ($\times\text{BW}$), as suggested in past literature.^{20,21,22,23} Similarly, the peak moments values ($\text{N}\cdot\text{m}/\text{kg}$) at each joint and time (% of one gait cycle) from start to these peak values were averaged in order to obtain the maximal and minimal joint moments and time for each participant. For all interest variables, an ensemble averaged of all participants were taken for each Tai Chi movements and separately compared with the ensemble average for normal walking.

Statistical Analysis

All five trials of three movements were average for each participant. The data was initially inspected to ensure that any outlier values were properly accounted for and that subsequent errors in the data were properly removed prior to analysis. Descriptive statistics were reported for the peak ground reaction force and joint moment using Statistical Package for Social Sciences (SPSS) version20 software for Windows (SPSS Science, Chicago, Illinois). Two-way ANOVA (Repulse Monkey $\times$ walking; Wave-hand in Cloud $\times$ walking) was used to compare the 3-dimensional joint moments and maximal ground reaction force. Tukey’s post-hoc analysis was used if any main effects or significant interaction were found. Significance level was set at 0.05.

RESULT

The two Tai Chi movements were performed under conditions similar to those during their weekly practice. The walking trials were performed as the subjects regularly would at their comfortable pace. Given the symmetry of the movements, only the results for the left limb (trailing limb) are reported. Table 2 highlights the ground reaction force (GRF) and normalized GRF by participants' body weight for comparison for one stride length of the left foot after foot-contact. Mean and standard deviation of the maximal and minimal moments for the hip, knee, and ankle are presented in Tables 3, 4, 5, respectively. P-values are provided beside each value for the two Tai Chi movements as a comparison with the baseline values for forward walking.

Maximal Ground Reaction Force

As seen in Table 2, the lateral and medial ground reaction forces (GRF) were significantly larger for walking than the two Tai Chi movements ($p < 0.001$). At contact with the floor, peak anterior GRF for RM was 5.97%BW while posterior GRF on impact for walking is 8.08%BW portion of the foot compared to heel-contact for walking. The exerted force after toe-contact for repulse monkey (RM) is directed laterally when the opposite leg is raised (6.83%BW). At this point, GRF is directed to the posterior portion of the foot. The vertical GRF also peaks (1.56BW) at this point when the opposite leg is raised. This peak vertical GRF for RM is notably smaller than for walking; the peak vertical GRF for walking occurs at the instance when the left heel contacts the floor (110%BW, 1.64BW). As the body weight is adjusted during single-limb support for RM, the GRF shifts medially on the supporting-foot before stepping backwards with the opposite leg.

For WHIC, vertical GRF peaks at the start of single-limb support on the left foot (1.46BW). The lateral stepping movement initially put pressure on the anterior portion of the foot then slowly shifts posterior. Posterior force for WHIC was significantly smaller than for walking (5.40%BW vs. 8.08%BW, respectively; $p < 0.001$ vs. Walking). The force vector is directed medially when the body weight is transferred sideways. Medial GRF peaks at 9.48%BW before stabilizing. Turning of the body back toward to centre increased lateral GRF (0.72%BW) before the left-support limb is raised.

Table B 2. Mean and standard deviation values for the 3-dimensional ground reaction force (GRF). The first peak of the GRF curve was analyzed after left-foot strike. The data was normalized by the software to body weight (%Body weight) and reported for the two Tai Chi movements and walking (n=15).

Parameter	Movements				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Lateral Force (%BW)	20.25 ± 4.96	6.83 ± 3.19*	0.000	0.72 ± 0.85*	0.000
Medial Force (%BW)	22.16 ± 3.29	9.21 ± 3.56*	0.000	9.48 ± 7.57*	0.000
Anterior Force (%BW)	1.56 ± 1.08	5.97 ± 2.85*	0.000	2.37 ± 1.89**	0.003
Posterior Force (%BW)	8.08 ± 1.65	1.73 ± 1.53*	0.000	5.40 ± 5.40*	0.000
Vertical Force (%BW)	110.71 ± 6.40	105.77 ± 1.98*	0.000	103.0 ± 1.62*	0.000
Normalized Lateral Force (×BW)	0.30 ± 0.10	0.09 ± 0.05*	0.000	0.03 ± 0.03*	0.000
Normalized Medial Force (×BW)	0.30 ± 0.08	0.14 ± 0.06*	0.000	0.13 ± 0.01*	0.000
Normalized Anterior Force (×BW)	0.03 ± 0.02	0.09 ± 0.05*	0.923	0.03 ± 0.03	0.098
Normalized Posterior Force (×BW)	0.12 ± 0.33	0.02 ± 0.02*	0.000	0.08 ± 0.08*	0.000
Normalized Vertical Force (×BW)	1.64 ± 0.27	1.56 ± 0.19**	0.046	1.46 ± 0.19*	0.000

* $p < 0.001$ vs. Walking

** $p < 0.05$ vs. Walking

Note: %BW = $N/(kg \cdot m/s^2)$; %BW = (normalized force)(BW)

Kinetics of the trailing lower limb

Tables 3, 4, and 5 show the joint loading at the hip, knee and ankle, respectively. At the hip joint, RM demonstrated larger extension moment than walking (1.06Nm/kg vs. 0.74 Nm/kg, respectively). Adduction and abduction moments along the frontal plane were smaller for RM than walking. RM had a smaller external rotation moment along the transverse plane but a larger internal rotation moment. For WHIC, no significant difference was seen for the extension moment or internal rotation moment. WHIC had significantly smaller flexion, adduction, and external rotation moments ($p < 0.05$). Adduction moment was larger for WHIC than walking ($p < 0.05$).

Table B 3. Mean and standard deviation of the maximum and minimum hip moments (N•m/kg) on the left limb in the two Tai Chi movements and walking (n=15).

Moment	Movement				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Extension Max.	0.74 ± 0.31	1.06 ± 0.21**	0.008	0.86 ± 0.22	0.068
Flexion Max.	-0.50 ± 0.26	-0.30 ± 0.06	0.113	-0.06 ± 0.06**	0.021
Abduction Max.	1.08 ± 0.11	0.69 ± 0.14*	0.001	0.41 ± 0.32**	0.008
Adduction Max.	-0.19 ± 0.18	-0.34 ± 0.20**	0.002	-0.34 ± 0.14**	0.016
External Rotation Max.	0.17 ± 0.05	0.04 ± 0.02**	0.019	0.07 ± 0.03**	0.046
Internal Rotation Max.	-0.14 ± 0.08	-0.38 ± 0.05**	0.011	-0.20 ± 0.04	0.492

* $p < 0.001$ vs. Walking

** $p < 0.05$ vs. Walking

At the knee joint (Table 4), there were no significant differences along the sagittal and frontal planes for RM and WHIC. Compared to walking, RM varus and valgus moment was smaller compared to walking ($p < 0.001$ and $p < 0.05$, respectively). The internal rotation moment was larger during WHIC than walking (-0.07Nm/kg vs. -0.02Nm/kg, respectively). At the ankle (Table 5), joint moment was significant different for all planes during RM. Flexion moment for

RM was smaller than walking (1.10Nm/kg vs. 1.56Nm/kg, $p = 0.000$). Larger inversion/eversion and ext/int. rotation moments were seen for RM ($p < 0.05$). For WHIC, smaller plantar-/dorsiflexion moments ($p < 0.001$) and eversion/inversion moment ($p < 0.05$) were recorded.

Table B 4. Mean and standard deviation of the maximum and minimum knee moments (N•m/kg) on the left limb in the two Tai Chi movements and walking (n=15).

Moment	Movement				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Extension Max.	0.28 ± 0.36	0.83 ± 0.35	0.906	0.62 ± 0.33	0.907
Flexion Max.	-0.39 ± 0.22	-0.32 ± 0.01	0.746	-0.10 ± 0.03	0.486
Varus Max.	0.75 ± 0.13	1.03 ± 0.30*	0.000	0.66 ± 0.18	0.446
Valgus Max.	-0.04 ± 0.01	-0.07 ± 0.03**	0.007	-0.14 ± 0.08	0.072
External Rotation Max.	0.26 ± 0.09	0.21 ± 0.08	0.248	0.16 ± 0.09	0.342
Internal Rotation Max.	-0.02 ± 0.01	-0.04 ± 0.02**	0.040	-0.07 ± 0.03**	0.018

* $p < 0.001$ vs. Walking

* $p < 0.05$ vs. Walking

Table B 5. Mean and standard deviation of the maximum and minimum ankle moments (N•m/kg) on the left limb in the two Tai Chi movements and walking (n=15).

Moment	Movement				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Plantarflexion Max.	1.56 ± 0.14	1.10 ± 0.12*	0.000	0.95 ± 0.15*	0.001
Dorsiflexion Max.	-0.12 ± 0.04	-0.03 ± 0.02**	0.037	-0.02 ± 0.03*	0.000
Eversion Max.	0.04 ± 0.04	0.08 ± 0.04**	0.025	0.07 ± 0.04	0.139
Inversion Max.	-0.09 ± 0.06	-0.17 ± 0.08**	0.048	-0.06 ± 0.04**	0.044
External Rotation Max.	0.32 ± 0.03	0.39 ± 0.11**	0.014	0.24 ± 0.07	0.383
Internal Rotation Max.	-0.02 ± 0.01	-0.05 ± 0.01**	0.006	-0.09 ± 0.03**	0.023

* $p < 0.001$ vs. Walking

* $p < 0.05$ vs. Walking

The following tables shows the normalized time to peak moment development at the hip, knee, and ankle joints. In table 6, it is evident that peak extension-moment generation took longer to reach for the two Tai Chi movements. RM and WHIC had significantly longer peak moment generation time than walking (44% and 43%, respectively vs. walking; $p < 0.001$). Peak hip abduction moment occurred quicker for RM than walking. However, hip adduction was significantly delayed for the two Tai Chi movements (64% and 18%, respectively).

Table B 6. Mean and standard deviation for time to peak hip moment generation (%) for the left limb during the two Tai Chi and walking conditions (n=15). Time was reported from the start of the movement and normalized as percentage of one complete gait cycle.

Parameter	Condition				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Extension Max.	12.94 ± 0.75	44.08 ± 7.02*	0.000	42.54 ± 0.07*	0.000
Flexion Max.	55.15 ± 3.48	36.19 ± 35.31	0.092	26.73 ± 27.18*	0.001
Abduction Max.	48.45 ± 1.81	33.61* ± 11.91	0.001	44.26 ± 9.81	0.519
Adduction Max.	2.93 ± 1.56	64.87* ± 14.28	0.000	18.96* ± 8.49	0.000
External Rotation Max.	45.81 ± 2.49	45.29 ± 27.11	0.950	40.27 ± 25.21	0.311
Internal Rotation Max.	12.49 ± 2.22	47.52 ± 5.14*	0.000	43.21 ± 4.96*	0.000

* $p < 0.001$ vs. Walking

** $p < 0.05$ vs. Walking

In table 7, again the peak knee extension moment occurred over a longer period of time for the two Tai Chi movements. RM reached peak knee extension moment at 30% while WHIC reached this at 34% of gait cycle ($p < 0.001$). Peak knee extension moment was reached much earlier for walking at 9%. Similarly, peak varus moment was reached much later for Repulse Monkey and Wave-hand (42% and 45%, respectively).

Table B 7. Mean and standard deviation for time to peak knee moment generation (%) for the left limb during the two Tai Chi and walking conditions (n=15). Time was reported from the start of the movement and normalized as percentage of one complete gait cycle.

Parameter	Condition				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Extension Max.	9.18 ± 5.25	30.38 ± 4.97*	0.000	34.26* ± 7.13	0.000
Flexion Max.	42.95 ± 2.82	69.56 ± 7.86*	0.000	59.09 ± 33.74	0.395
Abduction Max.	13.95 ± 2.62	42.31 ± 11.88*	0.000	45.58* ± 3.21	0.000
Adduction Max.	69.62 ± 21.84	62.91 ± 21.31	0.498	23.76* ± 26.68	0.000
External Rotation Max.	47.11 ± 1.16	39.32* ± 2.19	0.000	42.30 ± 8.84	0.259
Internal Rotation Max.	73.2 ± 13.26	33.16 ± 31.74**	0.002	21.38 ± 27.39*	0.000

* p < 0.001 vs. Walking
** p < 0.05 vs. Walking

Table B 8. Mean and standard deviation for time to peak ankle moment generation (%) for the left limb during the two Tai Chi and walking conditions (n=15). Time was reported from the start of the movement and normalized as percentage of one complete gait cycle.

Parameter	Condition				
	Walking	Repulse Monkey	p-value	Wave-hand	p-value
Extension Max.	49.29 ± 1.24	36.85 ± 4.99*	0.000	45.24 ± 8.71	0.338
Flexion Max.	38.19 ± 27.62	79.99 ± 5.19*	0.001	87.96 ± 6.66*	0.001
Abduction Max.	35.91 ± 15.14	32.22 ± 10.68	0.546	46.13 ± 11.45	0.369
Adduction Max.	27.17 ± 10.06	45.08* ± 0.47	0.001	35.93 ± 18.13	0.259
External Rotation Max.	46.95 ± 1.67	35.49 ± 1.69*	0.000	42.59 ± 8.41	0.293
Internal Rotation Max.	78.15 ± 12.36	66.42 ± 3.70**	0.044	5.80 ± 3.10*	0.000

* p < 0.001 vs. Walking
** p < 0.05 vs. Walking

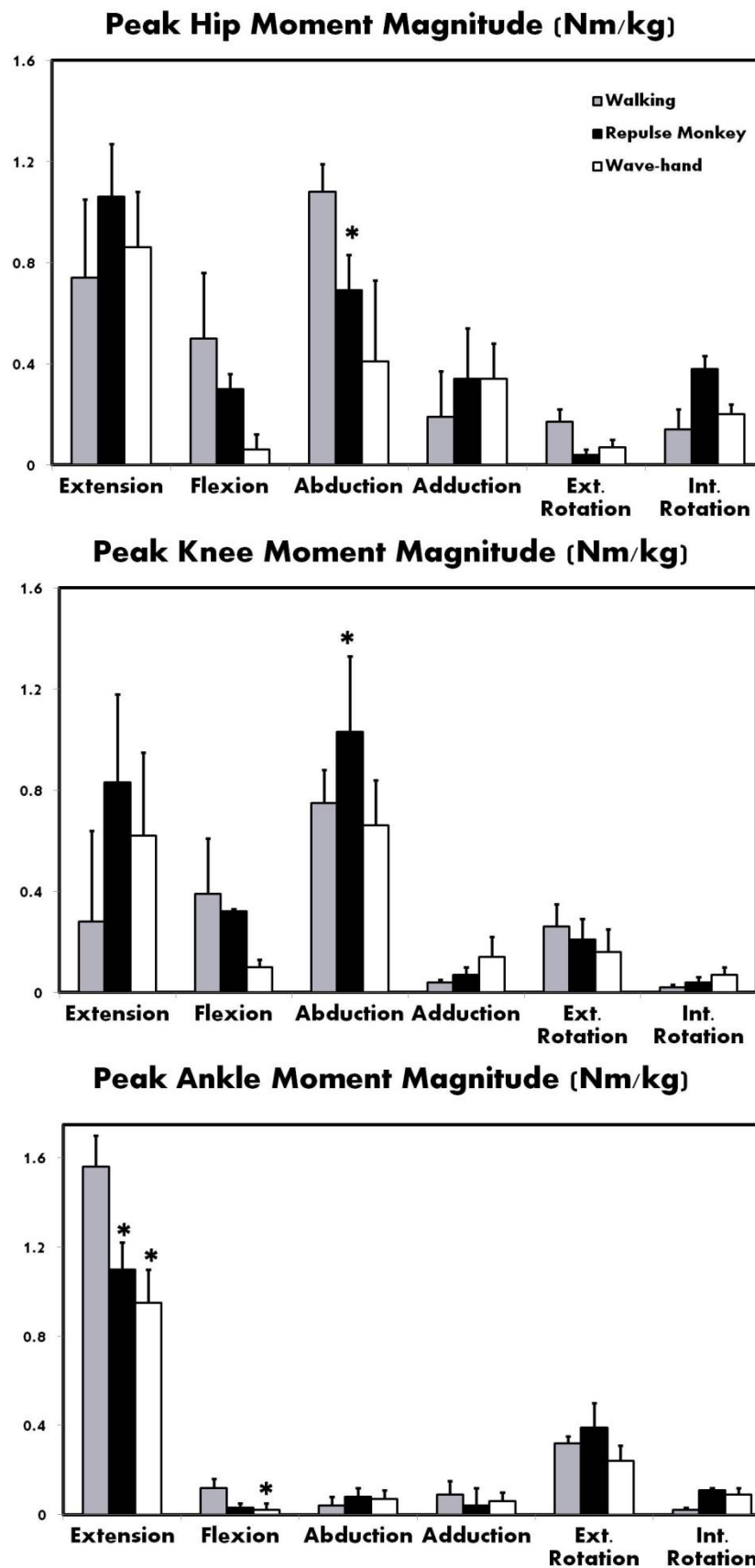


Figure B 3. The mean and standard deviations of three components of joint moments at the hip, knee, and ankle joints (*top to bottom*) of all subjects ($n = 15$) during walking (*grey*), “Repulse Monkey” (*black*), and “Wave-hand in Cloud” (*white*). Symbol * indicates significance difference ($p < 0.001$).

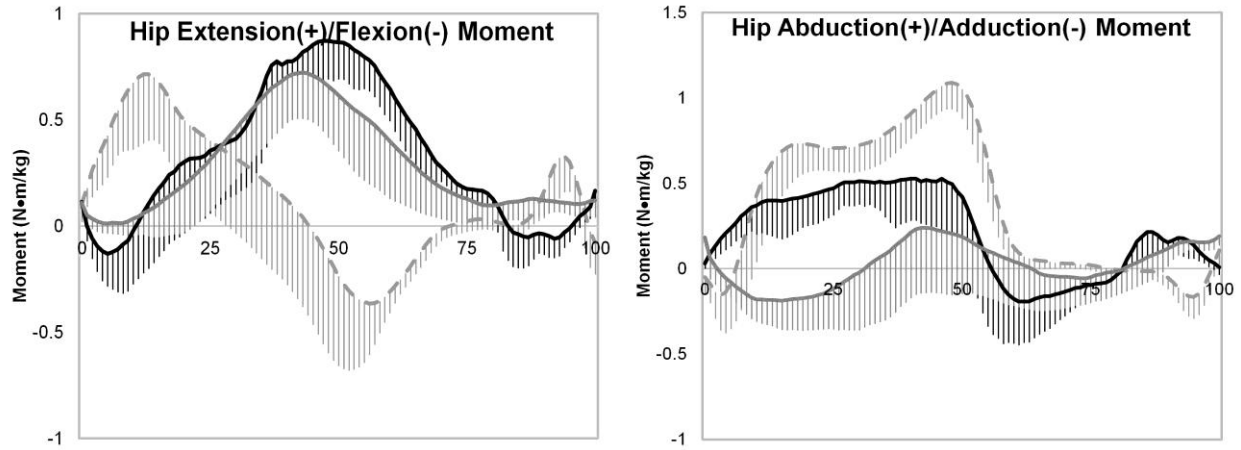


Figure B 4. Hip joint moment in sagittal and frontal planes for Repulse Monkey (*black*), Wave-hand in Cloud (*grey*), and walking (*dotted-line*) during one gait cycle (N = 15). * signify $p < 0.001$.

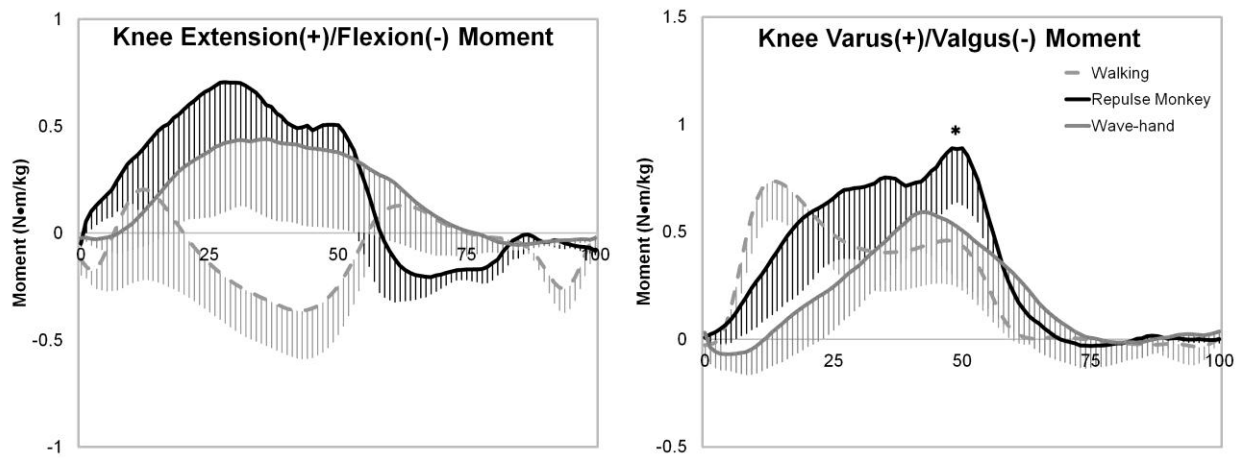


Figure B 5. Knee joint moment in sagittal and frontal planes for Repulse Monkey (*black*), Wave-hand in Cloud (*grey*), & walking (*dotted line*) during one gait cycle (N = 15). * signify $p < 0.001$.

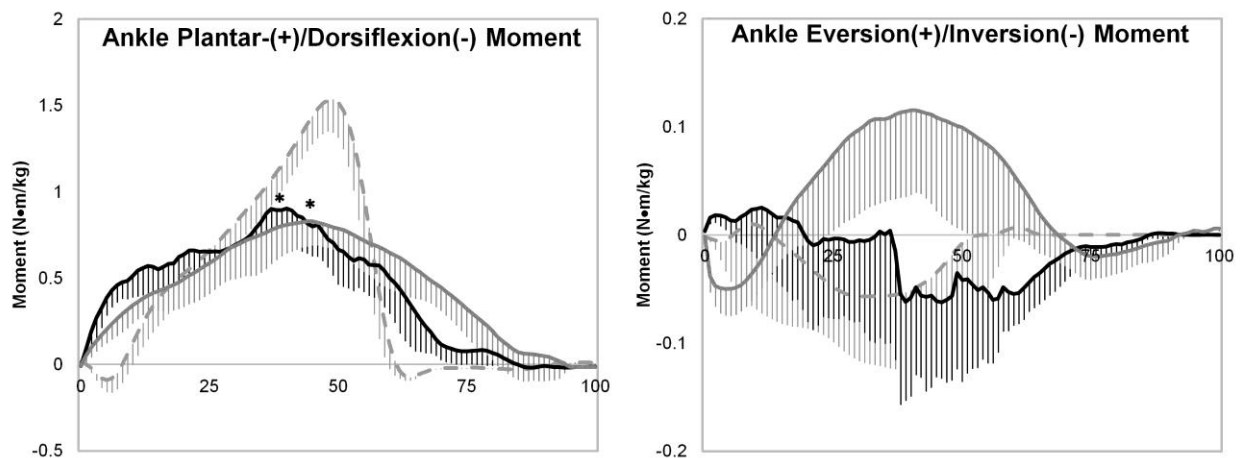


Figure B 6. Ankle joint moment in sagittal and frontal planes for Repulse Monkey (*black*), Wave-hand in Cloud (*grey*), and walking (*dotted-line*) during one gait cycle (N = 15). * signify $p < 0.001$.

DISCUSSION

The purpose of this study was to examine kinetic and stepping-patterns of two typical Tai Chi movements, “Repulse Monkey (RM)” and “Wave-hand in Cloud (WHIC)”, and to compare this data with walking. The three-dimensional joint moments and time to peak moment values at the hip, knee, and ankle were reported along with ground reaction force in order to determine whether there’s a significant difference between RM, WHIC, and walking. The findings in this study are unique as no other study has examined these parameters for backward and sideway Tai Chi movements. Only the temporospatial features of these two Tai Chi movements have been examined.^{24,25} A better understanding of the kinetic of RM & WHIC can help in the application of fall prevention and training programs to improve physical capacity among the elders. Only one study has examined the joint kinetics and ground contact characteristics during performance of Tai Chi gait.^{13,14} Comparisons can be made with these studies since this would help provide the necessary framework for further analysis and data interpretation.

Ground Reaction Force (GRF) during single-limb loading. Too much GRF can hinder bone growth and development; the threshold before joint failure or injury to occur is unknown. There is ambiguity in the classification of high- and low-intensity exercises since the characteristics which qualify high- or low-intensity exercises have not been formally defined in biomechanics or sports physiology. The first vertical GRF during walking is 1.2BW at speeds of 1.43m/s; GRF ranges from 1.0BW to 1.5BW from lowest to highest speeds.^{21,20} Compared with Tai Chi and walking, these values obtained while jumping are much higher. The normalized vertical GRF during RM and WHIC are 1.56BW and 1.46BW, respectively. These values were much smaller than for our walking data (1.64BW), which suggest that the participants were walking at a faster

pace. Future studies should focus on amount and intensity of an exercise that is necessary for sufficient improvement in bone mass and density measures.

The vertical GRF curve for walking usually shows two peaks; the initial peak is directed in the anterior direction which is then followed by a posterior-directed breaking force to stop and for the subject's body weight to be transferred forward.²⁰ Our data support this finding; the peak anterior and posterior GRF for walking was 1.56%BW and 8.08%BW, respectively. Although the data was found to be similar to WHIC and walking, the reverse is true for RM. During RM, a large anterior force (5.99%BW) is followed by a smaller posterior force (1.66%BW). No heel-contact was seen during RM to induce the posterior force because the initial contact force was with the toes in the anterior direction. During forward running, fore-foot strikers land on the anterior portion of the foot, which would imply that transmitted force is much higher through the Achilles tendon at impact.²² For backward running, there is no initial heel strike which avoids the loading seen during forward running.²³ The GRF at the anterior portion of the foot is small during backward running. Peak vertical GRF for backward running was significantly less than forward running, 2.5BW and 2.70BW respectively, at 3.58 m/s.²³ The low GRF during backward running suggest those who sustained joint trauma can use backward running to resume training and improve the strength of the quadriceps. Backward running would not be suitable for forefoot or midfoot runners who have dysfunctional soft tissues.²³ Compared with the two Tai Chi movements, the vertical GRF during backward and forward running are much higher. The vertical GRF force increased during faster movement. For slower movements like Tai Chi, this would be ideal for the elders because the impact force is reduced while movements like RM would still have similar benefits as backward running or walking. Furthermore, the larger "break force" in anterior direction (5.97%BW) during RM could be influence joint moments and in turn

lead to increased activation of the quadriceps. Tai Chi is a suitable choice for rehabilitation because slower movements and lower ground contact-force are incorporated into this exercise.

Few studies have examined ground reaction force in Tai Chi movement. During performance of TCG, medial peak force was 12%BW and significantly larger than walking ($p = 0.01$). Vertical GRF reached 109%BW during single stance of TCG. Both anterior-posterior and vertical forces were similar or significantly smaller for TCG than slow walking.¹⁴ The author concluded that low GRF during TCG require good coordination of muscle activation in the lower extremities. The vertical GRF during RM and WHIC were 105%BW and 103%BW, respectively. These values were significantly smaller than the peak vertical GRF at heel-strike for walking (110%BW, $p < 0.001$). Moreover, the onset time for the vertical GRF was delayed after initial foot-contact for the two Tai Chi movements.

Reasonable amounts of loading on the skeletal system is needed, however the level intensity necessary for bone remodelling to occur is unclear. In one study involving pre-menopausal women, bone and mineral density (BMD) significantly increased at the trochanter of the femur after 6-months of high-impact exercises.²⁶ However, the limitation with this study is the inclusion of young adults, particularly females, who naturally have fluctuations in bone mass and density within a 6 month period.²⁶ In another study, the effects of different type external stressors on the whole body were examined among post-menopausal women.²⁷ Ground reaction force (GRF) stress was obtained from walking, jogging, and stair exercises while joint reaction force (JRF) stress was from weight lifting and rowing. The researchers reported that both GRF and JRF stress on the skeletal system increased BMD at the lumbar, femur and forearm target areas. Engagement in moderate to light-intensity activities can provide the necessary stimulus for

proper bone and muscle development. Future studies should try to compare or modify the level of intensity to see if there are significant differences between types of physical exercises or activities. It would be interesting to see more longitudinal testing conducted with longer duration of low-to moderate exercises such as Tai Chi movements.

Kinetics of the Lower extremity. Figures 4, 5, and 6 of the result section present the calculated hip, knee, and ankle moments in the sagittal and frontal planes during stance phase of walking, “Repulse Monkey” and “Wave-hand in Cloud.” The two solid curves depict the Tai Chi movements and the curve drawn with dotted-lines depicts walking. Our joint moment data for walking corresponds to findings in past literature^{28,29,30}, although these studies provided only a qualitative description of the data without the peak values.

During RM, a small flexion moments was seen when the hip and knee are extended backwards. Extension moment gradually builds after initial foot-contact until it peaks when the opposite leg is brought up. The loading pattern is very typical of Tai Chi. Although a higher peak extension moment is seen for RM, the longer loading rate would help to improve endurance of the hip extensors. This extension moment helped to slow flexion of the hip as the body weight is lowered into a crouch position. Similarly, the knee extension moment *slowed* flexion when the weight of the body was lowered on the support leg. A smaller hip abduction moment is used for RM than walking, which is needed to prevent excessive drop in the opposite hemipelvis.²⁸ At the ankle joint, a large plantarflexion moment was seen after initial contact to slow dorsiflexion. Unlike walking, plantarflexion moment was not used to propel the toes off the ground, rather to support the weight of the body. Hence, no moment was generated for backward propulsion since

RM works with the natural flow of the body; this is said to have a similar effect as “sitting backwards.”

During WHIC, small flexion moment occurred when the hip was extended to the side while the extension moment peaked when the opposite leg was raised. There was some variability in the abduction/adduction moments due to the level of experience and individual flexibility at the hip. A large abduction moment should be seen if the practitioners were able to turn their hips sideway when bring the feet together side-by-side. Adduction moment was seen because the hemipelvis naturally drop on the other side of the hip when stepping sideways²⁸; experienced practitioners would have kept the hemipelvis leveled. The turning and sideway shifting of the body's COM lead to increase abduction moment at the knee. Interestingly, inversion moment was used to prevent the ankle from everting after stepping to the side. On one leg, tension is on the medial portion of ankle as the weight of the knee and body is on the lateral side of foot. The inward rolling of the ankle in the stance foot is prevented by presence of a large eversion moment to help stabilize this joint during single-limb support of WHIC.

There is a clear consensus that Tai Chi can be less stressful on the knee and ankle because of the slow performance speed.³¹ First, knee extension and knee varus moments are larger for RM and WHIC than walking, but the loading at the joints are spread over a much longer period of time. Muscles generate forces which act across the knee and ankle joints; these forces contribute to joint loading.³² The longer loading rate of the knee has good viscoelastic properties for the knee joint. Physiological loading of the joints is necessary to help stimulate chondrocyte synthesis and regeneration.³³ A slower loading rate means that the cartilage can deform and decrease the force applied to the joint and allow the surrounding muscles to absorb

and stabilize the joint.³³ There is little contribution of moments from the surrounding muscles during varus/valgus movements of the knee, which suggest a larger mediolateral moment at the knee would be beneficial to simulate cartilage remodeling and repairs.^{13,28} This would have some implication on the maintenance of the health of the knee joint and prevention of knee osteoarthritis among the elderly practitioners.

A larger plantarflexion moment is needed for forward propulsion during walking, whereas plantarflexion moment was used to support the weight of the body during WHIC and RM. Both WHIC and RM had smaller extension moment at the ankle joint, which would mean that the two Tai Chi movements are less demanding on the ankle joint. In our current study, hip extension moment was larger for RM and WHIC than walking but a smaller hip flexion moment was recorded for the two Tai Chi movements. The high hip and knee extension moment is consistent with past studies on Tai Chi gait, which suggest that the hip and knee extensors are heavily involved.¹³ Although the evidence gathered in this study are consistent with past studies, as mentioned by Song, Lee, Lam, & Bae³¹, it is important to note that not all Tai Chi styles are the same. The amount of loading on the knees and ankle can still vary depending on the Tai Chi style chosen by the practitioner. Hence, practitioners should consider their level of flexibility and physical conditioning when choosing the suitable style of Tai Chi to learn.

Older adults require muscle strengthening and higher weight-bearing activities to maintain or promote skeletal and muscle health.³⁴ However, the ability to tolerate strenuous or high-impact sport is reduced with age, which limits the elders overall physical activity engagement. The level of intensity and safety of these activities is unclear; the elders could risk serious injury or harm if their physical capacity to perform these types of activity is insufficient.

After increasing maximal heart rate from 40-50% at the start of the 8th week to 80-85% at the end of 15th week, it was found that the musculoskeletal system was the limiting factor in achieving and maintaining moderate-to-high exercise intensity.³⁵ Among the elderly females and males participants (age range 60-79), 4% suffered injuries related to going uphill on the treadmill walking, which suggest that training intensity was not a factor, rather injuries occurred when speed was increased too quickly. As stated by the American Heart Association and the American College of Sport Medicine, exercise prescription for the elderly should involve “more moderate-intense exercises that are more gradual and slow”.³⁶ Moreover, the training intensity should be reduced while frequency should be increased but high-impact loading should be slower.³⁵ Reasoning for this is because there an increased evidence to link high impact activities with injuries.³⁷ In contrast, joint loading is high enough and spread over a larger period of time during Tai Chi performance. Hence, Tai Chi would be a good exercise for the elders to maintain joint health.

CONCLUSION

In summary, Tai Chi movements like “Repulse Monkey” and “Wave-hand in Cloud” are safe exercises for the elderly because they have reduced posterior, mediolateral, and vertical GRF; the loading joints at the ankle and hip is gentle and smaller than walking. During Tai Chi performance, there is good training effects on the hip abductors and adductors because joint moments are small, but the loading duration occurs gradually over a longer period time than walking. Furthermore, the longer loading duration of the joints would help with to train muscle endurance. Varus/valgus moments were notably larger at the knee joint during RM and eversion moment was larger at the ankle joint during WHIC movement. A large, but slow loading rate at the knee joint has implication towards improving the viscoelastic properties of the knee and minimizing the risk of developing knee osteoarthritis. Clinicians can use this information to identify the weakness in which muscles that are contributing to falls and to select appropriate Tai Chi movements to help train and strengthen these targeted muscle groups. Like walking, Tai Chi movements can be considered a low-to moderate-intense exercise that can change depending on individual performance speed. The findings highlighted in this study would imply that Tai Chi is particularly safe exercise for the elders and those with knee osteoarthritis.

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CHAPTER 5: GENERAL DISCUSSION & CONCLUSION

The following section will briefly discuss and synthesize the key findings that were highlighted in the two research papers. The implications of the differences seen between the two Tai Chi movements and walking will be highlighted and further clarified.

Temporospatial and COM displacement. Larger mediolateral displacement COM was seen for both RM and especially WHIC. Vertical displacement of COM during the two Tai Chi movements was slightly higher than walking. Lateral instability is the culprit for falls to the side; increasing mediolateral displacement of the COM during WHIC could potential help the elders build the capacity to side-step over an obstacle when faced with such task challenge.

Stride width and stride length was reduced for RM, suggesting that this is a demanding task that could be used to improve balance. Displacement of the COM is performed with limited visual perception during backward stepping. When stride width is increased during WHIC, lateral displacement of COM can be safely performed by the elders. Exercises that encouraging the elders to increase stride width would help to reduce their fear of falling by improving their lateral stability. Both RM and WHIC had increased double-support duration and reduced single support-duration in comparison to walking. The two Tai Chi movements are slower than walking, yet the risk of falling is reduced because less time is spent in single-limb support.

Angles and Moments of Hip. The unique feature of RM movement is that it had a small extension angle to extend the leg back, but a large extension moment was recorded. For two Tai Chi movements, the hip remained mostly flexed throughout the entire gait cycle, which is good for the elderly because they experience weakness in the surrounding muscles in this area. This

extension moment was used to slow flexion of the hip as the body weight is lowered into a semi-squatting position. Large hip flexion angle was recorded for RM when the leg is driven upward, which helps to maximize full ROM of the joints in the lower extremity during Tai Chi practice. The semi-squatting posture pushes the practitioner to maximize their full joint capacity and ROM. This suggests that the muscle activation in the lower extremity would not only increase, but these types of Tai Chi movement can be used to help develop and build joint flexibility, balance, and proprioception. Peak abduction & adduction ROM was significantly larger for the two Tai Chi movements, meaning that the hip abductors and adductors muscles would have to work harder. Hip abduction angles were largest when the leg was extended out during WHIC and during toe-off of RM. A Larger hip abduction moment was needed for WHIC to maintain the opposite hemipelvis leveled, but this was a challenge even for the experienced practitioner.

Angles and Moments of Knee. Flexion/extension angles during RM was not significant, but larger maximal/minimal varus angles suggest the distal portion of the lower segment was bent inward during this movement. This was partially due to the lateral shifting of the COM as the practitioner turned sideways to push the palm forward, and due to the structural instability of the knee joint. Varus/valgus moments were much larger for RM than walking. A less vigorous movement for the elders would be WHIC. Compared to walking, ROM during WHIC was significantly smaller for hip flexion/extension, knee flexion/extension, and knee varus/valgus. The knee joint remained flexed during WHIC. The turning and sideways shifting of the body's COM lead to increase valgus moment, however no significant difference between WHIC and walking at the knee. This suggest that WHIC would be a good low-intensity exercise for the elders because the gentle stepping-action and fluidity movement sideways would help to minimize the stress on the knee joints, but hip abductors and adductors had to work harder.

Angles and Moments of Ankle. Abduction of the hip and the semi-circle action with the toes after toe-off could be important in helping build proprioception when stepping backwards. RM had larger changes to the ankle's ROM, notably a significantly larger dorsiflexion and plantarflexion angles than walking. These large ROM changes suggest that RM has high demands for muscle activity and joint flexibility which are important in postural stability. At the same time, the RM movement reduced the ankle joint moment since plantarflexion was not used to propel the toes off the ground. Furthermore, larger eversion/inversion moment at the ankle was seen for RM, which could lead to improve lateral stability of this joint. More studies are needed to clarify this.

In summary, the elders require low-impact exercises to improve functional capacity without the risk of injuring or overextending themselves. There were notable biomechanical differences between the two Tai Chi movements and walking. Both RM and WHIC recorded large varus/valgus movements of the knee which could help to stimulate cartilage remodeling and repairs. Vertical GRF were reduced during these types of movement. Tai Chi is suitable for the elders because it is performed slowly and joint loading on the knees and ankles is low. RM is a good Tai Chi movement to increase flexibility, improve extensor muscle strength, and balance. A large knee extension moment is required to step backward and place the toes gently onto the ground. It's a challenging task to step backwards without visual perception cues. In contrast, a less vigorous Tai Chi movement would be WHIC. This is a good lateral stepping movement for the elders to improve lateral stability and to safely develop fall prevention strategies. During RM and WHIC, the flexion of the knee was maintained throughout the duration of the gait cycle. This reduced the stress on the knee and hip, making Tai Chi a safe exercise for the elders and those with knee osteoarthritis. Overall, a better understanding of RM and WHIC would allow the elders to safely improve balance, physical capacity, muscle and joint flexibility.

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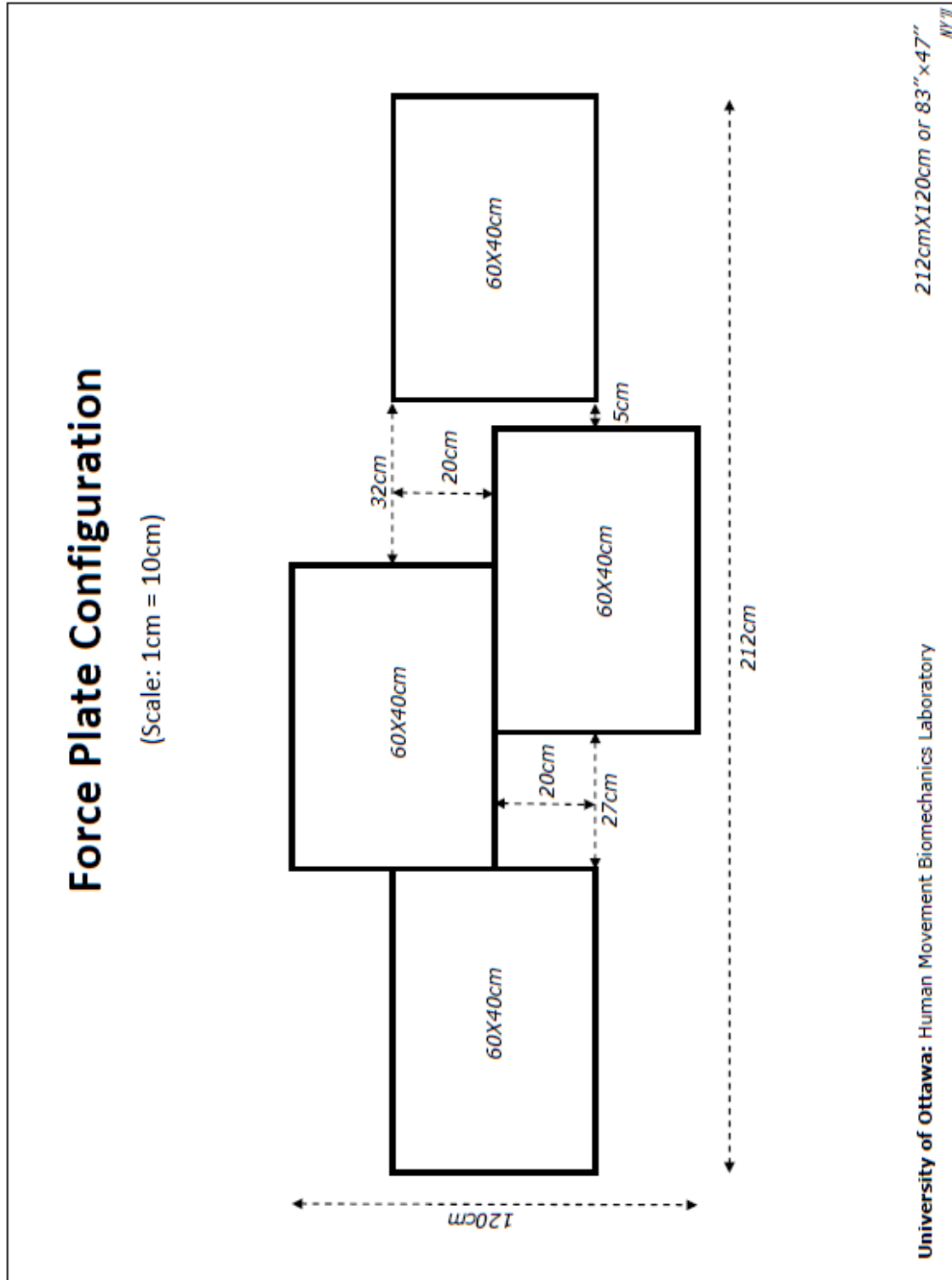
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Appendix A

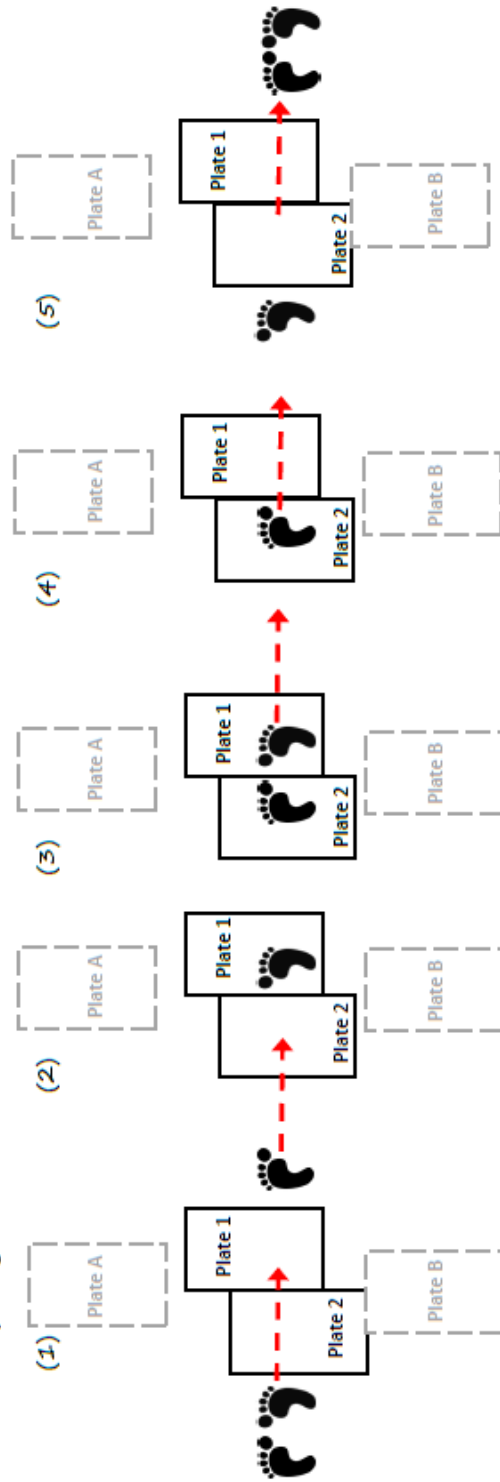


Appendix B

Tai Chi Movement Illustrations

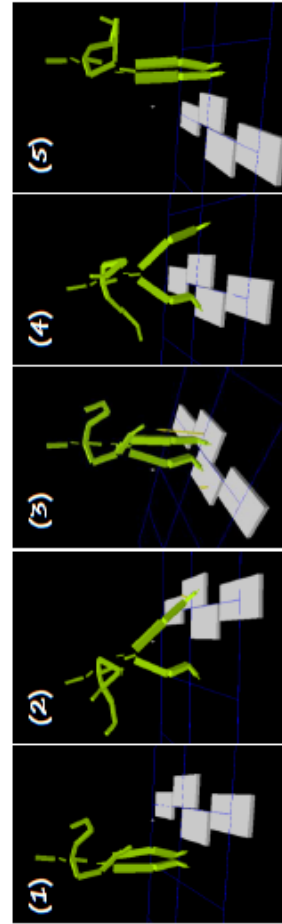
Wave-hand in Cloud

Wide Step-length



Instructions:

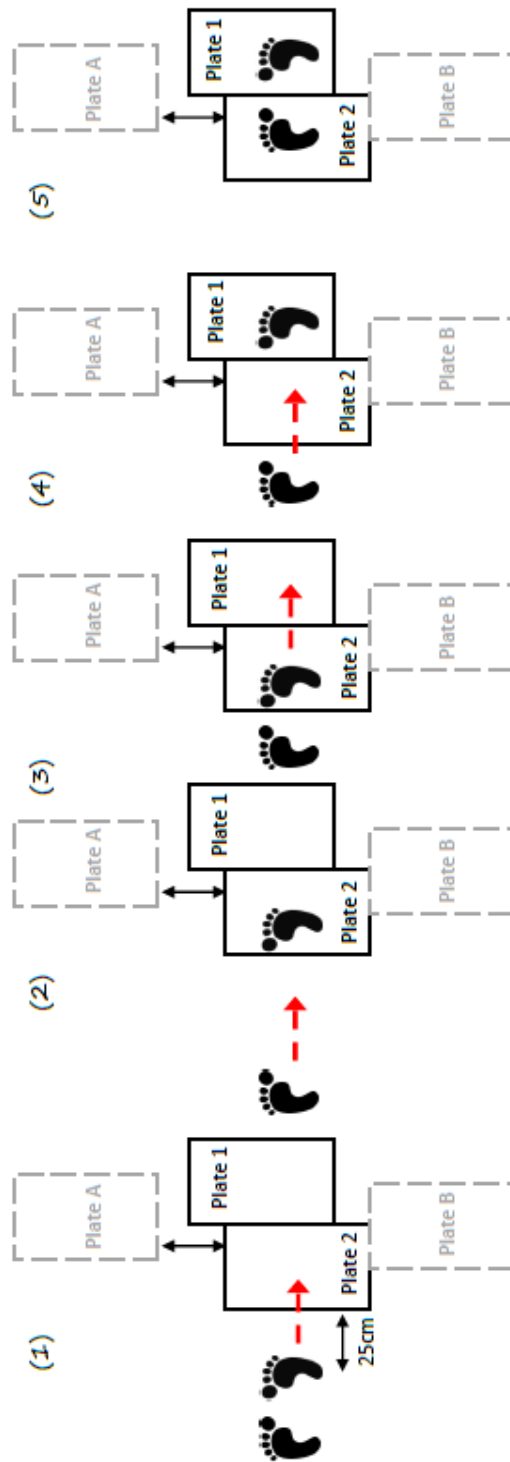
1. Right Foot steps on to Plate 1
2. Left foot steps on to Plate 2
3. Right Foot steps off Plate 1
4. Left Foot steps off Plate 2
5. Both feet are off the force plates



NY13

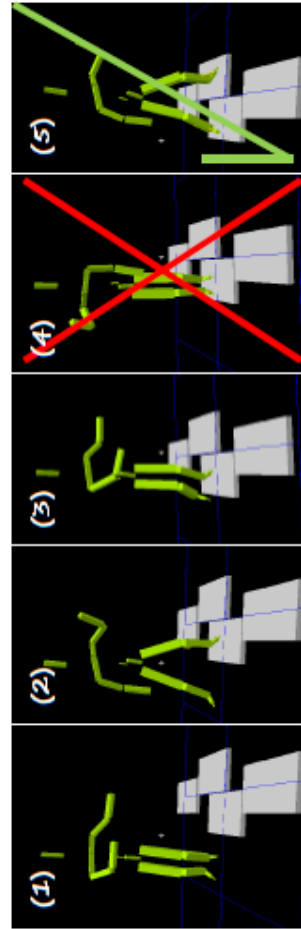
Tai Chi Movement Illustrations

OR Narrow Step-length



Instructions:

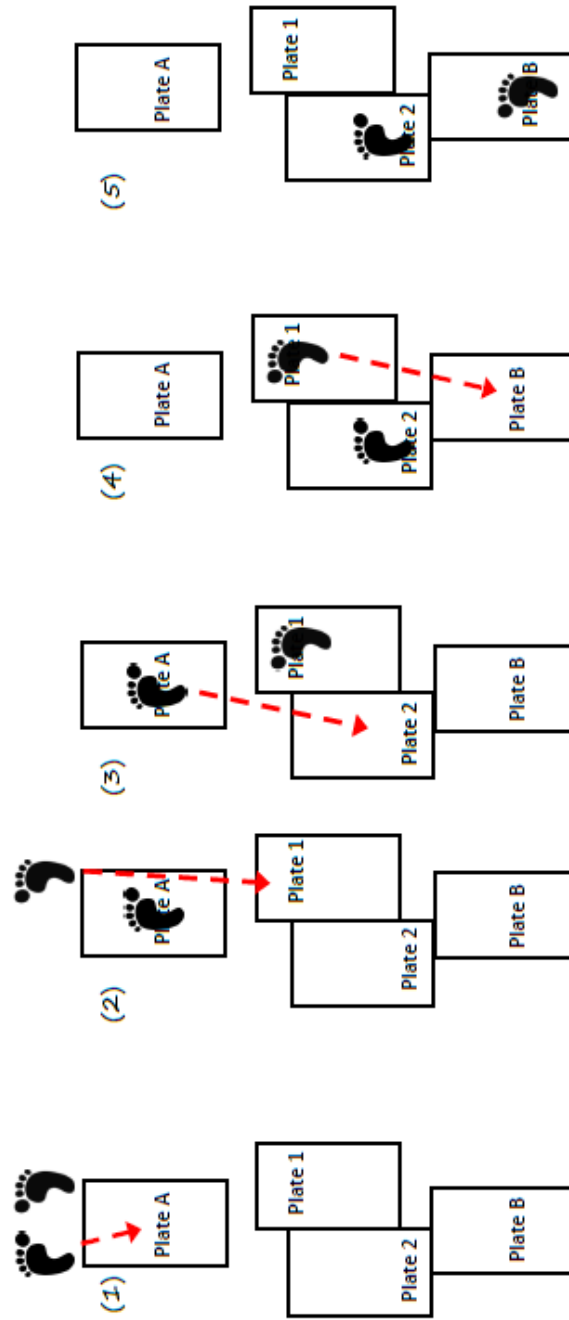
1. Right Foot steps on to Plate 2
2. Left foot steps beside Plate 2
3. Right Foot steps on to Plate 1
4. Left Foot steps on to Plate 2
5. Both feet are together on the force plates



NY-11

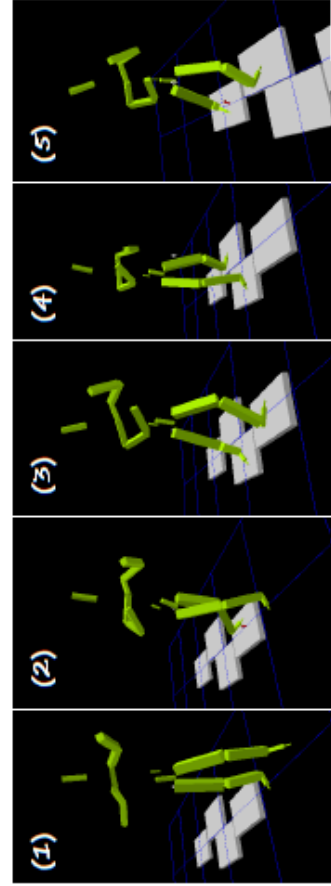
Tai Chi Movement Illustrations

Repulse Monkey



Instructions:

1. Left Foot steps on to Plate A
2. Right foot steps on to Plate 1
3. Left Foot steps on to Plate 2
4. Right Foot steps on Plate B
5. Both feet are on force plates



NY-11

Appendix C

						
Starting	Parting The Wild Horse's Mane. 3 times.	White Crane Spreads It's Wings.	Brush Knee, Push. 3 times.	Playing The Guitar/Lute/Pipa.	Repulse Monkey. 4 times.	Hold The Ball, Ward Off.
						
Grasp The Bird's Tail	Press, Sit Back.	Open up and Push. Repeat the last 4 moves, going right.	Single Whip.	Cloud Hands, going left.	Single Whip again, High Pat on Horse.	Right Heel Kick.
						
Carry The Tiger Over The Mountain.	Turn.	Left Heel Kick.	Snake Creeps Through The Grass.	Stand on one leg. Repeat on Right side.	Shuttle Back And Forth.	Needle At Bottom Of The Sea.
						
Fan Through The Back.	Turn.	Right Back Fist.	Parry and Punch.	Apparent Closing.	Cross Hands.	Close.