BIOMECHANICS OF ORIENTAL MARTIAL ART: WHY PRACTICING TAI CHI CHUAN HELPS TO IMPROVE THE HUMAN BALANCE CONTROL

Youlian Hong
The Chinese University of Hong Kong, Shatin, Hong Kong, China

Four studies were devoted to explore the mechanism of why practicing Tai Chi Chuan (TCC) can improve balance control especially for elderly people. In the first study, it showed that foot stepping patterns of TCC were better than those of walking in simulating the gait challenges that may be encountered in daily activities. The second study found that the characteristics of plantar pressures in TCC movements not only enhances muscle strength, but also improves the somatosensory input and feedback in the great toe area to assist in balance control. The third study found that the elderly people who regularly practiced TC not only showed better kinesthesia in ankle and knee joints than sedentary controls, but also their ankle kinesthesia were better than the elderly regular swimmers/runners. In the fourth study the continuous shifting of the center of gravity (CG) and a wide range of motion (ROM) of lower extremity joints were found. The continuous alteration of muscle loading and contraction types produced different levels of muscle activity – vigorous contraction, moderate tension, or relaxation. All findings supported that TCC movement provides training possibility for proprioception and neuromuscular control, which made TC exercise to confer particular benefits for postural control.

KEY WORDS: Tai Chi Chuan, balance control, gait pattern, plantar pressure, proprioception, center of gravity, EMG

In most English literature Tai Chi Chuan, abbreviated as TCC, is a traditional Chinese exercise form derived from martial arts folk traditions, handed down from generation to generatio n for more than 1200 years. TCC was gradually and systematically developed to the point of formalization more than 300 years ago. The words Tai Chi first appeared in the book "I Ching", where they refer to the creation of heaven and earth (the sky and the world). The state of the universe before the creation of heaven and earth is called Tai Chi. In simple terms, TCC firstly means, each movement is circular, as represented by the circle in the Tai Chi diagram. Within the circular movement are concealed many variations and changes; there is emptiness and fullness; there is movement and stillness; there is expressed strength and softness; there is forward and backward. All these are the meaning contained in the words Tai Chi. Secondly, TCC is the interplay of Yin and Yang. The theory of Yin and Yang is the theoretical basis of traditional Chinese Medicine. According to the principles of the Yin and Yang theory, in any thing or material are contained two aspects, Yin and Yang. Human beings can be expressed as Yin and Yang, the female as Yin, the male as Yang. Human physiological activity can be described as Yin and Yang, for example with digestion, the intake of nutrients as Yang and the excretion of metabolites as Yin. In traditional Chinese medicine, health is contingent upon the balance between Yin and Yang. Imbalances in these energy forces are thought to produce physical dysfunction that may lead to sickness. TCC is used to seek serenity in action and also to seek action in serenity. The emphasis is in the exercise of mind and consciousness. Lastly, movements of TCC are continuous, from beginning to end, from one posture to the next, the movement is never broken, it is a complete integrated circle.

There are many different schools or styles of TC and each has its own distinctive features, but the basic principles are the same. Today millions of people on the world practice TCC, an activity that has become one of the most popular and favored sports and exercise forms, especially among the older people. The observed beneficial effects of TCC on health, especially for older adults, evoked research interest from scientists. (DQ paper 1) A number of cross-sectional and longitudinal studies have provided positive evidence that TC practitioners not only have better cardiorespiratory function (Lai et al. 1995; Young et al. 1999) but also performed better in balance control, flexibility and muscle strength tests (Hong et al. 2000; Tse & Bailey 1992). Moreover, a study conducted by Wolf et al (1996), with a relatively large sample size, identified that the intervention of TC reduced the risk of multiple falls by as much as 47.5%. Although a lot of studies have demonstrated the effects of TC exercise on balance control for the elderly, little effort has been devoted to the underlying mechanism. Hence, we designed three studies to investigate the underlying mechanism that makes TCC practice improve balance control and thus prevent falls.

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STUDY 1: Foot Movement Pattern in TCC Helps to Improve Balance Control

INTRODUCTION: Several studies have shown the beneficial effects of TC exercise on balance control, muscle strength, and flexibility (Hong et al. 2000; Li et al. 2001) According to the theory of TCC, foot posture and movement are the foundation of the whole body posture, and the concept of proper position and direction are always emphasized (Editors 2000) Walking is the basic form of ambulation in daily activities. Regular walking has been recommended for the elderly to increase physical activity and decrease the risk of falls (Cooper 2001) Hence, it is necessary to evaluate the unique foot characteristics of TCC exercise as compared with normal walking. Thus, the aim of our study was to describe the foot characteristics during the whole set of TCC exercise in terms of foot support pattern and step direction, and to investigate whether various support patterns and step directions in TCC may simulate the gait challenges that are encountered during daily activities.

METHODS: The performance of sixteen experienced TCC practitioners performing a whole set of 42-form TCC was recorded with two cameras. In accordance with the foot movement and support characteristics, the foot support pattern was divided into seven categories: 1) full double support, 2) single left support, 3) single right support, 4) left support with right toe touch, 5) left support with right heel touch, 6) right support with left toe touch, and 7) right support with left heel touch. On the other hand, according to the characteristics of TCC movement described as "Five Stages of Change" (Editors 2000) the foot stepping direction was divided into six categories. They are 1) stepping forward – an anterior movement of one foot in relation to the support foot, 2) stepping backward – a posterior movement of one foot in relation to the support foot, 3) stepping sideways – a lateral movement of one foot in relation to the support foot, 4) up-down stepping – upward lifting of one foot above the knee height of the support leg, 5) stepping turning – pivotal rotation (medial or lateral) on the support foot with stepping action of other foot, and 6) stepping fixing or fixed step – both feet are fixed to the ground with no foot movement. The APAS motion analysis system was used to identify the foot supporting and stepping characteristics during the practice.

RESULTS AND DISCUSSION: Seven foot support patterns and six step directions were identified. The results revealed that compared with normal walking, in TCC movement, the duration of each support pattern was longer and movement from one pattern to the next was slow. The longer time interval of each single support may contribute to the improved single leg support balance ability in TCC exercise. The increased period in each support pattern reduced the speed of motion and slowed the changes from one pattern to another, thus prolonging the duration of contraction of the relative muscles, which may improve the strength and endurance of those muscles (Chan et al. 2003). In addition, the performance of TCC relies on full double weight bearing, single weight bearing and one weight bearing with other toe or heel semi-weight bearing maneuvers. These patterns demand a high balance control capacity. The balance control of the centre of gravity and the accurate adjustment of foot position during the practice of TCC forces more muscles to be involved in the exercise, which may lead to increased muscle strength. The results also revealed that the duration of each step direction was short, and changes of direction were frequent. The challenges of maintaining balance during daily life are often likely to demand changes in the base of support to enhance stability. Successful balance recovery by means of stepping requires accurate control of the foot movement as well as controlling the motion of the center of mass to arrest it within the boundaries of the new base of support established by the step (Maki 1999). Hence, compensatory stepping in all directions is an important strategy for preserving stability (McIlroy, Maki 1996) The TC movements in our study were combinations of stepping forward, backward, sideways, up-down, turning, and fixing that are similar to challenges to balance control that are encountered in daily activities. To prevent falls in the elderly, Campbell et al (1997) developed a home-based exercise program that included walking backward and sideways, turning around and stepping over an object. They found that the program improved physical function and was effective in reducing falls and injuries in elderly people.

CONCLUSION: The movements of TCC were found to be better than those of walking in simulating the gait challenges that may be encountered in daily activities.

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STUDY 2: Plantar Pressure Characteristics in TCC Helps Improve Balance Control

INTRODUCTION: To further investigate why TCC exercise can benefit the balance control we designed the present project emphasizing on foot force exertion on the ground during TCC exercise. The reason to study the foot force exertion is that the ground reaction force is applied on the foot during human locomotion and varies continually from the instant of initial contact until the foot leaves the supporting surface (Cook et al. 1997). Numerous studies on the ground reaction force during walking showed that it is a reliable and repeatable feature of gait (Cook et al. 1997; Takahashi et al. 2004). TCC contain specific human locomotion movements. The broad consensus is that TCC exercise improves balance control and muscle strength in the lower extremities (Li et al. 2001; Hong et al. 2000). However, there have been few studies on the foot ground reaction force in TC movements. Wu et al. (in press) studied the foot ground contact characteristics during TC exercise using force platforms and pressure plates, but just one forward movement, known as the TC Gait, was analyzed. According to the theory of TC, foot posture and movement are the foundation of the whole body posture, and the concept of proper position and direction are always emphasized (Editor Group 2000). Stepping forwards, backwards, sideways, moving body up and down, and fixing feet on the ground are the five typical movements of TC (Editor Group 2000). Studying the force exertion of foot may add knew knowledge as to why TC improves balance control and subsequently prevents falls in older people. Therefore, the objective of this study is to describe and quantify the plantar pressure distribution characteristics in the fundamental forward, backward, sideways, up-down and fixing movements and to explain why TC movements benefit balance control and muscle strength.

METHODS: Sixteen elite TC masters participated in this study. Five typical movements were selected from the set of 42-form TCC for analysis: the 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 represent the forward, backward, sideways, up-down and fixing movements, respectively. The Pedar-X insole system (Germany) was used to collect data on the plantar forces during performance of the movements. The same data were also collected during normal walking for comparison. The plantar regions of the foot was divided into nine distinct regions: the medial heel, lateral heel, medial midfoot, lateral midfoot, first metatarsal head, second and third metatarsal heads, forth and fifth metatarsal heads, great toe and lesser toes.

RESULTS & DISCUSSION: A one-way ANOVA analysis showed that in the TC movements, the peak pressure and pressure-time integral of the first metatarsal head and the great toe were significantly greater ($p < 0.05$) than those of the other regions across all five TC movements. However, the peak pressure and pressure-time integral of the second and third metatarsals and the fourth and fifth metatarsals were significantly greater than those of the other regions during normal walking. Studies have demonstrated that the great toe and the forefoot play a very important role in both cutaneous feedback and the muscle activity of the toe in maintaining balance control during gait (Tanaka et al. 1996; 1999). TCC exercise presents a strong challenge to the exertion of the great toe, and subsequently has a training effect on the great toe muscle. Furthermore, the greater pressure in the anterior and medial regions may intensify the sensory input from the great toe (Tanaka et al. 1996; 1999) and the first metatarsal, because the first metatarsal area is one of the most sensitive regions on the bottom of the foot (Nurse, Nigg 1999). Results showed that the shapes and amplitudes of the ground reaction forces varied between the five TCC movements and the peak values were all lower than in normal walking. This not only makes TCC a safe weight-bearing exercise (Wu, Hitt in press) but also an exercise that recruits more muscles of the lower extremities to adapt to the different force shapes on the bottom of the foot. Results also showed that the locations of the centre of pressure (COP) in the TC movements were more medial and posterior at initial contact ($p < 0.05$), and were more medial and anterior at the end of contact with the ground ($p<0.05$). The ranges of motion (ROMs) of the COP were significantly wider ($p < 0.05$) in the mediolateral direction in the forward, backward and sideways TC movements. The ROM was significantly larger ($p < 0.05$) in the anteroposterior direction in the forward movement than in normal walking. When the location of the COP is more posterior at initial contact, the ankle posture is more dorsiflexed, and when the location of the COP is more anterior at end contact, the ankle posture is more plantarflexed. The increase in the ROM of the ankle in the sagittal plane in TC movements may thus be expected. Studies (Mecagni et al. 2000; Whipple et al. 1987) have reported that there is a positive relationship between the ROM of the ankle joint and balance control and muscle strength in the lower extremities. Studies also (Nakamura et al. 2001) found that an increase in the displacement of the COP not only increases the magnitude of the EMG, but also the number of muscles that are used in the lower extremities. Thus, the larger ROM of the COP in TC movements may induce the lower extremities to recruit more muscles that contract at a higher level (Wu et al. 2004) than in normal walking.

CONCLUSION: The plantar pressure during TC movements is redistributed as compared with normal walking. It is expected that long-term TC exercise not only enhances muscle strength, but also improves the somatosensory input and feedback in the great toe area to assist in balance control. The specific ground reaction force and COP pattern found in TCC movement may induce the lower extremities to recruit more muscles that contract at a higher level (Wu et al. 2004) than in normal walking.

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STUDY 3: TCC Benefits Proprioception of Ankle and Knee Joints

INTRODUCTION: Postural equilibrium needs proprioceptive acuity and precise neuromuscular control. Proprioception is the afferent information that contributes to conscious sensation (muscle sense), total posture (postural equilibrium), and segmental posture (joint stability), which is mediated by proprioceptors located in the skin, muscles, tendons, ligaments, and joint capsules (Lephart et al. 1997). A number of studies have indicated that proprioception diminishes with age (Pai et al. 1997; Petrella et al. 1997; Skinner et al. 1984) Gerontologists have postulated that impaired proprioception makes it difficult for older people to detect changes in body position until it is too late for compensatory behaviors to prevent falls (Robbins et al. 1995; Mion et al. 1989). It is very important for old people to retain this ability as much as possible. For elderly persons, one strategy to reduce the incidence of poor proprioception and falls with aging may be regular physical activity (Petrella et al. 1997) Exercise can play a role in improving a number of sensorimotor systems that contribute to stability. Av study (Petrella et al. 1997) found that active old people had better proprioception than the sedentary controls. However different forms of exercise may have different effects on postural equilibrium. It has been (Gauchard et al. 1999) reported that proprioceptive exercise (Yoga and soft gymnastics) appeared to have the better impact on balance control in the elderly compared with bioenergetic physical activities. TCC exercise requires continuous, slow movement with small to large expressions of motion, the shift of body weight from unilateral to bilateral, and circular movements of the trunk and extremities, involving both isometric and isotonic contractions. All forms of TCC emphasize conscious awareness of body position and movement, which seem to contain the characteristics of proprioceptive exercise. Then does TC exercise have particular benefits for old people's proprioception? Jacobson et al (1997) reported that a 12-week TC program could increase participants' shoulder kinesthetic sense at 60°. But in Jacobson's study, the average age of the subjects was 30.4 ± 4.3 years, and the investigators did not refer to the principal joint systems of lower extremity (ankle, knee and hip) involved in postural control. The present study was therefore designed to investigate the proprioception of ankle and knee joints in long-term elderly TC practitioners, long-term elderly swimming/running exercisers and elderly sedentary controls. The purpose of this study was to assess whether long-term TC practice could produce benefits for old people's proprioception and whether this impact of TC on proprioception was more evident compared with other common activities in the elderly. Such knowledge would be very helpful to explain the mechanisms that TC exercise improves balance capacity.

METHODS: Joint kinesthesia is the sensation of joint movement, which is one of important measurement techniques that are used to evaluate proprioception. Kinesthesia is usually determined by establishing the threshold to detect passive motion, an assessment of the ability to detect relatively slow passive joint motion. In this study, this method was used to assess knee and ankle joint proprioception with the custom-made device ProKnee-I for ankle kinesthesia and KneeKine-1 for knee kinesthesia. Through detecting the threshold of passive movements, ankle and knee joint kinesthesia were measured in 21 elderly long-term TC practitioners (TC group), 20 elderly long-term swimming/running exercisers (S/R group), and 27 elderly sedentary controls (control group).

RESULTS AND DISCUSSION: Ankle joint kinesthesia significantly differed among the three groups ($P = 0.001$). TC practitioners could detect a significantly smaller amount of motion than could the swimming/running exercisers ($P = 0.022$) and sedentary counterparts ($P = 0.001$). No significant difference was found between the S/R group and the sedentary control group ($P = 0.701$). For the knee joint, the threshold for detection of passive motion was significantly different in extension and flexion of this joint. For flexion, the TC group showed a significantly smaller mean threshold for detection of passive motion than did the subjects in the control group ($P = 0.026$). While there were no significant differences between the S/R group and control group ($P = 0.312$), the TC group and S/R group ($P = 0.533$). For extension, no significant difference was noted among the three groups ($P = 0.597$). The better kinesthesia associated with TCC than with swimming and running may due to the fact that compared with TC exercise, swimming or running is a kind of cyclic repetitive action. The awareness of joint position and movement is not specially emphasized during these exercise forms. The different relationships associated with knee and ankle might be attributed to the characteristics of TC movements. Although almost all TC forms are performed in semi-squat position, which enhance the loading of muscles and motion ranges of knee joints, the continuous transformation of different postures and steps cause more changes of ankle joint movements, such as turning toes outward or inward, raising toes or putting down and so on. Moreover while making stride, foot placement is slow and deliberate. These movements might benefit for retaining proprioceptors sensitivity located in the joint capsules, ligaments, tendons and muscles. College and his colleagues (Colledge et al. 1994) studied the relative contributions to balance of vision, proprioception, and the vestibular system in different age group. They found all age groups were more dependent on proprioception than vision in the maintenance of balance. Decline in proprioception with age may be an important contributing factor to falls in the elderly, and this may be influenced by regular physical activity.

CONCLUSIONS: The elderly people who regularly practiced TC not only showed better proprioception in ankle and knee joints than sedentary controls, but also their ankle kinesthesia were better than the elderly regular swimmers/runners. The prominent benefits of TC exercise on proprioception may be one of the most important factors in that TC practices maintain balance control in older people.

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STUDY 4: Lower Extremity Movement and Muscle Activity in TCC Helps Improve Balance Control

INTRODUCTION: Our previous study (Xu, Hong, Li et al. 2003) showed that the elderly people who regularly practiced TC not only showed better kinesthesia in their ankle and knee joints than sedentary controls, but also showed better ankle kinesthesia than the elderly regular swimmers/runners. Jacobson et al (1997) reported that a 12-week TC program could increase adult participants' shoulder kinesthetic sense at 60°. Exercise is one of the most important methods to improve proprioception and neuromuscular control. In the rehabilitation of sports injuries, therapeutic exercise for proprioception is particularly emphasized in order to restore agility, balance, and coordination. These proprioceptive exercises include many closed kinetic chain exercises with a progressive reduction in stability (wobble board, ankle disk) and increasing the number of repetitions and rate of contraction (Ceruli, Ponteggia, Caraffa et al. 2001). The beneficial effects of TCC exercise on balance capacity, proprioception, and muscle strength have also been proved in several studies. However the question of how TCC exercise improves proprioception and neuromuscular control has not been answered. Analyzing the kinematical characteristics and muscle activity level of TC movements might lend insight into which aspect of postural control are affected by TCC.
To date, studies on muscular activity and movement kinematics of TCC exercise are limited Zhang et al. (1989) reported an EMG study on Chan style TC. Through analyzing integrative EMG and power frequency EMG, they provided evidence that TCC exercise demands muscle coordination of the upper and lower extremities, with continuous alteration of muscle activity from strong contraction to full relaxation. Using a force platform, EMG, and 3-D video filming, Lu et al. (1991) analyzed the characteristics of the kicking movement in Chan style TCC The results showed that there was an appreciable change in both the CG and the momentum of each body segment. However, these studies were limited to only describing the kinetic and kinematical data in TC movements; they did not subsequently correlate these results with a physiologic interpretation. The purpose of this study was to investigate the kinematics and

muscular activity characteristics of BKTS, one of the most typical, representative movements of TCC, and subsequently to find whether TC exercise contains training components in proprioception and neuromuscular control, which are essential for maintenance of joint and postural stability.

METHODS: Six TC masters performed BKTS three times. Video filming and electromyographic (EMG) signals of the rectus femoris (Rf), semitendinosus (St), gastrocnemius (Gn), and anterior tibialis (Ta) muscles were synchronously recorded throughout the whole movement. Before the trial, subjects performed a maximal voluntary contraction (MVC). This MVC was of isometric nature against manual resistance, maintained for a period of 3 seconds (Arsenault, Winter and Marteniuk 1986). For each chosen muscle, EMG signals produced by MVC were also recorded All EMG signals were recorded at a frequency of 2000 Hz by Delsys EMG System (USA) The raw EMG data were high-pass filtered at 20 Hz, fully rectified, and linear enveloped with a cut-off frequency of 10 Hz. The average amplitude of a 1-second segment of this envelope became the normalizing factor for the specific muscle, for a given subject. The amplitude of envelope of each muscle while performing BKTS was normalized as a percentage of its corresponding EMG obtained while performing MVC. The normalized EMG signals were converted into amplitude probability distribution functions (APDF) and the estimated amplitude of each muscle at the probability of 0.5 was calculated. Meanwhile, the average integrated EMG (AIEMG) value of each phase in BKTS was also calculated and normalized to its corresponding MVC. To reduce small variations in the duration of movement between subjects, the time of the whole movement was normalized (0 to 100%). The Labview Software (National Instruments, USA) was used for signal analysis.
For kinematic analysis of BKTS, two video cameras (Sony, 50 Hz filming rate) were used to film the movement following the 3-D filming requirements. The video signals were then digitized and analyzed on APAS (Ariel Dynamics, USA) to provide kinematical variables including the displacement, velocity, and acceleration of the CG in medial-lateral (X), anterior-posterior (Y), and superior-inferior (Z) directions, the ROM of the knee joint angle and foot-ankle complex throughout the whole movement. The motion of the foot-ankle complex occurs around medial-lateral (dorsi-plantar flexion in sagittal plane), vertical (abduction-adduction in frontal plane) and longitudinal (inversion-eversion in transverse plane) axes of the foot (Sarrafian 1993). Each subject was asked to perform BKTS three times and the best one rated by the subject was analyzed.

RESULTS AND DISCUSSION: CG frequently altered its direction of motion. There were four obvious changes of direction along the X and Y axes. By comparison, the motion of the CG along the Z axis appeared more stable. Although the CG continuously changed its position and direction throughout the performance, its rate of motion was low. The ROM of knee was greater than that in running and walking. The motions of the foot-ankle complex occur around multiple axes at a considerable value. The continuous shifting of the center of gravity (CG) and a wide range of motion (ROM) of joints might facilitate the improvement in balance and proprioception. For the EMG data, a higher AIEMG level occurred in the Rf and Ta than in St and Gn muscles. For the muscles with a higher level of activity (Rf, Ta), the AIEMG values showed a remarkable variation. For the muscles with lower levels of activity (St, Gn), the values of AIEMG remained relatively constant. In addition, the EMG patterns of the agonist and antagonist showed the well-coordinated recruitment of lower extremity muscles during the performance of the movement. The continuous alteration of muscle loading and contraction types produced different levels of muscle activity – vigorous contraction, moderate tension, or relaxation – which was helpful in developing muscle strength and endurance. The slow and smooth action of the BKTS also required well-controlled muscle coordination.

CONCLUSION: The kinematics and EMG characteristics of BKTS evidenced that practicing this movement provides training possibility for proprioception and neuromuscular control, which made TC exercise to confer particular benefits for postural control.

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