EFFICACY OF TAI CHI IN IMPROVING SENSORI-MOTOR AND POSTURAL CONTROL IN THE WELL ELDERLY

BY

WAI NAM TSANG

A THESIS SUBMITTED IN FULFILMENT OF THE DEGREE OF DOCTOR OF PHILOSOPHY

THE HONG KONG POLYTECHNIC UNIVERSITY

2004

STATEMENT OF SOURCES

The idea of the present investigation originated from Professor Christina W.Y. Hui-Chan. The design of the study, the planning of the experiment and data interpretation resulted from discussions between the author and Professor Hui-Chan.

All experiments in the present investigations were completed solely by the author.

The author declares that the work presented in this thesis is, to the best of the author's knowledge and belief, original, except as acknowledged in the thesis, and that the material has not been submitted previously, either in whole or in part, for a degree at this University.

Tsang Wai Nam, William

April 2004

ABSTRACT

With aging, deficits of the multiple sensori-motor systems and neural mechanisms, as well as deterioration in postural control have been shown to contribute to an increased likelihood of falls in the elderly. Increasing evidence demonstrates that behavioral and neural plasticity occurs in response to enriched environment, multi-sensory, and complex motor skill training. Tai Chi, a Chinese mind-body exercise, is now practiced by millions of elderly and believed to be beneficial to their health. Investigation of the effects of Tai Chi practice on postural control has been conducted over the last two decades. However, a comprehensive study into the effects of Tai Chi on the sensory, motor and integrative components of postural control is lacking or inconclusive. Thus, proper studies were needed before broad recommendations on the use of Tai Chi in falls prevention in the elderly could be formulated.

This project consisted of a cross-sectional as well as a prospective study. The hypotheses were that repeated practice of Tai Chi could improve the sensori-motor and postural control of elderly subjects when compared with age-, gender-, and physical activity level matched control subjects. The improved performances of these elderly practitioners could be comparable to those of the young, healthy subjects. Also, short term (8 weeks) intensive Tai Chi training could improve the balance control of healthy elderly when compared to an educational control group. Finally, we hypothesized that golf, like Tai Chi, could improve the joint proprioception and stability limits, as both exercises demands accurate knee joint positioning and weight shifting during practice.

Four groups of subjects participated in the cross-sectional study. The elderly Tai Chi practitioners were recruited from local Tai Chi clubs. All had practiced Tai Chi for a minimum of 1.5 hour·week^{-1} for at least 1 year. The elderly golfers were recruited from local golf clubs. Elderly control subjects were recruited from several community elderly centers. They had no previous experience in either Tai Chi or golf. Young healthy subjects were university students

who exercised regularly for at least 2 hours·week^{-1}. Elderly participants in the prospective study responded to advertisements via pamphlets through several community elderly centers and voluntarily joined either a Tai Chi intervention program or a general education group. All the sensori-motor and postural control assessments were conducted at the Hong Kong Polytechnic University. Experiment 1: Passive knee joint repositioning was used to test joint proprioceptive acuity. Experiment 2: Body sway was measured during static standing. Experiment 3: Subjects' intentional weight shifting to eight different spatial limits of stability within their base of support was conducted using force platforms. Experiment 4: Body sway under different somatosensory, visual and vestibular conditions was measured using computerized dynamic posturography, whereby subjects underwent six combinations of visual and support surface conditions, the so-called sensory organization test. Experiment 5: Concentric and eccentric isokinetic tests of the subjects' dominant knee extensors and flexors were conducted at angular velocity of 30°·s^{-1}. Experiment 6: Control of body sway was tested in single-leg stance perturbed by forward or backward platform perturbations. Experiment 7: The elderly subjects' perception of their balance confidence in daily activities was assessed. Subjects in the cross-sectional study participated in all 7 experiments, whereas subjects joining the intervention program participated in only experiments 3 and 4 only at four time intervals: before, at 4-week intervals during the 8 week of training, and at 4 weeks after the training ended.

Outcome measurements included: 1) Absolute angle error in passive repositioning of the knee joint at 3° of knee extension, 2) Body sway in the anteroposterior and mediolateral directions during static standing, 3) Reaction time, maximum of leaning trajectory, and control of the leaning trajectory in the limits of stability test, 4) The amplitude of anteroposterior body sway under the 6 sensory conditions in the sensory organization test, 5) Peak torque-to-body weight ratios in the concentric and eccentric isokinetic muscle strength measurements of their knee extensors and flexors, 6) Maximum anteroposterior body sway of subjects undergoing perturbation during single-leg stance, and 7) The Activities-specific Balance Confidence score ratios were used to assess the elderly subjective report of their balance confidence.

Results from our study demonstrated that long-term elderly Tai Chi practitioners achieved significantly better acuity in knee proprioception sense, in that they showed smaller knee angle errors in the passive knee repositioning test when compared with those of control subjects similar in age, gender, and physical activity level. No significant difference was found in the anteroposterior and mediolateral body sway during static standing. However, Tai Chi practitioners initiated voluntary weight shifting in the limits of stability test more quickly than elderly control subjects. They could lean further without losing stability, and showed better control of their leaning trajectory. In the sensory organization test, the Tai Chi practitioners had improved their balance control when there was an increased reliance on the visual and vestibular systems during stance. Of particular interest is that these practitioners attained the same level of balance control performance as did young, healthy subjects when standing under reduced or conflicting somatosensory, visual and vestibular conditions.

Our results further showed that experienced Tai Chi practitioners had developed higher peak torque-to-body weight ratios in concentric and eccentric isokinetic muscle strength measurements of their knee extensors and flexors than those of the elderly control subjects. Their strength increase in the agonist and antagonist muscles was to a similar extent. In the perturbed single-leg stance test, Tai Chi practitioners achieved less body sway during both forward and backward platform perturbations than did the elderly control subjects. Also, they had greater balance confidence in performing their daily tasks when compared with that of the control elderly subjects.

After 4 and 8 weeks of intensive Tai Chi training, the elderly subjects achieved significantly better: 1) vestibular ratio in the sensory organization test and 2) directional control of their leaning trajectory in the limits of stability, when compared with those of the control group. These improvements were maintained at 4 weeks follow-up afterwards. Furthermore, the improved balance performance from week 4 on was comparable to that of experienced Tai Chi practitioners.

Our last study showed that, like elderly Tai Chi practitioners, elderly golfers also had better knee joint proprioceptive acuity than did the elderly control subjects. Their performance was even similar to that of the young subjects. Like Tai Chi practitioners in the limits of stability test, the golfers had faster reaction time, leaned further without losing stability, and showed better control of leaning trajectory than did elderly control subjects. The latter 2 outcome measures were also comparable to those of the young subjects.

The above findings lead to 5 main conclusions: 1) Long-term Tai Chi practitioners had improved knee joint proprioception and expanded their limits of stability during weight shifting in stance. 2) Furthermore, long-term Tai Chi practitioners had improved balance control when there was an increased reliance on the visual and vestibular systems in the sensory organization test. They even attained the same level of balance control performance as did young, healthy subjects despite multi-systems degeneration with aging. 3) In addition, long-term Tai Chi practitioners had better knee muscle strength and less body sway in perturbed single-leg stance. 4) Four weeks of intensive Tai Chi training are sufficient to improve balance control in the elderly subjects. 5) Like experienced Tai Chi practitioners, experienced golfers had improved knee joint proprioception and limits of stability, when compared with those of elderly control subjects similar in age, gender (male) and physical activity level. Such improved outcome measures were also comparable to those of young male subjects. Taken together with the previous findings by other investigators that Tai Chi practitioners have decreased the probability of their falling, our present findings indicated that Tai Chi has the potential of being a cost-effective falls prevention program that could be implemented community wide.

ACKNOWLEDGEMENT

I wish to express my deepest gratitude to my supervisor, Professor Christina W.Y. Hui-Chan, Chair Professor and Head of the Department of Rehabilitation Sciences, The Hong Kong Polytechnic University. Through her all-round training, I am learning how to formulate ideas, conduct research, analyze data, write and publish the findings. Also, through her guidance, the new knowledge generated doesn't just end in scientific journals but can reach the community through education and services. Through her enthusiasm, insight and critical mind, research has become an enjoyable and fascinating activity to me.

My deepest gratitude also goes to my wife, Ruth, for her great love, understanding and unfailing support throughout the course of my study.

My warm thanks also go to the following individuals:

- Professor Sing Kai Lo, former- Professor and Mr. Peggo Lam, scientific officer, Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, for their invaluable advice to the statistical analysis in this thesis.
- The elderly centers, Tai Chi and golf clubs, all the elderly Tai Chi practitioners, golfers and elderly control subjects and university students.
- Ms. Wong Lin Ying, Tai Chi master from the Hong Kong WuShu institute, for her Tai Chi training and advice.
- Finally, the technical team, Mr. Man Cheung, Mr. Ken Kan, Miss Y.Y. Wong, Miss Marcella Kwan and Ms. Heather Lee.

This project was supported by a grant from The Hong Kong Polytechnic University to Christina W.Y. Hui-Chan.

PREFACE

Chapter 1 provides a general introduction to and problem formulation of the present series of studies. Chapter 2, 3, 4, 5 and 6 are either published papers (Chapters 2, 3, 5 and 6) or manuscript in press (Chapter 4). The full authorship and titles are listed below. These papers have been reformatted to provide consistency throughout the thesis, especially in the citing of references and in the order of the main sections: Abstract, Introduction, Methods, Results and Discussion. Chapter 7 summarizes the main conclusions of the studies. All references have been compiled at the end of the thesis in the References section.

REFERENCE LIST

Chapter 2:	TSANG, W. W. N., and C. W. Y. HUI-CHAN. Effects of Tai Chi on joint proprioception and stability limits in elderly subjects. *Med. Sci. Sports Exerc.* 35:1962-1971, 2003.
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Chapter 5:	TSANG, W. W. N., and C. W. Y. HUI-CHAN. Effect of 4- and 8-wk intensive Tai Chi training on balance control in the elderly. *Med. Sci. Sports Exerc.* 36:648-657, 2004.
Chapter 6:	TSANG, W. W. N., and C. W. Y. HUI-CHAN. Effects of exercise on joint sense and balance in elderly men: Tai Chi versus Golf. *Med. Sci. Sports Exerc.* 36:658-667, 2004.

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LIST OF ABBREBIATIONS

ABC	:	Activities-specific balance confidence
ANOVA	:	Analysis of variance
CI	:	Confidence intervals
CDP	:	Computerized dynamic posturography
COG	:	Center of gravity
COM	:	Center of mass
COP	:	Center of pressure
EQ	:	Equilibrium quotient
EMG	:	Electromyography
FICSIT	:	Frailty and Injuries: Cooperative Studies of Intervention Techniques
H_{COM}	:	Height of the center of mass
H/Q	:	Hamstrings to Quadriceps strength ratio
ICC	:	Intraclass correlation coefficient
kg	:	kilogram
LOS	:	Limits of stability
m	:	meter
MANOVA	:	Multivariate analysis of variance
METS	:	Metabolic equivalents
MMSE	:	Mini-Mental Status Examination
N·m	:	Newton meter
P_{COP}	:	Maximum distance traveled by the subject's center of mass
s	:	second
SD	:	Standard deviation
SOT	:	Sensory organization test

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CHAPTER 1

INTRODUCTION

1.1 Aging and falls

1.1.1 Aging population

With advances in medical technology, improved standards of living, fewer children being born and more people reaching old age, the elderly population is increasing (Fries 1980; Kalache et al. 2002). According to the World Health Organization, there will be more than 1,000 million people aged 60 and older in 2020 (World Health Organization 1998). The number of people aged 90 to 99 is expected to rise from just over 8 million in 2002 to 60 million in 2050 (Kalache et al. 2002). In Hong Kong, the life expectancy of elderly people has increased from 72.3 in 1981 to 78.2 years in 2001 for men, and from 78.5 to 84.1 years for women. The Hong Kong government projects further increases to 82.3 and 87.8 years for men and women respectively by 2031, which will place Hong Kong people to be among the highest life expectancies in the world. In 2001, people aged 65 or above were 11% of the Hong Kong population. This percentage is expected to rise to 24% by 2031 (Census and Statistics Department 2002), an increase of 118%.

1.1.2 Prevalence of falls

Falls have been identified as one of the major causes of morbidity and mortality in the elderly people (Carter et al. 2001; Wolter and Studenski 1996). In fact, in western countries, 32% of community-dwelling older subjects over the age of 75 are reported to have fallen at least once in the previous year (Tinetti et al. 1988). Ho et al. (1996) conducted a similar cross-sectional study among Hong Kong Chinese aged 70 years and above to estimate the occurrence of falls. Eighteen percent of their 1,947 subjects who could walk either independently or with aids reported having experienced at least 1 fall in the previous 12 months. Among them, 40% were multiple fallers. The authors also showed that about one-third of the falls resulted in soft tissue injuries, with 4.6% of the falls in men and 8.5% in women resulted in fractures. In the United States, the cost of hip fractures in the elderly attributable to falls has been reported to be about $ 10 billion in 2001 (Carter et al. 2001). This represents a major financial burden to its society.

Among the various intrinsic (within the person) and extrinsic (within the environment) causes of falls, impaired postural control has been identified as a major intrinsic factor that causes falls in the elderly (Berg and Kairy 2002; Carter et al. 2001; Lin and Woollacott 2002; Shumway-Cook et al. 2000). An understanding of the different components of postural control is deemed necessary and a review will be presented in the next section.

1.2 Postural control

Many daily activities involve sitting, standing and walking, motor tasks that place heavy demands on the peripheral and central nervous systems that control posture and balance. Over the past several decades, research into posture and balance control and their disorders has broadened and deepened our understanding of the underlying neural mechanisms. Posture and balance control were once regarded as the summation of hierarchical reflex pathways (Roberts 1978), but are now viewed as the output of a complex integration of multiple sensori-motor systems, including those associated with cognition (Andersson et al. 1998; Melville-Jones 2000).

1.2.1 Definition of postural control

The postural control system controls 2 important behavioral goals, namely, *postural orientation* and *postural equilibrium*. Postural orientation is defined as the ability to maintain an appropriate relative positioning of the body segments with respect to one another (the egocentric reference frame), and to the environment (the exocentric reference frame) (Horak and Macpherson 1996; Melville-Jones 2000; Shumway-Cook and Woollacott 2001). A third frame of reference is that of the gravitational field (the geocentric reference frame). Postural equilibrium is defined as the state in which all forces acting on the body are balanced so that the body rests in an intended position (static equilibrium), or moves in a controlled manner (dynamic equilibrium) (Horak and Macpherson 1996; Melville-Jones 2000; Shumway-Cook and Woollacott 2001). The terms *postural equilibrium* and *balance control* are often used interchangeably in the literature to represent the same concept (Shumway-Cook and Woollacott 2001).

1.2.2 Postural orientation

Postural orientation has 2 perspectives: aligning the various parts of the body in a specific orientation with respect to one another, and orientating the body to environmental variables such as earth vertical (Horak and Macpherson 1996). Animals, including humans, align their body postures in ways that are characteristic of each motor task, so as to optimize sensory inputs and to facilitate the respective motor output. In the process of establishing a vertical orientation, they use multiple sensory references, including the somatosensory system based on information from the support surface, neck and body, the visual system based on the relationship of the body to objects in the surrounding environment, and the vestibular system based on gravitational force (Melville-Jones 2000; Shumway-Cook and Woollacott 2001).

Orientation of the trunk has been considered to be one of the important elements of postural orientation, as this will determine the spatial positions of the limbs in relation to the objects with which an animal wishes to interact. Mouchino et al. (1993) observed that the amplitude of leg movement appears to be computed with reference to the trunk axis (an egocentric reference frame), rather than the external environment (an exocentric reference frame), when dancers and control subjects performed a leg elevation task. However, the dancers spontaneously aligned their trunks parallel to the earth vertical (a geocentric reference frame), whereas the control subjects did not (Mouchnino et al. 1992). In this connection, investigators have hypothesized that trunk orientation is controlled through a difference between two signals, namely, signals from neck receptors and vestibular otolith signals (Mittelstaedt 1991; Young et al. 1984). The neck receptors signal the orientation of the head relative to the trunk, while the vestibular otolith signals the head orientation relative to the gravity vector. The difference is an error signal that is proportional to the deviation of the trunk from earth vertical. Thus, through this proposed mechanism, human subjects control the orientation of the trunk with respect to a geocentric reference frame (Mergner et al. 1993).

Orientation of the head as the geocentric reference frame is another important postural variable that is controlled during daily functional tasks. For example, knowing the position of the head relative to earth vertical is important in stabilizing vision. The head is controlled in a stable position so that the vestibulo-ocular reflex can compensate to maintain gaze stability (Grossman et al. 1988). This is especially true when the available somatosensory information is inadequate for postural orientation (Nashner et al. 1988). Pozzo et al. (1992) found that subjects stabilized their head and trunk more actively when they stood on an unstable, rocking platform when compared to a stable surface. Mouchnino et al. (1990) also observed that training improved head stability as a result of comparing skilled and unskilled dancers and skaters.

1.2.3 Postural equilibrium

Postural equilibrium, or balance control, is the ability to maintain the body in a stable condition. In static equilibrium, a subject is considered to be stable when the center of mass (defined as a point at the center of the total body mass) is maintained over the base of support (defined as the area contained within the perimeter of contact between the surface and the two feet) (Winter 1995a). During movements such as walking, the vertical projection of the center of mass rarely lies within the base of support, but is continuously regulated to maintain dynamic equilibrium (Winter et al. 1990; Winter 1995a). In quiet standing, the base of support is nearly a quadrangle bounded by the heels and toes.

1.2.4 Systems for postural control

Postural control for orientation and equilibrium requires both sensory inputs (to detect the position and movement of the body in space) and motor outputs (to generate forces for movement of the body) (Gardner et al. 2000; Shumway-Cook and Woollacott 2001). Shumway-Cook and Woollacott (2001) have proposed a conceptual model illustrating the close interaction of the musculoskeletal and neural systems (Fig. 1.1). The musculoskeletal components consist of muscles as active elements, joint range of motion, trunk flexibility, and ligaments and joint capsules as passive elements. Neural components fundamental to postural control consist of sensory processes including the somatosensory, visual and vestibular systems; central nervous system processes integrating sensation to action and including anticipatory and adaptive aspects of postural control; and motor processes including neuromuscular responses (Shumway-Cook and Woollacott 2001; Woollacott 1991).

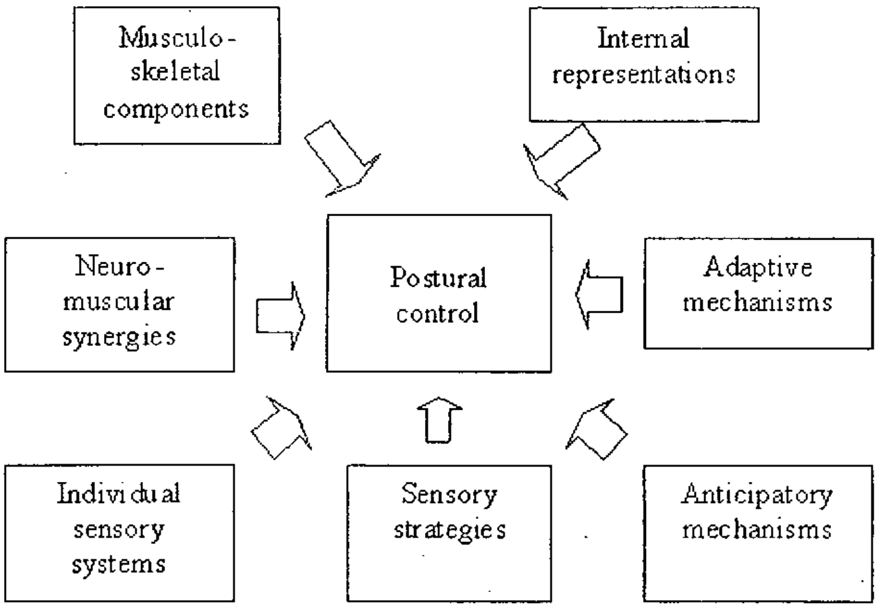


FIGURE 1.1 – Conceptual model illustrating peripheral and central nervous systems contributing to postural control, adapted from Shumway-Cook & Woollacott (2001).

1.2.5 Postural control in stance

The sensory and motor systems work together to maintain a stable standing position. To illustrate, the body sways even in quiet standing in accordance with the goal to maintain the COM within the base of support (Winter 1995b). Research on stance usually focuses on the anteroposterior direction. However, investigators have started to study mediolateral stability in recent years (Clark and Rose 2001; Mak and Ng 2003). To understand the mechanism underlying postural control in standing, sensory, central integrative and motor mechanisms should all be considered, as reviewed separately below.

1.2.5.1 Sensory mechanisms

Sensing the body's position in space requires a combination of somatosensory, visual and vestibular inputs (Gardner et al. 2000; Nashner 1994; Shumway-Cook and Woollacott 2001). These three sensory modalities are required, as each modality provides the central nervous system with specific information coming from different sensory receptors about the position and motion of the body.

The somatosensory system provides the central nervous system with information on the orientation of body segments with respect to one another and with respect to the support surface (Nashner 1994). Somatosensory receptors include muscle spindles and Golgi tendon organs, joint receptors, and cutaneous mechanoreceptors such as Pacinian corpuscles, Meissner's corpuscles, Merkel's discs and Ruffini endings (Gardner et al. 2000; Horak and Macpherson 1996).

Proprioception is a sense of the position and movement of one's own limbs and body in the absence of vision, termed "limb-position sense" and "kinesthesia" respectively (Gardner et al. 2000). Limb proprioception is mediated via cutaneous receptors in the skin and proprioceptors in limb muscles, tendons, ligaments and joints, signaling to the central nervous system both the stationary position of a limb and the speed and direction of limb movement. These sensations are important for the generation of smooth and coordinated movements, maintenance of normal body posture, and motor learning and relearning (Gardner et al. 2000).

Proprioceptive inputs also originate from the neck and body. The vestibular apparatus detects the orientation of movements only of the head. Therefore, it is necessary for the central nervous system to receive appropriate information describing the spatial position of the head with respect to the body. This information is transmitted from the proprioceptors of the neck and body directly into the brain stem and indirectly through the function of cerebellum (Amaral 2000). To illustrate the interaction of the vestibulospinal and cervicospinal reflexes in regulating postural stability, the head and trunk of a quadruped were moved together or independently (Melville-Jones 2000; Roberts 1978). Passive rotation of both the head and trunk of a quadruped to the left resulted in left limbs extension and right limbs flexion. This was thought to be due to the vestibulospinal reflex as a result of activating the vestibular receptors, since no relative movement occurred between the head and neck. If only the trunk was passively tilted left while the head was kept stationary to activate the neck (rather than the vestibular) receptors, the cervicospinal response would produce the same behavior to oppose the tilt. Moreover, if the head was tilted while the trunk remained stationary to activate both vestibular and neck receptors, the quadruped's stance was not disturbed due to cancellation of the two reflexes.

Visual inputs report information concerning the position and motion of the head with respect to surrounding objects. Based on external cues in the surroundings, visual inputs provide a reference for verticality (Patla 1997; Wade and Jones 1997). The absence of vision increases sway during stance, with the amount of sway dependent on the particular stance posture, the availability of accurate surface and vestibular information, and cognitive factors such as fear of falling (Horak and Macpherson 1996). The contribution of vision to postural control has been demonstrated by comparing eyes-open and eyes-closed sway while a person stands on a compliant foam rubber pad (Nashner 1994).

Vestibular inputs provide the central nervous system with information about the position and movement of the head with respect to gravity and inertial forces, providing a geocentric frame of reference for postural control (Melville-Jones 2000). The vestibular system has 2 types of receptors that sense different aspects of head position and motion. The semicircular canals detect angular accelerations of the head and report their magnitude and orientations to the brain (Goldberg and Hudspeth 2000). The 3 semicircular canals in each labyrinth are almost perpendicular to one another. Each canal encloses a slender semicircular duct that contains endolymph and a sensory receptor. The semicircular canals are sensitive to fast head movements such as those occurring during gait or during postural instability, for instance, slips, stumbles and falls (Horak and Shupert 1994). The otoliths, including the utricle and saccule, detect all the linear accelerations acting on the head, including constant head acceleration due to gravity (Goldberg and Hudspeth 2000). Thus, the otoliths are stimulated as the head tilts with respect to gravity, such as during postural sway (Horak and Macpherson 1996).

1.2.5.2 Central integration

Prior to any movement, all the information arising from the sensory systems is organized and integrated by the central nervous system, in particular the brain (Gardner et al. 2000). No single sensory system can provide accurate postural information, since one or more of the sensory systems may not provide optimal or accurate information for the purpose of postural control (Nashner 1994). When a combination of inputs is used, the weight given to a sensory modality with less accurate information is reduced, while the weight of sensory modalities providing more accurate information is increased. The process of selecting and integrating appropriate sensory information was termed *sensory organization* by Nashner (1994).

One approach to investigating how the central nervous system adapts the combination of 3 sensory inputs for postural control was developed by Nashner and colleagues, termed "sensory organization test" (Nashner 1993a; Nashner and Peters 1990). In their protocol, subjects' postural control is tested during stance under reduced or conflicting somatosensory, visual, and/or vestibular conditions. Altogether, there were 6 sensory conditions, including combinations of 3 visual conditions (eyes open, eyes closed, sway-referenced) with 2 support surface conditions (fixed, sway-referenced). Subjects sway less when they stand on a fixed support platform (with eyes open, eyes closed, or with a sway-referenced visual surround). However, they sway more when they stand on a sway-referenced support under the same 3 visual conditions when somatosensory information is unavailable (Camicioli et al. 1997; Hamid et al. 1991; Wolfson et al. 1992).

Based on the available sensory information, the body's biomechanical constraints, the requirements of the task, the environmental context and prior experience, the central nervous system will integrate the information and execute an appropriate motor output. Examples of motor outputs are postural adjustment in anticipation of a disturbance of the center of gravity or in carrying out a voluntary movement (Krakauer and Ghez 2000). The motor mechanisms underlying postural control are reviewed below.

1.2.5.3 Motor mechanisms

The control of the body's position in space requires the generation and coordination of muscle forces. A number of elements contribute to maintaining stability in quiet stance, including body alignment and muscle tone (Basmajian and De Luca 1985; Woodhull et al. 1985). Good alignment of the body in stance will ensure equilibrium, which results in minimal energy expenditure. In a normally aligned posture, the vertical line of gravity goes through the mastoid process, passes in front of the shoulder joint, through the hip joints or slightly behind, goes through a point just in front of the knee joint, and passes through a point just in front of the ankle joints (Danis et al. 2004; Woodhull et al. 1985). Muscle tone can be viewed as the force with which a muscle resists being lengthened, depending on its intrinsic elasticity or stiffness (Pearson and Gordon 2000). The stretch reflex, which contributes actively to muscle tone, also acts to resist lengthening of the muscle. However, there has been controversy over the role of the stretch reflex in the control of stance. One school of thought suggests that in stance, the ankle muscles can be stretched by body sway in the opposite direction, thus activating the stretch reflex to oppose the sway to maintain body equilibrium. Another school of thought questions the significance of the stretch reflex in controlling body sway, since its gain is quite low during quiet stance (Gurfinkel et al. 1974).

Maintaining postural control in stance is a dynamic process which requires muscle forces to control the position of the center of mass (COM) of the body (Winter 1995a; Wolfson et al. 1996). These muscles forces are reflected in the ground reaction force. The center of gravity (COG) is defined as the vertical projection of the COM. Center of pressure (COP) is the point location of the vertical ground reaction force vector, and it represents a weighted average of all the pressures over the surface of the area in contact with the ground (Winter 1995b). The difference between the COG and COP has been documented by a number of researchers (Benda et al. 1994; Nardone et al. 1990; Winter 1995b), and care is necessary when interpreting balance control performance if COP data are used to estimate the position of the COG (Benda et al. 1994).

Postural sway is the corrective body movement resulting from the control of body position. It has been measured in several ways, including the amplitude of COP excursions, the total path length of COP excursions and the speed of movement of the COP during stance. The amplitude of COP motion in quiet stance is often employed by researchers to quantify postural sway (e.g., Patla et al. 1990). Subjects whose amplitude of COP excursions is large are considered to be exerting greater effort and thus to have poorer balance, whereas small amplitude is often interpreted as good balance control. This notion has been supported to some extent by experimental results. When there is diminished sensory input to postural control, either due to pathology or aging, the amplitude of COP displacements in quiet stance has been shown to be increased (Shumway-Cook and Woollacott 2001). However, people who stand with very small postural sway are not necessarily stable. For example, researchers have found that Parkinsonian patients with rigidity and bradykinesia often show little COP motion (Horak 1992), despite their higher probability to falling.

The limits of stability (LOS) defines the region in space through which a subject can move their COG without altering the base of support. If the COG passes the LOS boundary, a step will be necessary to establish a new base of support, or else a fall will occur (Nashner 1993b). The LOS depends on the area of the base of support (the anteroposterior length of the foot and mediolateral width of stance). If a subject stands on a flat and firm surface with feet separated at shoulder width, the LOS can roughly be described as an ellipse (Fig. 1.2).

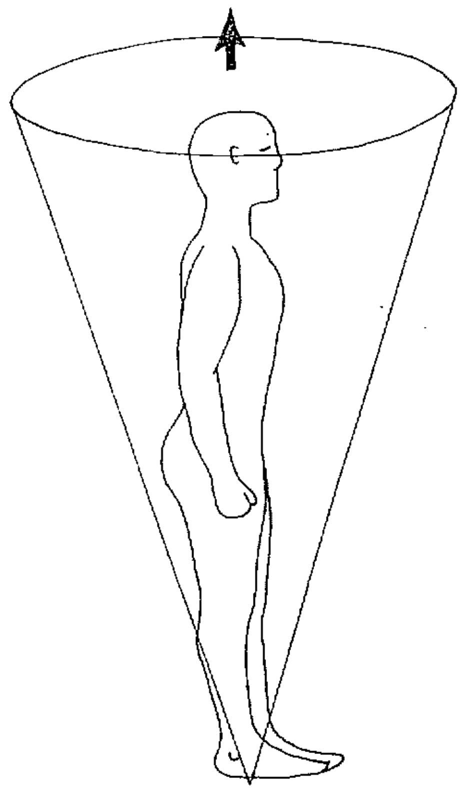
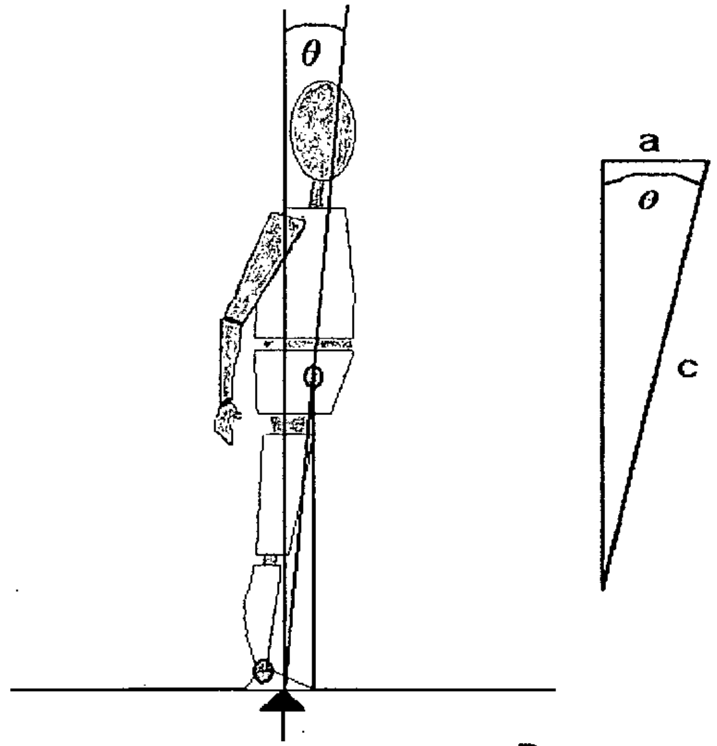


FIGURE 1.2 – The limits of stability can be represented as an ellipse when the subject stands on a flat and firm surface with feet separated at shoulder width, adapted from Nashner (1993b).

Researchers have been using either normalized COP excursions to describe a person's limits of stability (King et al. 1994), or the angular displacement of the COM from the vertical (Shepard et al. 1993). Normalized COP excursions describe the COP trajectory normalized with respect to either the subject's height or foot length. The angular displacement of the COM is measured from the gravitational vertical (Shepard et al. 1993). The *sway angle* is defined as the angle between a line extending vertically from the center of foot support and a line extending from the center of foot support through the COM, assuming that a person moves as a rigid mass about the ankles (Fig. 1.3).



$$\sin\theta = \frac{P_{COP}}{H_{COM}} = \frac{a}{c}$$

FIGURE 1.3 - Definition and calculation of the sway angle, θ. Adapted from the Smart EquiTest® System operators manual (NeuroCom 2000).

P_{COP} denotes the maximum distance traveled by the subject's center of mass (approximated by "a" in the diagram to the right).

H_{COM} denotes 55% of the height of the subject (equal to "c").

θ denotes the maximum body sway angle.

The center of foot support is the projection of the COM when a person stands erect (Nashner 1993b). This point is located 2.3° in front of the ankle joint and midway between the lateral borders of the feet. In a standing balance test, the maximum distance swayed was recorded and denoted as P_{COP}. The height of the COM, denoted as H_{COM} in the equation below, was estimated to be 55% of the subject's body height (Bioastronautics Data Book, NASA, 1962). The normalized

COP, denoted as P_{COP}/H_{COM}, was employed to estimate the maximum sway angle (θ) as follows:

$$\theta = \arcsin\left(\frac{P_{COP}}{H_{COM}}\right) - 2.3° \qquad [1]$$

The formula takes into consideration the 2.3° "forward shift" of the COM from the vertical when calculating θ from the ankles (Nashner 1993b). The COP measured from the force platform was used to determine the P_{COP}. The sway angle defining the LOS in the anteroposterior direction is approximately 12.5° from the most backward point to the most forward point of the ellipse.

When a person's postural stability is disrupted by a brief displacement of the supporting surface, one of 3 movement strategies (ankle, hip and stepping strategies), or a combination, is used to recover stability (Nashner 1994). These movement strategies are invoked when responding to external perturbations, such as a disturbance from a potentially destabilizing voluntary movement, or unexpected disruptions during locomotion (Shumway-Cook and Woollacott 2001). The *ankle strategy* restores the COM to a position of stability while maintaining the placement of the feet, by rotating the body as an approximately rigid mass about the ankle joints (Fig. 1.4a). The *hip strategy* controls motion of the COM by producing a large and rapid movement centered about the hip joints with smaller opposing ankle joint rotations (Fig. 1.4b). The *stepping strategy* is the only movement strategy effective in preventing a fall when the perturbation displaces the COG beyond the LOS perimeter (Fig. 1.4c) (Nashner 1994; Shumway-Cook and Woollacott 2001).

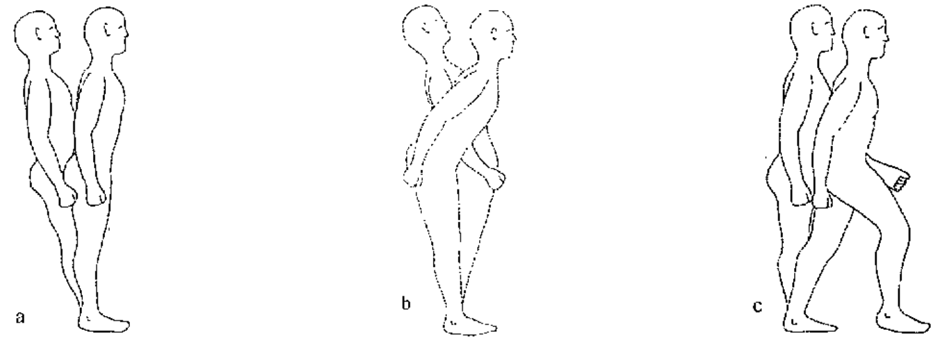


FIGURE 1.4 – Three movement strategies used for controlling the upright sway position: (a) ankle strategy, (b) hip strategy and (c) stepping strategy, adapted from Nashner (1994).

In sum, postural control in humans involves complex integration of multiple sensori-motor systems and neural mechanisms to control postural orientation and postural equilibrium. This review forms a basis for discussing how aging can affect the postural control systems in the section below.

1.3 Effects of aging on postural control

Studies have suggested that deterioration in postural control in the elderly can affect both static and dynamic equilibrium, which may lead to falls (Berg and Kairy 2002; Clark and Rose 2001; Patla et al. 1990). Investigators have learned about how changes in the different sensory and control systems contribute to the increased likelihood of falls in the elderly.

1.3.1 Sensory deficits

Limb proprioception has been found to diminish with age, after ligamentous injuries, and as a result of some pathological conditions such as stroke and osteoarthritis. More specifically, Skinner and co-workers (1984) found that both the threshold for detection of joint movement and the ability to reproduce passive knee joint positioning deteriorated with age. Hurley and colleagues (1998) found that elderly subjects, with a mean age of 72 years, scored significantly higher errors in an active knee joint repositioning test. Yan and Hui-Chan (2000) showed that the joint detection threshold was 50% higher in older subjects (aged 57–77 years) than in young subjects (aged 25–35 years) for both knee flexion and extension. Lord and co-workers (1999) reported that elderly fallers, with a mean age of 76.5 years, showed significantly reduced proprioception of the lower limb when asked to match the position of the big toe on each side by extending the knee. Similarly, Sorock and Labiner (1992) found that the frequency of first falls in elderly subjects (average age = 79.8 years) was significantly elevated in those with reduced toe joint position sense.

The Romberg quotient, often used to describe visual contribution to stabilize posture, is a ratio between body sway values recorded during standing with the eyes open and closed. The lower the quotient, the more effect vision has on postural stabilization. Pyykkö and colleagues (1990) reported that, in old age groups (age > 80 years), the Romberg quotient was 0.48, while the value at ages ranging from 50 to 60 years was 0.78. This finding confirms that vision is important in maintaining balance in elderly subjects. However, with aging, there is a decrease in visual acuity, restriction of the visual field, increased susceptibility to glare, and poorer depth perception (Harwood 2001; Stelmach and Worringham 1985; Woollacott 1993). These deficiencies may result in a longer delay before the visual system manages to alert the central nervous system to a potential fall. They could also affect the visual sampling necessary to accurately assess the rate and direction of a fall and the time to landing (Stelmach and Worringham 1985). As a result, an older person's use of visual information for balance control could be diminished, thus increasing his/her chances of falling. Investigators using the sensory organization test have found that elderly subjects also had greater difficulty when the visual input was manipulated to make it inappropriate to the postural task, and when both proprioception and visual inputs were reduced or absent (Ledin et al. 1991; Shepard et al. 1993; Wolfson et al. 1992; Woollacott et al. 1986).

The effect of aging on the vestibular system has also been investigated in posturography studies (Camicioli et al. 1997; Whipple et al. 1993; Wolfson et al. 1992). Elderly subjects were found to sway significantly more than did younger subjects in conditions when their eyes were closed whilst standing on a sway-referenced support surface, or when both the surround and the support surfaces were sway-referenced (Fig. 3.1). Poorer balance control in the elderly could also be attributed to age-related structural degeneration in the vestibular receptors. For example, Rosenhall and Rubin (1975) reported a 40% reduction in the sensory cells of the vestibular apparatus in subjects more than 70 years of age. This implies that the amount of peripheral vestibular input associated with a perturbation of the standing position is possibly reduced with aging.

1.3.2 Motor deficits

Muscle size and related neuromuscular functions are known to decrease with age (Vandervoort 2002). The decline in muscle strength is minor until about the sixth decade of life. Average declines in maximal isometric knee extension strength by 34%, ankle plantarflexor strength by 32%, ankle dorsiflexor strength by 23% and hand grip strength by 34% have been found in subjects over 70 years of age (Vandervoort 1992). This is due to an overall loss of type I (slow-twitch) and type II (fast-twitch) muscle fibers, with a significant atrophy of the latter (Vandervoort 2002). Such a modification in the proportion of these two muscle fiber types probably explains the significant increase found in the time to peak force in the triceps surae of elderly subjects (Davies et al. 1986). In this connection, Patla and colleagues (1993) compared a group of healthy elderly subjects (mean age = 69 years) with young subjects (mean age = 20 years) by asking them to step forward, sideways or backward with a designated leg, in response to a light signal. They found significantly longer reaction times in the elderly subjects. Further analysis of the vertical force component of the motions measured with a forceplate revealed that elderly subjects took longer to reach peak force in all 3 stepping directions, as well as producing lower peak force during forward stepping. The peak force developed in the stepping leg was required to transfer body weight to the non-stepping leg. These findings indicate that the muscles of the elderly subjects are not only weaker when compared to those of young persons, but they are also less capable of generating fast contractions. These deficits could play a role in impaired postural control, resulting in falls of elderly subjects (Carter et al. 2001; Schwendner et al. 1997; Wolfson et al. 1995).

1.3.3 Postural deficits

Stability in the standing position decreases with age, as reported by Overstall and colleagues (1977), who found that the amount of anteroposterior displacement of the subjects' waist during quiet stance increased almost linearly, from 18 to 96 years of age among 303 normal subjects. Investigators also found that older subjects swayed significantly more than young subjects when there was an increased reliance on visual and vestibular inputs, when other sensory inputs were reduced and/or distorted (Ledin et al. 1991; Shepard et al. 1993; Wolfson et al. 1992). Such an increase in sway was thought to be attributable to the deterioration that occurs with aging in the somatosensory, visual, and vestibular systems responsible for balance control (Alexander 1994; Hageman et al. 1995; Horak et al. 1989). King and colleagues (1994) found that active older subjects (60–91 years) had a decrease of 30% in the maximum forward and backward displacements of the COP normalized with respect to foot length, when compared with those of younger subjects (20–59 years). This decrease in the limits of stability with age was found to play a significant role in predicting multiple falls (Girardi et al. 2001). In another study, Hageman and colleagues (1995) measured the total time moving from the center of base of support to 8 target positions in space (termed "movement time"), and the mean distance traveled from the center to each of the 8 target positions normalized with its respective shortest distance (termed "path length"). They found that older adults (mean age = 65.3 years) had longer movement time (by 49%) and path length (by 12%) when compared to those of young adults (mean age = 25.3 years).

In sum, deficits of the multiple sensori-motor systems and neural mechanisms, as well as deterioration in postural control have been shown to contribute to an increased likelihood of falls in the elderly. However, interventions such as exercises have been shown to maintain and/or improve postural control in the elderly and decrease the likelihood of falls. These studies are now reviewed below.

1.4 Exercise training to improve postural control

Various studies have investigated the effects of exercise training on improving postural control in the elderly. Lichtenstein et al. (1989) conducted 16 weeks of a general exercise program that included stretching, single-leg standing, tandem heel/toe gait, walking, as well as reaction time exercises for women with mean age of 77.5 years. The investigators found an insignificant effect of the exercise program on postural sway measured in 4 conditions, namely single- and double-leg stance with subjects' eyes open or closed. Among the possible reasons for such insignificant results might be inadequate intensity and/or inappropriate type of exercise training. Sauvage et al. (1992) conducted 12 weeks of a moderate to high intensity program of weight training and stationary cycling for frail male nursing home residents (mean age = 73 years). They found significant improvements in the lower limb muscle strength and endurance, as well as gait and Tinetti mobility scores when compared with those of a control group who only received usual care including maintenance physical therapy. Judge et al. (1993) compared the effects of a combined exercise group receiving lower limb muscle strengthening, walking and postural control exercises, with those of a flexibility training program in a group of elderly women (mean age = 68 years). After 6 months of training, the subjects in the combined exercise group had achieved a 17% decrease in the mean postural sway in single-leg stance ($P = 0.023$), whereas those in the flexibility group had only a 5% decrease ($P = 0.3$). They also found no correlation between lower limb muscle strength as measured by leg press in sitting and postural sway. The investigators postulated that postural training could contribute to the improvement of postural sway in single-leg stance.

In studies on the rehabilitation outcome of subjects with peripheral vestibular disorders, specific vestibular exercises were found to produce better balance performance than nonspecific general conditioning exercises. Horak et al. (1992) examined the effectiveness of a specific vestibular rehabilitation program, a general conditioning exercise program, and vestibular suppressant medication in reducing symptoms in patients with chronic peripheral vestibular disorders. Although their sample size was small and the age range was wide (18–60 years), patients in the vestibular rehabilitation groups achieved less anteroposterior postural sway than the other two groups in the sensory organization test when they stood on a sway-referenced platform, with either absent vision or swayed-reference surround. The vestibular rehabilitation program included balance re-education using functional activities such as walking with head turns and pivot turning, or with altered surface or visual inputs. Horak and colleagues suggested that these activities might improve patients' ability to use the remaining vestibular inputs to achieve better balance control.

Hu and Woollacott (1994a) studied the effect of multi-sensory training, which was designed to improve inter-sensory interaction including somatosensory, visual and vestibular systems. The training program included standing quietly on the platform for 1 hour each day while sensory inputs relevant to postural stability were systematically manipulated. These included standing with eyes open or closed, head in neutral or extended posture, and on firm or foam support surface. After 4 weeks of training, the investigators found that the healthy elderly participants (aged from 65–90 years) fell less frequently, when the somatosensory inputs from the feet were minimized during stance in a sway-referenced support surface. The latter were also able to stand longer in single-leg stance. Furthermore, the onset latencies of their neck flexor muscles in response to anterior platform translation were significantly shorter after training. Hu and Woollacott (1994b) suggested that multi-sensory training could have effectively improved dynamic balance performance in healthy elderly.

In sum, given the appropriate exercise type and intensity of training, exercise has been shown to improve postural control of the elderly subjects. Increasing evidence demonstrates that the brain's ability to change is not just in response to normal developmental processes, but also to experience, injury and training. The possibility of considerate residual malleability of the brain will form an important scientific basis for developing the strategy to maintain and/or improve the sensori-motor and postural control systems due to aging. A review of the mechanisms underlying neural plasticity is hence presented below.

1.5 Neural plasticity

The ability of the brain to modify itself in response to changes in environmental conditions or brain injuries does not end with puberty. The view of the central nervous system as a static and unalterable structure persisted until researchers began to discover growth and reorganization of neurons in both adult animals and humans (Gordon 2000; Stein et al. 1995). The term 'plasticity' refers, in general, to the adaptive capacities of the central nervous system to modify its own structural organization and functioning (Bach-y-Rita 1992; Shumway-Cook and Woollacott 2001). Neural plasticity may be seen as a continuum from short-term changes in the synaptic efficiency to long-term structural changes in the organization and numbers of connections among neurons (Asanuma and Keller 1991; Kandel 2000), as detailed below.

1.5.1 Mechanism underlying neural plasticity

Neural plasticity can be viewed as the ability of the nervous system to show modification as a result of learning and training (Shumway-Cook and Woollacott 2001). The considerable evidence for neural plasticity can be broadly categorized into 4 mechanisms.

1) Latent synapses. Many synaptic connections exist between the cortex and the periphery in addition to intra-cortical connections, but some may not be normally apparent because of inhibitory influences (Wall 1977). However, these so-called "latent" synapses could be recruited during recovery of function, and the recruitment is an important recovery mechanism in the acute phase after injury to the central nervous system. An example to illustrate this mechanism is that stimulation of a point on the skin excites neurons near the center of the area of cortical representation which inhibits activity in neurons near the periphery. This inhibition is due to the activation of inhibitory interneurons near the center of cortical representation. Destruction of these cells in a focal cerebral lesion will remove the inhibition on the periphery, and the inhibitory fringe may become a new center of activation. Such findings could explain why compensation can occur within a few hours of a brain lesion, when creation of new neuronal circuits could not have occurred yet (Merzenich et al. 1984; Mountcastle 1980).

2) Increase in strength of synaptic connection. The effectiveness of synaptic connections is adjusted in response to functional demands. Hence, synaptic transmission becomes facilitated in a pathway that is frequently activated. In fact, activity-related changes in the excitability of synapses have been investigated most extensively in the hippocampal neurons. Briefly, repetitive stimulation of the hippocampal neurons was found to increase their neuronal excitability and to facilitate their synaptic transmission. This phenomenon is called long-term potentiation (Bliss and Lomo 1973). If this finding could be extrapolated to all neurons of the brain, repeated practice of a task can lead to increased speed and accuracy of performance.

3) Axonal sprouting. Preserved neurons at the edge of a lesion sprout new axonal branches (axonal collaterals) to the damaged region and innervate dendrites that have lost their synaptic inputs. Darian-Smith and Gilbert (1994) reported axonal sprouting in neurons of the visual cortex after bilateral, symmetrical retinal lesions. Initially, the cortical area deprived of input from the retina was electrically silent. However, after several weeks, this cortical region began to respond to visual stimuli from neighboring, uninjured retinal areas. Labeling of axons by antegrade transport showed that this was accompanied by the formation of laterally projecting axonal sprouts from cortical neurons near the margin of the area that had lost its input.

4) Formation of new neurons. The question of whether new neurons form during adult life for learning and memory is slowly resolved through recent researches in animals. New neurons have been found to form in adult primate brains in specific areas, especially the dentate gyrus in the hippocampus (Eriksson et al. 1998). Evidence for adult neurogenesis in cortical association areas, but not in the primary visual cortex, has been reported in subhuman primates (Gould et al. 1999a). However, the number of new cells was reported to be small. The authors questioned whether they could be incorporated into a functioning system. Also, there is no direct evidence for widespread adult neurogenesis in the cerebral cortex of humans. Investigators are now probing methods by which the number of such cells could be increased in the case of focal brain injury, so that the newly formed neurons could be directed to the site of the lesion to enhance the rehabilitation process (Gould et al. 1999b).

In sum, evidence supporting the adaptability of the central nervous system to changing circumstances is increasing. Plasticity can be found in both intact and lesioned brains. It involves various mechanisms, namely unmasking of latent synapses, increase in strength of synaptic connection, axonal sprouting, and/or formation of new neurons. Hence, the question is not whether adaptability occurs in the nervous system, it is whether and how the environment, training and rehabilitation program could promote behavioral plasticity and functional return which will now be elaborated upon.

1.5.2 Plasticity of the intact brain: animal studies

The parallel and distributed nature of brain organization appears to play an important role in its capacity for flexibility and adaptation (Merzenich et al. 1991). Evidence has shown that there is a continual competition between neuronal groups for the domination of neurons located along their mutual borders in the cortex (Merzenich et al. 1991). This competition for cortical territory appears to be use-dependent. Studies in monkeys have demonstrated that the internal representation of cortical maps of the body surface are modifiable by experience and training (Jenkins et al. 1990). Jenkins and colleagues (1990) showed that several months of practice with a repeated touch task, in which monkeys used their middle finger to obtain food, could greatly expanded its representation in the cortex, as measured by evoked potentials. Such organizational changes in the nervous system are considered to be a general property of the somatosensory system. Studies of rats being taught complex skills further suggest that increased demands for repeated physical activity stimulated angiogenesis and synaptogenesis (Black and Greenough 1989; Isaacs et al. 1992). Angiogenesis means development of new blood vessels, whereas synaptogenesis describes the process of forming new synapses. As afore-mentioned, neuronal elements are inherently flexible, responding according to usage patterns, as illustrated in animal studies involving training.

1.5.3 Motor learning, training and neural plasticity: human studies

Evidence for the effectiveness of training on brain reorganization, including functional changes in cortical motor and sensory neurons, also originate from human studies. For instance, studies of humans following surgery have also illustrated such neural plasticity. Mogilner and colleagues (1993) employed magnetoencephalography and found that the cortical representation of the human hand area can be modified after surgical separation in subjects with congenital fusion of the fingers. More specifically, the distance between sites of cortical representation of the thumb and little finger increased significantly 26 days after their surgical separation. Furthermore, humans with an intact brain also shows functional changes in the brain associated with training and use, such as increased use of a body part or enhanced sensory feedback from it. To elaborate, subjects were asked to practice a finger opposition task for about 20 minutes every day, touching the thumb to each fingertip in a specific repeating sequence (Karni et al. 1995). Both the speed and accuracy of the movement increased, and reached a plateau in about 3 weeks. Functional magnetic resonance imaging revealed that the area of cortex activated during the trained sequence was larger than that activated during a novel untrained sequence. In other words, more extensive representation in the motor cortex was found in subjects after repeated practice of a single motor task for only 3 weeks.

These studies demonstrate the tremendous capacity of the brain for plasticity or "rewiring" after only a few weeks of training. In another example, skilled Braille reading was found to be associated with a relative enlargement of the cortical sensorimotor representation of the reading finger. This was demonstrated by Pascual-Leone and Torres (1993) using focal transcranial magnetic stimulation. Sadato and colleagues (1996) using positron emission tomography also showed that the visual cortex receives input from the somatosensory system in blind subjects. They demonstrated that during Braille reading, the primary and secondary visual cortex areas were activated in blind subjects, in contrast to their being deactivated in subjects with normal vision. These experiments suggest that adult cortical maps are flexible and dynamic. Since each individual is nurtured in a different environment and has practiced very different types of motor skills, the map of each brain is unique and constantly changing as a result of these experiences.

1.5.4 Plasticity following brain lesions

In a rat study, Donoghue and colleagues (1990) observed that activation of the whisker area of the motor cortex elicited forelimb activity, rather than activity of the whisker only 95 minutes after its facial nerve had been lesioned. Weiller and colleagues (1993) studied a group of subjects with infarcts in the internal capsule. In patients who showed recovery of hand function, there was a ventral extension of the hand area of their cortex into the area normally controlled by the face. These studies illustrate that the nervous system is capable of reorganization following nerve or brain lesions in rats and humans. The rat study suggests that some "latent" synapses may already exist but are nonfunctional or weak under normal conditions. Through appropriate situations, these dormant synapses could be quickly activated or unmasked (Mountcastle 1980; Wall 1977).

Is such plastic change just a part of spontaneous recovery? Or is reorganization of neural mechanisms dependent on use and experience? The relationship between reorganization and early rehabilitative training after stroke had been studied by Nudo and Milliken (1996). These investigators induced focal ischemic infarct in the motor cortex area representing the fingers in 5 adult monkeys. Without any post-infarct training, intracortical microstimulation technique was employed to map the distal forelimb movement representations in the primary motor cortex after 3 to 5 months. Although a recovery in hand movement was observed within 2 months, the intracortical microstimulation failed to show any increase of digit representation in the area adjacent to the infarct. Furthermore, the surrounding tissue underwent a further territorial loss in the functional representation of the affected body part. Subsequently, Nudo and colleagues (1996) repeated the experiment, but with intensive retraining in hand use starting 5 days after induction of the lesion and involving two 30-minute sessions per day for 3 to 4 weeks. They demonstrated that the hand area in the undamaged area surrounding the lesion was expanded after the treatment period. These experimental findings suggest that proper rehabilitative therapy can prevent further loss of hand area in the adjacent, intact cortex tissue, possibly by directing the intact tissue to compensate for the damaged function.

Is rehabilitative training effective in promoting behavioral plasticity in chronic pathology? In a study on the effectiveness of forced use of the affected arm, Taub and colleagues (1993) randomly assigned patients with chronic stroke (average chronicity = 4.4 years) to either an experimental group or an attention-placebo control group. Patients in the experimental group carried their less-affected arm in a sling during waking hours for 14 days to prevent its usage. On 10 of those days, they received 6 hours of daily supervised practice using their more affected arm in various activities of daily living (ADL) tasks. After the short intervention period, the restrained subjects demonstrated a significant increase in motor ability of the affected arm as assessed by both laboratory tests and real-world arm use, whereas the control patients showed no change. Visintin and colleagues (1998) investigated the effect of gait training on a treadmill with body weight support on some clinical gait outcome measures in patients with stroke. After 6 weeks of training, the body weight support group achieved significantly better balance control, walking speed and walking endurance than the control group whose subjects were trained to walk on the treadmill without body weight support. Based on our understanding of neural plasticity as detailed in section 1.5.1, the mechanism underlying such improvements could be attributed to the ability of the brain for cortical reorganization as a result of a short period of training (Nudo 1998; Taub and Uswatte 2003).

Will different forms of training lead to similar degree of neural and/or behavioral plasticity? Emerging evidence from animal studies has shown that the level of neuropil expansion in cerebral cortex positively correlate with the degree of environmental complexity in which the animals were reared (Globus et al. 1973; Juraska 1984; Volkmar and Greenough 1972). In this connection, Black and colleagues (1990) studied plastic changes in the cerebellar cortex by comparing the paramedian lobule of adult rats (10 months old) randomly allocated to acrobat training, running wheel exercise or inactive conditions. The rats receiving acrobat training had to traverse a progressively difficult path, which consisted of balance beams, seesaws, rope bridges, and different kinds of obstacles. In these rats, the latency to navigate the task and the number of errors made decreased dramatically across training sessions. After 30 days, the left and right paramedian lobules of the cerebellum among the 3 groups were investigated using transmission electronic microscopy technique. Acrobatic rats had greater numbers of synapses per Purkinje cell than those allocated to running wheel exercise or inactive groups. Furthermore, no significant differences in number or size of the synapses between the latter 2 groups were found. The authors concluded that the motor learning required of the acrobatic animals, and not simply repetitive use of synapses during a physical exercise such as running wheel in this experiment, generated new synapses in the cerebellar cortex.

In a more recent study, Klintsova and colleagues (1998) investigated the effects of complex motor skill learning on the motor performance deficits produced by postnatal exposure (days 4 through 9) to alcohol in a rat model. Until the rats were 6 months old, they were allocated to one of the following three interventions for 20 days: 1) rehabilitation training the rats to transverse a set of 10 obstacles, 2) motor control training the rats to exercise on a flat oval track, or 3) inactive training. After that, all the rats were tested using parallel bars, rope climbing, and traversing a rotating rod which had been found to be sensitive to balance and coordination deficits. The investigators found that the rats receiving 20 days of rehabilitation improved in some of the captioned motor performance deficits, whereas those trained to walk on an oval track or remain inactive had virtually no noticeable improvement in skilled motor performance. In a follow-up study, Klintsova and colleagues (2002) evaluated the morphological plasticity in the paramedian lobule of cerebellum of rats using the same training regimens as just described except that only two groups were studied, rehabilitation and inactive. They found that the rats who underwent 20 days of rehabilitation had more parallel fiber synapses per Purkinje cell than those of the inactive animals.

These findings suggest that complex motor skill training improves the motor performance (Black et al. 1990; Klintsova et al. 1998), and is responsible for synapse formation in the cerebellar cortex (Black et al. 1990; Klintsova et al. 2002). As reviewed in the previous sections, postural control involves complex integration of multiple sensori-motor systems and neural mechanisms to control postural orientation and postural equilibrium. Any deficit in these systems has been shown to contribute to an increased likelihood of falls in the elderly. Based on our understanding of the effect of training in promoting neural plasticity, appropriate exercise modalities should be selected and devised to maintain or improve the health of elderly, including their abilities in postural control. Tai Chi, a mind-body exercise, had a long history and is now practiced by millions of elderly both in the East and the West. Its original 108 forms are comparable to complex motor skill training (Chan et al. 2003; Wolf et al. 1997a), and requires a great deal of balance control during various forms that involve weight shifting and single-leg stance. Thus, repeated practice of Tai Chi may improve the sensori-motor and postural control of elderly subjects despite multi-systems degeneration with aging. In this connection, golf is selected as a comparison exercise to determine the specificity of Tai Chi on the sensori-motor and postural control performance. Like Tai Chi in the East, golf is a popular sport with older subjects in the West. It involves swinging of the body and upper limbs, precise control of the COM during weight shifting, and lots of concentration in order to hit the ball to the targeted location. Studies on these two "exercises" will now be reviewed in the sections below.

1.6 Tai Chi

Tai Chi is a Chinese martial art which is regarded as a gentle, relaxing, yet invigorating form of exercise. Tai Chi is both an integrated exercise and an enjoyable sport for all kinds of people: strong and weak, young and old, male and female. Weather does not inhibit its practice indoor. Requirements of traveling time and space are minimal (Tsao 1995).

Studies show that the movements involved in Tai Chi provide a stimulus for increased flexibility, strength, balance, vascular health and body awareness, so they are recommended for the elderly people (Levandoski and Leyshon 1990; Lumsden et al. 1998; Ross and Presswalla 1998). Tai Chi movements are not too difficult to learn. They exercise the major joints of the body, and involve low-impact and low-risk movements (Levandoski and Leyshon 1990; Lumsden et al. 1998). Tai Chi can produce an average of 50% increase in heart rate and has a metabolic demand of 4 to 5 metabolic equivalents (METs) (Fu and Fung 1996). Hence, it is recommended as a form of exercise suitable for elderly subjects.

Tai Chi is thought to have been devised by Chang San Feng for meditation and self-defense in the thirteenth century (Koh 1981). The term Tai Chi is derived from a concept in Chinese philosophy meaning "supreme ultimate". Philosophically, Tai Chi is said to be the primary principle of all things and is represented by a circle divided into light and dark segments, representing the "yin" and "yang" concepts. The latter reflect opposite attributes such as female and male, inactivity and activity, softness and firmness, darkness and light, and negative and positive. Over the years, the practice of Tai Chi changed, and various schools have emerged such as the Yang, Chen, Sun, Ng and Yin schools. Each school has its own distinctive features, but the basic principles are similar (Koh 1981). The most widely recognized form of Tai Chi involves 108 forms (Tsao 1995; Wolf et al. 1997a). A routine involving all 108 forms takes about 30 minutes to complete. However, the 108 forms are difficult for some of the elderly to learn. Therefore, the Chinese National Council of Sports and Physical Education in 1956 designed a 24-form simplified Tai Chi, which includes representative components of the conventional schools (Chinese Sports Editorial Board 1986).

1.6.1 The essentials of Tai Chi

Tai Chi has been practiced by millions of elderly Chinese for the past 300 years. Initially, it was practiced as a fighting form that emphasized strength, balance, flexibility, and speed. Over time, it has evolved into a soft, slow and gentle form of exercise that is practiced by people of all ages (Tsao 1995). Ten essential elements of Tai Chi as originally proposed by a famous Tai Chi master, Yeung Siu Ching, slowly evolve and are described below (Yu 2002):

1) Straightening the head (虛靈頂勁). Practitioners are required to stand straight and hold their head and neck naturally erect, and concentrate on the vertex of the head.

2) Correct positioning of chest and back (含胸拔背). Practitioners are instructed to keep the chest slightly inward, which will enable them to hold their breath at the level of the "lower belly" (丹田) to enhance their diaphragmatic breathing.

3) Relaxation of waist (鬆腰). Tai Chi practice requires lots of attention to the trunk, and practitioners have to relax their "waist" during practice. Tai Chi theory suggests that in daily function, all movements rely heavily on the action of the "waist". Also, the theory proposes that if one can relax the waist, the feet will then be "strong enough" to form a firm base. The practitioners can then use the trunk to lead the 4 limbs. Inaccurate movements in Tai Chi are believed to stem from erroneous actions of the "waist".

4) Solid and empty stance (分虛實). It is of primary importance in Tai Chi to distinguish between *empty* (虛) and *solid* (實). If one shifts the body weight to the right leg, the right leg is solidly planted on the ground and the left leg is said to be in an *empty* stance, and vice versa. Tai Chi theory considers that only by distinguishing the two different types of stance in this way can one turn and move the body adroitly and without effort; otherwise one tends to be slow and clumsy in movements.

5) Sinking of the shoulders and elbows (沈肩墜肘). Practitioners are enjoined to keep their shoulders in a natural, relaxed position by "sinking" (relaxing) their shoulders and keeping the elbows down. Relaxed shoulders are considered to help the body move with ease.

6) Using the mind instead of force (用意不用力). According to Yeung's theory, the practice of Tai Chi relies entirely on using the mind not force. That means the whole body is relaxed, and there is not an element of "stiff or clumsy strength" in the "veins" or "joints" to hinder the movement of the body.

7) Coordination of the upper and lower parts of the body (上下相隨). According to the theory of Tai Chi, the root is the feet. The force is launched through the legs, controlled by the waist and expressed by the fingers. The feet, the legs and the waist must form a harmonious whole. When the hands, the waist and the legs move, the eyes should follow their movements. This is termed "coordination of the upper and lower parts". If any part should cease to move, then the movements are considered to have become disconnected and to have fallen into disarray.

8) Harmony between the internal and external parts of the body (內外相合). In practicing Tai Chi, the focus is on the mind and consciousness. The mind is seen as the commander, while the body is subservient to it. With the tranquility of the mind, movements will be gentle and graceful. For example, when one "opens" (開)(spreading) the 4 limbs, it is not just the external parts which are involved. The mind is "opened" as well. Perfection is achieved when one unifies the two and harmonizes the internal and external parts into a coordinated whole.

9) The Importance of continuity (相連不斷). In Tai Chi, one focuses the attention on the mind instead of force, and the movements from the beginning to the end are continuous and in an endless circle, "like a river which flows on and on without end".

10) Tranquility in movement (動中求靜). In the fighting forms of martial arts, the emphasis is on leaping, bouncing, punching and the exertion of force, and the athlete is left gasping for breath after practice. In Tai Chi, the movement is blended with tranquility. While performing the movements, one maintains tranquility of mind.

These 10 essentials represent the Eastern view of Tai Chi. The Western view has been summarized as 3 basic principles in the work of Wolf and colleagues (1997a). The first principle requires the practitioners to extend and relax their bodies. They should be aware of trunk alignment and focus on deep breathing. This is similar to the postural requirements in the Eastern view (straightening the head, correct positioning of chest and back, relaxation of waist, and sinking of the shoulders and elbows). The second principle of Tai Chi focuses on the mind. During practice, it requires the practitioners to have a calm but alert mind, leading to the awareness of body movement and their environment. This principle relates to the essence of Eastern philosophy in that the mind is the source of body movement (using the mind instead of force, harmony between the internal and external parts of the body, the importance of continuity and tranquility in movement). The third principle requires the practitioners to have a well-coordinated sequencing of body segments and this originates from the waist and pelvis. The concept of coordination and proper sequencing coincides with the Eastern view embedded in the essentials of distinction between *solid* and *empty* stances, and coordination of the upper and lower parts of the body. In this connection, a research group led by Hong has employed kinematic and electromyographic analysis to study the underlying biomechanical principles of a Tai Chi form called "push hand" (Chan et al. 2003). They studied the path of the center of pressure of a Tai Chi master during the "push hand" movement, and found that the anteroposterior and mediolateral trajectories were unique and repeatable. Also, the height of the master's center of gravity was maintained in a low but stable level during body movements. The authors demonstrated that the repeatable trajectory and the stable height of the center of gravity required the smooth coordination of bilateral hip, knee and ankle movements.

1.6.2 Tai Chi and balance control

It is a common belief that practicing Tai Chi can improve a person's mental and physical status (Jin 1992; Kutner et al. 1997). Some qualitative reports on the benefits of Tai Chi began to be published in China in the mid 1970s, and in the Western literature in the 1980s (Van Deusen and Harlowe 1987; Zhuo et al. 1984).

These initial investigations focused on joint range of motion, cardiorespiratory and metabolic responses (Lan et al. 1996; Van Deusen and Harlowe 1987; Zhuo et al. 1984).

Studies of Tai Chi and balance control began in the 1990s (see the reviews by Li et al. 2001; Lan et al. 2002; Wu 2002; Wang et al. 2004). In 1992, Tse and Bailey were the first to evaluate the influence of Tai Chi on balance control. In a cross-sectional study, they found that elderly people with more than 1 year of Tai Chi practice had better balance control than their sedentary counterparts in right and left leg standing with the eyes open. In 2000, Hong et al. found that practitioners with more than 10 years of Tai Chi experience could maintain single-leg standing with their eyes closed for a significantly longer period than non-Tai Chi practitioners.

In 1993, the Atlanta Frailty and Injuries: Cooperative Studies of Intervention Techniques (FICSIT) group evaluated 2 types of interventions, namely, Tai Chi and computerized balance training, with an education group serving as the control (Wolf et al. 1993). After 15 weeks of intervention, only the subjects in the Tai Chi group had reduced their fear of falling and the risk of multiple falls (by 47.5%) when compared with the education group (Wolf et al. 1996). This article has been regarded as playing a major role in the acceptance of Tai Chi as a means to improve balance and decrease fall risk in the Western world (Lavery and Studenski 2003). According to Lavery and Studenski (2003), a search of PubMed revealed about 10 publications on Tai Chi before the FICSIT study and more than 90 articles since then.

However, these early FICSIT findings were contradicted by objective balance measurements in the FICSIT group's own subsequent study in 1997 (Wolf et al. 1997b). The results in that study showed significantly reduced maximum sway amplitude after toe-up perturbations in the computerized balance training group, but not in the Tai Chi group. The use of toe-up perturbation as an outcome in a Tai Chi study was criticized by other researchers as being either inappropriate (Horak 1997) or not challenging enough to the balance control system (Wong et al. 2001). As previously mentioned, postural control involves complex mechanisms requiring close interactions between the musculoskeletal and various neural systems (Shumway-Cook and Woollacott 2001). Therefore, a comprehensive investigation into the effects of Tai Chi on the sensory, motor and integrative components of postural control under more functional context seems warranted. This forms the main substance of the present thesis. Since golf was used for comparison with Tai Chi in our studies on its effects on balance control, it is reviewed below.

1.7 Golf

Like Tai Chi in the East, golf is a sport that is popular among the older westerners, and increasingly so among the Chinese people, old and young. The task of a golfer is to hit the ball from tee to hole with as few number of shots as possible (Draovitch and Westcott 1999). Hitting a golf ball is estimated to occur in less than 2 s for a complete golf swing (Selicki and Segall 1996). This demands the golfers to hit the ball in the right direction and to a precise location with the most efficient motion. With repeated practice, golfers should possess the correct skills and be able to execute shots in a reproducible and consistent manner. Moreover, a round of golf usually involves 8 km of walking up and down hills and sometimes through sand dunes, and approximately 3 hours of walking for 18 holes (Parkkari et al. 2000; Stauch et al. 1999). Hence, golf also demands sensory, motor and dynamic postural control with precise weight shifting during golf swing and prolonged walking on uneven ground.

1.7.1 Golf and health benefits

Golf is regarded as a moderate intensity activity and has a metabolic demand ranges from 3.0 to 5.5 metabolic equivalents (METs) (Ainsworth et al. 1993). Parkkari et al. (2000) studied the health benefits of golf by recruiting 55 healthy male golfers, aged 48 to 64 years, who stopped golfing for 7 months prior to the investigation. During the 20-week study period, these golfers played a mean average of 10 hours per week. The investigators found that golfers improved significantly in treadmill walking time and static back extension time when compared with those of the age-matched sedentary controls without any intervention. They attributed the improvement observed in golfers to the regular walking on the golf course, estimated to be 20 km per week. Stauch et al. (1999) studied the heart rate of 30 golfers (average age = 53 years) during a round of golf on a hilly course with a cumulative altitude difference of 142 m. A heart rate monitor applied to the chest wall was employed to measure the mean heart rate every 15 s. The heart rate level during a golf round not using electric cart reached an exercise intensity of 50–85% of maximum heart rate reserve, which was defined as the difference between baseline and maximum heart rate attained during a test to volitional exhaustion on a cycle ergometer. Thus, the investigators suggested that repeated golf practice could be beneficial to the cardiovascular system.

Good postural control is believed to be necessary in maintaining appropriate trunk position throughout a golf swing. This is because poor postural control will affect the swing action, shoulder turn, weight shift, as well as force transfer leading to inaccurate shots (Draovitch and Westcott 1999). Shatil and Garland (2000) prescribed a therapeutic golf program for patients suffering from stroke. The authors postulated that the therapeutic effect might come from golf training which included midline postural alignment, trunk rotation with large shoulder girdles movement, weight shifting and hand-eye coordination. However, no data is available to evaluate the effectiveness of this golf program.

In sum, golfing requires coordinated trunk and arm movements and controlled weight shifting during precise golf swings, as well as prolonged walking over uneven ground such as a hilly course (Selicki and Segall 1996). All of these could be said to culminate in a good balance training regime. However, there has been a lack of research into the effects of golfing on sensory, motor and integrative postural control.

The present thesis consist of 5 studies aimed at investigating the extent to which Tai Chi – an ancient Chinese exercise grounded in martial arts (Lavery and Studenski 2003; Tsao 1995), could improve the sensory, motor and integrative postural control in the elderly subjects. The rationale and objectives of each study will be presented here and in the following 5 chapters. It is hoped that these results will contribute to the design of a fall-prevention program for the progressively aging population.

1.8 Rationale and objectives

Study 1: Effects of Tai Chi on joint proprioception and stability limits in elderly subjects

Rationale. Limb proprioception has been found to diminish with age. Yan and Hui-Chan (2000) showed that the joint detection threshold was 50% higher in older subjects (aged 57–77 years) than young subjects (aged 25–35 years) for both knee flexion and extension. In view of the finding that elderly faller manifest significantly reduced proprioception in their lower limbs (Lord et al. 1999), it becomes important to determine whether Tai Chi practice, which puts great emphasis on exact joint positions, could improve joint proprioception in the lower limbs of elderly subjects.

With regard to balance control, impaired balance performance has been identified as a major factor that causes falls in the elderly (Berg and Kairy 2002). More specifically, the ability to control intentional movements of the center of gravity in different directions has been found to be important in the performance of various functional activities involving weight transfer between the two legs (Topp et al. 1998). Since Tai Chi practice involves precisely controlled weight transfer during voluntary shifting of the body in double-leg stance, and from double- to single-leg stance (Tsao 1995), such a demand for precise balance control during Tai Chi practice could have helped elderly subjects to attain better limits of stability during weight shifting in stance.

Limb proprioception is known to be essential for the generation of smooth and coordinated movements, maintenance of normal body posture, and motor learning and relearning (Gardner et al. 2000). Therefore, it becomes important to determine whether a systematic relationship exists between knee joint proprioception and balance control.

Objective 1. To examine whether experienced elderly Tai Chi practitioners have developed better knee joint proprioception than elderly healthy control subjects similar in age, gender and physical activity level.

Objective 2. To compare the control of body sway during static standing and the limits of stability during intentional weight shifting within the base of support between the two elderly groups.

Objective 3. To investigate whether any relationship existed between knee joint proprioception on the one hand, and static standing and the limits of stability during voluntary weight shifting on the other.

The study on "Effects of Tai Chi on joint proprioception and stability limits in elderly subjects" will be presented in Chapter 2.

Study 2: Effects of Tai Chi on standing balance control under reduced or conflicting sensory conditions

Rationale. Prior to any movement, all the information gathered from the sensory systems responsible for balance control – namely somatosensory, visual and vestibular systems, will be organized and integrated by the central nervous system (Gardner et al. 2000). Therefore, deficits in any or all of the three sensory systems, as well as in the process of selecting and integrating appropriate sensory information will increase the likelihood of falls in the elderly. Many Tai Chi forms require practitioners to focus their eyes on their hand movement by rotating their head and/or trunk. In other words, practicing Tai Chi involves limb, head and trunk movements that will stimulate the somatosensory, visual and vestibular systems. Hence, long-termed repeated Tai Chi practice may improve balance control of the practitioners when they stand under reduced or conflicting somatosensory, visual, and vestibular conditions. If so, would the balance performance of these elderly practitioners be comparable to that of young, healthy subjects?

Objective. To investigate the effects of Tai Chi practice on balance control when elderly Tai Chi practitioners stand under reduced or conflicting somatosensory, visual and vestibular conditions, as compared with elderly and young control subjects.

The study on "Effects of Tai Chi on standing balance control under reduced or conflicting sensory conditions" will be presented in Chapter 3.

Study 3: Effects of Tai Chi on knee muscles, perturbed stance and balance confidence in elderly

Good balance control during functional activities requires sufficient strength of the agonist and antagonist muscles across the joints (Wolfson et al. 1995). Tai Chi is performed with the knees bent most of the time. It requires both concentric and eccentric contractions of the leg muscles, especially those of the knee. Tai Chi is also performed in a closed kinetic chain position in which the knee extensors and flexors co-contract to stabilize and control knee movements (Kannus 1994). Therefore, long-term practice of Tai Chi may enhance the strength of both knee agonist and antagonist muscles.

Falls seldom occur during double-leg stance, as the center of mass is well within the base of support. Thus, evaluation of balance control confined to double-leg stance may not reflect the functional capability required of elderly people in certain activities of daily living. Practice of Tai Chi requires constant shifting between double-leg and single-leg stance (Tsao 1995). This requirement could improve balance control in single-leg stance under less stable conditions, such as when stepping onto a moving support platform.

Better knee muscle strength and balance control during perturbed single-leg stance may enhance elderly subjects' balance confidence, which has been shown to be an important indicator of functional mobility and independence in older adults (Myers et al. 1998). Therefore, it is important to determine the relationship between knee muscle strength on the one hand and balance control as well as balance confidence on the other.

Objective 1. To examine whether, at lower isokinetic speed, elderly Tai Chi practitioners had developed better concentric and eccentric knee extensor and flexor strength than elderly healthy control subjects, and whether the increase in strength of the agonist and antagonist muscles was to a similar or different extent.

Objective 2. To compare the control of body sway between the elderly Tai Chi practitioners and control subjects during both static double-leg stance and single-leg stance subjected to anteroposterior platform perturbations.

Objective 3. To investigate whether repeated practice of Tai Chi could improve the elderly practitioners' subjective report of balance confidence.

Objective 4. To investigate whether or not any relationship existed between knee muscle strength on the one hand, and 1) control of body sway in static double-leg stance, 2) control of body sway in perturbed single-leg stance, and 3) balance confidence on the other.

The study on "Effects of Tai Chi on knee muscles, perturbed stance and balance confidence in elderly" will be presented in Chapter 4.

Study 4: Effects of 4- and 8-weeks intensive Tai Chi training on balance control in the elderly

Rationale. Long-term Tai Chi training has been shown to improve balance control in elderly subjects (Hong et al. 2000; Tse and Bailey 1992; Wong et al. 2001). However, these studies employed a cross-sectional design. As such, the improved balance control could have been attributed to factors other than long-term Tai Chi practice. For instance, it could be argued that these Tai Chi practitioners already had better balance control before they took up Tai Chi practice. To circumvent the possibility of sample bias, a control trial with a prospective design is needed. Quite aside from the design issue mentioned above, most if not all of the cross-sectional studies have examined Tai Chi practitioners with from 1 to over 10 years of experience (Hong et al. 2000; Tse and Bailey 1992). In considering Tai Chi training as a possible falls-prevention strategy, a question naturally arises. How long will it take practicing Tai Chi for the elderly subjects to achieve significantly better balance control than their sedentary counterparts?

Objective 1. To investigate the effects of short-term (8 weeks of) intensive Tai Chi training on the balance performance of elderly subjects, by comparing their outcome measures with 1) those of a control group receiving general education for a comparable time period, and 2) those of practitioners who had practiced Tai Chi for a year or longer.

Objective 2. In order to map out the time course of the effects of this intensive Tai Chi training program on balance control, we conducted assessments at 4 time intervals: before, at 4-week intervals during the 8 weeks of training, and at 4 weeks after the training had ended.

The study on "Effects of 4- and 8-weeks intensive Tai Chi training on balance control in the elderly" will be presented in Chapter 5.

Study 5: Effects of exercise on joint sense and balance in elderly men: Tai Chi versus Golf

Rationale. Elderly fallers were found to have significantly reduced proprioception in their lower limbs (Lord et al. 1999) and impaired balance control (Berg and Kairy 2002). It therefore becomes important to determine whether exercise could help improve limb proprioception and balance control in the elderly. Since the practice of Tai Chi requires precise control of joint position and weight shifting in standing, repeated practice could enhance the knee joint proprioception and stability limits. If the knee proprioception and balance control are improved, it is not known these were comparable to those in young, healthy subjects. Also, is improvement in knee joint proprioception and stability limits specific only to Tai Chi training? What about other sports such as golf which also demands accurate knee joint positioning and weight shifting during golf swings? Finally, since joint afferents are known to contribute to the control of balance (Horak and Macpherson 1996), it is also important to determine if any relationship exists between knee joint proprioception and balance control as a result of long-term Tai Chi and golf practices.

Objective 1. To examine whether male elderly Tai Chi practitioners have improved their knee joint proprioception and control of their limits of stability more than elderly healthy control subjects and to levels comparable to those of young university students.

Objective 2. To determine the specificity of Tai Chi on knee joint proprioception and control of limits of stability, by comparing these parameters in experienced elderly Tai Chi practitioners with those of elderly golfers and elderly healthy control subjects.

Objective 3. To investigate if any relationship exists between knee joint proprioception and limits of stability during voluntary weight shifting through a correlation study with the 3 groups of male elderly Tai Chi practitioners, golfers and healthy elderly control subjects.

Study on "Effects of exercise on joint sense and balance in elderly men: Tai Chi versus Golf" will be presented in Chapter 6.

The main findings of the 5 studies are highlighted in Chapter 7, where the summary of original contributions are reiterated and synthesized to make some recommendations for future research.

CHAPTER 2

EFFECTS OF TAI CHI ON JOINT PROPRIOCEPTION AND STABILITY LIMITS IN ELDERLY SUBJECTS

Publication

TSANG, W. W. N., and C. W. Y. HUI-CHAN. Effects of Tai Chi on joint proprioception and stability limits in elderly subjects. *Med. Sci. Sports Exerc.* 35:1962-1971, 2003.

Conference abstract

TSANG, W. W. N., and C. W. Y. HUI-CHAN. Tai Chi can improve joint proprioception in the older subjects. In *1st International Conference on Tai Chi Chuan*. Hong Kong, pp.25-27, 2001.

2.1 Abstract

Purpose: The objectives of this study were to examine whether elderly Tai Chi practitioners have developed better knee joint proprioception and standing balance control than elderly healthy control subjects.

Methods: Elderly Tai Chi and control subjects ($N = 21$ each, aged 69.4 ± SD 5.5 and 72.3 ± 6.1 years respectively) were matched with respect to age, sex and physical activity level. Passive knee joint repositioning was used to test joint proprioceptive acuity. Control of body sway during static standing and subjects' intentional weight shifting to eight different spatial limits of stability within their base of support were conducted using force platform measurements.

Results: Tai Chi practitioners were found to have better knee joint proprioceptive acuity, in that they made less absolute angle error (2.1 ± 1.2°) than control subjects (4.0 ± 3.4°, with $P = 0.023$) in passive knee joint repositioning. No significant difference was found in the anteroposterior and mediolateral body sway during static standing ($P > 0.05$). However, Tai Chi practitioners initiated voluntary weight shifting in the limits of stability test more quickly (reaction time: 0.8 ± 0.2 s for Tai Chi practitioners) than control subjects (1.1 ± 0.3 s; $P = 0.008$). Moreover, they could lean further without losing stability (maximum excursion: 5.2 ± 0.6% for Tai Chi practitioners and 4.6 ± 0.5% for control subjects; $P = 0.001$), and showed better control of their leaning trajectory (directional control: 75.9 ± 10.0% for Tai Chi practitioners and 68.5 ± 6.9% for control subjects; $P = 0.008$).

Conclusions: These results demonstrate that long-term Tai Chi practitioners had improved knee joint proprioception and expanded their limits of stability during weight shifting in stance.

Key Words: AGING, JOINT POSITION SENSE, FALLS, EXERCISE, BALANCE CONTROL

2.2 Introduction

Proprioception is a sense of position and movement of one's own limbs and body in the absence of vision, termed "limb-position sense" and "kinesthesia" respectively (Gardner et al. 2000). Limb proprioception is mediated via cutaneous receptors in the skin and proprioceptors in muscles, tendons, ligaments and joints, signaling to the central nervous system both the stationary position of a limb and the speed and direction of limb movement. These sensations are important for the generation of smooth and coordinated movements, maintenance of normal body posture, and motor learning and relearning (Gardner et al. 2000).

Limb proprioception has been found to diminish with age, ligamentous injuries and in some pathological conditions such as stroke and osteoarthritis. Skinner and co-workers (1984) found that both the threshold for detection of motion and the ability to reproduce passive knee positioning deteriorated with increasing age. Hurley and colleagues (1998) found that the elderly subjects, with a mean age of 72 years, scored significantly higher errors in an active knee repositioning test. Yan and Hui-Chan (2000) showed that the joint detection threshold was 50% higher in older subjects (aged 57–77 years) than young subjects (aged 25–35 years) for both knee flexion and extension.

Recent investigation by Lord and co-workers (1999) revealed that elderly fallers, with a mean age of 76.5 years, showed significantly reduced proprioception of the lower limb when asked to match the position of the big toe on each side by extending the knee. Similarly, Sorock and Labiner (1992) found that the frequency of first falls in the elderly subjects (average age = 79.8 years) was significantly elevated in subjects with reduced toe joint position sense.

In this connection, exercise has been found to improve the acuity of joint proprioception. Petrella and colleagues (1997) conducted a cross-sectional study to compare knee joint proprioception among young, active-old, and sedentary subjects, using an active joint repositioning test. They found that the active-old subjects, who had exercised 3x $week^{-1}$ for a period of 1 year or more, could achieve a significantly lower absolute angle error in the active knee joint repositioning test than the sedentary subjects.

Tai Chi is a Chinese mind-body exercise, which has been practiced by millions of Chinese elderly for the past 300 years. Recent studies (Lan et al. 2002) have demonstrated that the practice of Tai Chi could reduce anxiety, improve mood and self-esteem, and is beneficial to the cardiorespiratory system, muscle strength and balance. Tai Chi puts a great emphasis on the exact joint position and direction (Tsao 1995). Therefore, the repeated practice of Tai Chi might be expected to develop a heightened sense of the position of the joints. Jacobson and co-workers (1997) conducted a Tai Chi interventional program with 24 subjects, who were aged from 20 to 45 years. After 12 weeks of Tai Chi training, they found a significant improvement in the accuracy of repositioning of the glenohumeral shoulder joint at 60° of shoulder rotation in these adults.

Some investigators noted that the knee joints are often held in some degrees of flexion during certain functional activities performed by the elderly subjects (Hurley et al. 1998). Others had chosen knee joint proprioception to correlate with selected functional activities in the elderly people (Hurley et al. 1998; Lord et al. 1999). In view of the finding that elderly fallers manifested significantly reduced proprioception of the lower limb (Lord et al. 1999), it becomes important to determine whether repeated Tai Chi practice could also improve joint proprioception sense in the lower limbs of the elderly subjects. Therefore, the first objective of this study was to examine whether elderly Tai Chi practitioners have developed better knee joint proprioception than elderly control subjects.

Tai Chi practice also involves precisely controlled weight transfer in double leg stance, and weight shifting between double leg stance and single leg stance in a smooth and coordinated manner (Tsao 1995). Because the ability to control intentional movements of the center of gravity in different directions is important to the performance of various functional activities involving weight shifting between the two legs (Topp et al. 1998), the second objective of this study was to compare the control of body sway during the static standing and the limits of stability during intentional weight shifting within the base of support between the elderly Tai Chi practitioners and control subjects. The third objective was to investigate whether any relationship existed between knee joint proprioception on the one hand, and static standing and the limits of stability during voluntary weight shifting on the other.

2.3 Methods

2.3.1 Subjects and study design

Forty-two community-dwelling elderly subjects, aged 60 or older participated in this study. Twenty-one Tai Chi practitioners (12 males and 9 females, mean age = 69.4 ± 5.5 years) were recruited from the Tai Chi clubs of four Hong Kong elderly social centers. All of them had practiced Tai Chi for a minimal of 1.5 $hour \cdot week^{-1}$ for at least 3 years (mean Tai Chi experience = 10.1 ± 9.5 years). Twenty-one elderly control subjects (7 males and 14 females, mean age = 72.3 ± 6.1 years) were recruited from several community elderly centers. They had no previous experience in practicing Tai Chi, though some took morning walks or did stretching exercises. All the subjects were independent in their activities of daily living, and no walking aids were required. They were able to communicate and follow the testing procedures. Exclusion criteria were the presence of severe cognitive impairments, symptomatic cardiovascular diseases at moderate exertion level, poorly controlled hypertension or symptomatic orthostatic hypotension, the diagnosis of a stroke, Parkinson's disease, or other neurologic disorder, peripheral neuropathy of the lower extremities, crippling arthritis, and metastatic cancer. In addition, subjects with a history of falls in the past 12 months were excluded.

Clinical evaluation of the subjects included 1) a general health questionnaire, 2) Mini-Mental Status Examination, and 3) a physical activity level questionnaire. A general health questionnaire was used to screen out subjects according to the exclusion criteria. The Mini-Mental Status Examination is a measure of cognitive ability developed by Folstein and co-workers in 1975. The Chinese version of the test had been validated (Chiu et al. 1994) and was employed in the present study. The scale ranges from 0 to 30, with a score below 24 suggesting cognitive dysfunction (Chiu et al. 1994). Elderly subjects who scored below 24 were excluded from this study. The physical activity level questionnaire was a modified version of the Minnesota Leisure Time Physical Activity Questionnaire (Van Heuvelen et al. 1998). It was designed to evaluate the subjects' energy expenditure in leisure-time physical activities. The activities included household tasks, leisure and sports. They were categorized into three levels according to their metabolic equivalent (MET) status: light (intensity $\leq$ 4.0 METs), moderate (4.0 METs $<$ intensity $\leq$ 5.5 METs), and heavy activities (intensity $>$ 5.5 METs). The results were used to compare the physical activity levels between the elderly Tai Chi and control subjects. The project was approved by the Ethics Committee of the Hong Kong Polytechnic University, and written informed consent was obtained from all subjects.

2.3.2 Knee joint repositioning test procedure

The methods for testing joint proprioception include: 1) determining the lowest threshold for detecting joint movement, 2) determining joint position sense from the accuracy with which contralateral joint angles can be matched, or 3) limb segment repositioning without the aid of vision, called the "joint repositioning test". Since Tai Chi puts a great emphasis on exact joint positions and directions (Tsao 1995), the repeated practice of Tai Chi could have developed a heightened sense of the position of the lower limb (e.g., knee) joints. Therefore, a passive joint repositioning test was adopted in this study. Joint repositioning tests can be performed under either nonweight-bearing or weight-bearing conditions. The latter condition has the advantage of information being obtained in a more functional context (Bullock-Saxton et al. 2001) but involves both motor and sensory skills. In some cases, improved joint reposition sense could be due to an improvement in the performance of the motor task associated with weight bearing (Ashton-Miller et al. 2001). To avoid the motor contribution required in weight-bearing tests, the non-weight-bearing method was chosen for this study. Similarly, passive repositioning was employed here to minimize motor involvement.

The dominant leg of each elderly subject underwent the passive knee repositioning test with the set-up shown in Figure 2.1. The leg that the elderly subject used to kick a ball was defined as the dominant leg. The subject sat on the chair of a Cybex Norm dynamometer (Cybex International Inc., Ronkonkome, NY), with the hips kept at 60° of flexion. To minimize the influence of cutaneous (e.g., pressure) input, an air-splint was applied to the subject's ankle region with an air pressure of 20 mm Hg. The set-up was attached to the knee adaptor of the Cybex dynamometer, with the rotation axis in line with that of the subject's knee joint, defined using the lateral femoral epicondyle. An electrogoniometer was attached to the lateral aspect of the knee (Penny and Giles Biometric Ltd., type XM180, Blackwood, UK). The subject was blindfolded and sat so that the edge of the seat was 4–6 cm from the popliteal fossa of the knee. This ensured that both vision and cutaneous sensation were respectively occluded and minimized. The knee was passively moved to 3° of extension, from the initial position of 30° of knee flexion, at a constant velocity of approximately $3°\cdot s^{-1}$. The knee was held for 3 s once the target position was reached. It was returned to the initial position, then moved to the same target position at the same speed of $3°\cdot s^{-1}$. The initial position was chosen to be 30° of knee flexion, because the mid-range of knee flexion has been shown to be reliable for similar measurements in both healthy subjects and subjects with knee pathology (Petrella et al. 1997; Skinner et al. 1984). The slower speed of $3°\cdot s^{-1}$ was used in this study, as Tai Chi practice involves slow movement. When the subject perceived that the knee had regained the previous target position, he/she produced an audio signal by pressing on a thumb switch. The EMG activity of the thenar eminence muscles, mainly the flexor pollicis brevis of the thumb, was recorded with surface electrodes (NeuroCom International Inc., Portland, OR). The onsets of the EMG signals were used to indicate the moment when the subject perceived that the knee had regained the previously targeted position. The signals from the electrogoniometer, thumb switch, and EMG were fed into an A/D card (DataQ® Instruments Inc., type DI-720P, Akron, OH) and stored for off-line analysis. The error with which the subject reproduced the initial position was calculated. A total of three trials were performed. The three absolute error values were averaged and the average value was termed the absolute angle error.

FIGURE 2.1 – Experimental set up for the passive knee joint repositioning test. The blindfolded subject sat on the chair of a dynamometer, with its knee adaptor attached to ankle region enclosed within an air-splint. An electrogoniometer was attached to the lateral aspect of the knee. The EMG of the thenar eminence muscles was recorded, when the subject pressed on a thumb switch to signal that his/her knee had reached the target position during the passive knee joint repositioning test.

2.3.3 Static standing balance test procedure

After the knee joint repositioning test, the elderly subjects underwent a static standing balance test by standing quietly with the feet together on a force platform (Kistler, model 9286AA, Gommiswald, Switzerland) for 30 s, with their eyes open. The center of pressure (COP) in the anteroposterior and mediolateral directions during the 30-s stance were recorded. The COP trajectory with respect to height, termed normalized COP, was used to compare the balance performance of the two elderly groups.

2.3.4 Limits of stability test procedure

After the static standing balance test, the elderly subjects underwent a dynamic standing balance test. This measures the subjects' intentional weight shifting to different directions within their base of support and their ability to briefly maintain stability in these positions. An EquiTest® Computerized Dynamic Posturography unit (NeuroCom International Inc., type Smart EquiTest®) was employed to record displacements of the COP during the test (Fig. 2.2). The Smart EquiTest® consists of dual force platforms and a screen on which the current normalized COP was continuously displayed. The initial normalized COP was displayed in the center together with eight target positions on the screen. These were front, right front, right, right back, back, left back, left, and left front. The locations of the eight target positions appeared the same for each subject on the screen, but he/she had to weight shift to achieve their 100% limits of stability (NeuroCom 2000). The subject's task was to move the normalized COP trace to one of the eight randomly selected target positions as quickly and smoothly as possible, through shifting of their center of mass (COM) within their base of support and without moving their feet.

Three outcome measures: reaction time, maximum excursion, and directional control were used to assess dynamic balance control. Reaction time is defined as the time between the presentation of a visual cue (response signal) to the initiation of voluntary shifting of the subject's COM toward the target location. Maximum excursion measures the maximum displacement of the normalized COP within the subject's theoretic limits of stability. The limits of stability (LOS) define the region in space through which a subject can move his/her body without altering the base of support. If the body passes the LOS boundary, a step will occur to reestablish a new base of support, or else a fall will occur (Nashner 1993b). Directional control measures the smoothness of the displacement of the normalized COP to the target positions. For more detailed recording and calculation of these 3 outcome measures, please refer to the appropriate paragraphs in the section below. The subject's task was to move his/her body as fast, as smoothly and as far as possible to one of the eight randomly preselected target positions located at 100% of his/her LOS. For each target position, one trial was performed. There were familiarization trials to each target position before data recording to ensure that subjects understood how to weight shift to the target positions.

FIGURE 2.2 – Experimental set up for the limits of stability test. Subject stood on the force platform of a computerized dynamic posturography unit. The screen in front showed the eight target positions and the subject's normalized COP trace. The subject's task was to move his/her body so that the normalized COP trace was displaced to one of the eight randomly pre-selected target positions.

2.3.5 Data recording and analysis

2.3.5.1 Knee joint repositioning test

EMG onset time was used to determine the joint angle perceived by the subject during repositioning of the knee joint. The EMG signals of the thenar eminence muscles, mainly the flexor pollicis brevis, were sampled at a rate of 1000Hz, filtered with a bandwidth of 10–500 Hz, and amplified with a gain of 4048. They were full-wave rectified. EMG onset was determined by the time when EMG activity was >3 standard deviations above the baseline. We chose EMG onset time as the moment at which the perceived target position was determined, as variations ranging from 47 to 568 ms (corresponding to 0.14–1.7° with a movement speed of $3°\cdot s^{-1}$) were found between EMG onset and thumb switch signals in our pilot study. This approach served to minimize the error that could have arisen from the thumb pressing on the switch at slightly different locations and/or with slightly different forces.

2.3.5.2 Static standing balance test

The COP, as measured by four sensors attached to the force platform, was recorded. The normalized COP was used to compare the static standing balance of the two elderly groups in the anteroposterior and mediolateral directions during the 30 s of quiet standing.

2.3.5.3 Limits of stability test

All the data from EquiTest® Computerized Dynamic Posturography were smoothed, using second order Butterworth low pass filter with a cutoff frequency of 0.85 Hz, and were used for calculation of the following outcome measures.

1) Reaction time. The reaction time was measured from the presentation of a visual cue (response signal), denoted by the appearance of a blue circle in the target position, to the onset of the voluntary shifting of the COM toward the target position. The onset of a subject's voluntary shifting was defined as the time when the normalized COP exceeded the peak amplitude of the normalized COP recorded over a 2 s control period before the response signal (NeuroCom 2000).

2) Maximum excursion. The subjects leaned as far as possible to one of the eight randomly selected spatial target positions, located at 100% of their LOS. The maximum distance traveled by the normalized COP was measured by the four sensors attached to the support surface of the EquiTest® machine. The average value of the maximum excursions to the 8 directions was used to compare the balance performance between the two elderly groups.

3) Directional control. The directional control is defined as a comparison of the amount of movement of normalized COP in the on-target direction (toward the target) to the amount of off-target direction (away from the target). Its value was computed as the difference between the amount of on-target movement and that of the off-target movement of the normalized COP, expressed as a percentage of the total on-target movement as follows (NeuroCom 2000):

$$\frac{\text{(amount of on-target movement)} - \text{(amount of off-target movement)}}{\text{(amount of on-target movement)}} \cdot 100\% \quad [2]$$

A straight-line path means no off-target movement and the directional control score will be 100%. The algorithm provided by the computerized dynamic posturography equipment was employed to determine the directional control.

2.3.6 Statistical analysis

Independent t-tests were conducted to compare the demographic data describing the two elderly groups, namely age, weight, and height. Due to the categorical nature of the variables for gender and physical activity levels, Chi-square test was used for between-group comparison. ANCOVA model with gender and group as fixed factors was used to investigate the effect of gender on the outcome measures and across the two groups. To ensure data reliability, the intraclass correlation coefficient, model ICC(3,k), was employed to assess the test-retest reliability of the knee joint repositioning test and the static standing and limits of stability tests. The ICC model 3 was used for assessing intra-rater reliability, with "k" denoting the number of trials used in the different tests. For between-group comparison of the knee joint repositioning test, an independent t-test was employed. Multivariate analysis of variance was used to compare the outcome measures recorded during static standing and limits of stability tests between the elderly Tai Chi and control subjects. If statistically significant differences were found in the multivariate tests, univariate tests were conducted for each of the outcome measures of the balance control tests. A Pearson product-moment coefficient of correlation was used to correlate the absolute angle error obtained in the knee joint repositioning test, with 1) normalized COP in anteroposterior and mediolateral directions in the static standing balance test and 2) reaction time, maximum excursion, and directional control of the normalized COP in the limits of stability tests. A significance level (α) of 0.05 was chosen for the statistical comparisons.

2.4 Results

2.4.1 Subjects

Forty-two community-dwelling elderly subjects, 21 Tai Chi and 21 control, aged 60 or older, participated in this study. Relevant demographic data are shown in Table 2.1. Independent t-tests showed that there was no statistically significant difference in the age, height, and weight ($P > 0.05$; Table 2.1) between elderly Tai Chi and control subjects. Chi-square tests found no statistically significant between-group difference in gender and physical activity levels ($P > 0.05$; Table 2.1). Also, all the elderly subjects had a Mini-Mental Status Examination score above 24, thus showing the absence of cognitive impairment (Chiu et al. 1994). The Tai Chi and control subjects were thus similar with respect to age, height, weight, gender, physical activity levels and Mini-Mental Status Examination score. The ANCOVA model showed no gender difference in passive knee joint repositioning, static standing and limits of stability tests. The gender effect was consistent across the two groups of elderly subjects (all $P > 0.05$; Table 2.2). Therefore, data from male and female subjects in both groups were combined for between-group comparison.

2.4.2 Test-retest reliability of the knee joint repositioning test and the two standing balance tests

Eleven elderly subjects, seven Tai Chi practitioners and four control subjects, were recruited for the test-retest reliability trials. They were four males and seven females with a mean age of 70.8 years (± S.D. 4.0 years). After administering the knee joint repositioning test and the two standing balance tests, the procedure was repeated 1 week later.

The ICC(3,3) value for the absolute angle error of the knee joint repositioning test was found to be 0.90 (confidence intervals 0.64–0.97), which indicated excellent reliability. For the static standing balance test, the ICC(3,3) values for the normalized COP in anteroposterior and mediolateral directions were 0.83 (confidence intervals 0.23–0.96) and 0.85 (confidence intervals 0.22–0.97) respectively, which indicated satisfactory reliability. For the limits of stability test, the ICC(3,8) values for the reaction time, maximum excursion, and directional control were 0.82 (confidence intervals 0.29–0.96), 0.93 (confidence intervals 0.72–0.98), and 0.83 (confidence intervals 0.30–0.96) respectively, which also indicated satisfactory reliability.

TABLE 2.1. Comparison of age, height, body weight, gender and physical activity level between elderly Tai Chi and control subjects.

	Tai Chi subjects (*N* = 21)	**Control subjects (*N* = 21)**	***P***
Age (years)	69.4 ± 5.5	72.3 ± 6.1	0.120
Height (cm)	157.2 ± 8.6	153.5 ± 9.6	0.190
Body Weight (kg)	59.9 ± 7.7	57.1 ± 8.8	0.270
Gender (male/female)	12 / 9	7 / 14	0.121
Physical activity levels			0.132
Light ≤ 4 METs	*N* = 14	*N* = 19	
Moderate ≤ 5.5 METs	*N* = 5	*N* = 2	
Heavy > 5.5 METs	*N* = 2	*N* = 0	

NOTE: Values are mean ± SD for this and all subsequent tables

TABLE 2.2. Compare the effect of gender on the outcome measures and across the two elderly groups.

	Gender *P*	Gender x group *P*
Passive knee joint repositioning test	0.773	0.629
Static standing test	0.672	0.401
Limits of stability test	0.166	0.930

"x" Denotes interaction between gender and group variables.

2.4.3 Knee joint repositioning test

The Tai Chi practitioners exhibited significantly less absolute angle error in the knee joint repositioning test than the control elderly, being 2.1 ± 1.2° and 4.0 ± 3.4° respectively ($P = 0.023$). In other words, the control subjects had approximately twice the angle error of the Tai Chi subjects. This finding suggests that the Tai Chi subjects had more acute joint proprioception in their dominant knee joint than the control subjects.

2.4.4 Static standing and limits of stability balance tests

The multivariate tests of the static standing balance results showed no significant difference between the Tai Chi and control subjects (P = 0.290). The mean normalized COP in the anteroposterior direction for the Tai Chi and control subjects were 1.6 ± 0.4% and 1.7 ± 0.5% respectively (P = 0.423; Table 2.3). The mean normalized COP in the mediolateral direction were 1.4 ± 0.3% and 1.6 ± 0.5% respectively (P = 0.139; Table 2.3). In other words, the Tai Chi and control subjects performed equally well in the static standing balance test, as measured by normalized COP in anteroposterior and mediolateral directions.

The multivariate tests for the limits of stability indicated an overall statistically significant effect across the three outcome measures between the Tai Chi and control subjects (P = 0.005). The univariate tests showed that there were statistically significant differences in the reaction time (P = 0.008; Table 2.3), maximum excursion (P = 0.001), and directional control of the normalized COP (P = 0.008) between the two elderly groups. The Tai Chi practitioners achieved shorter reaction times when leaning to the different target positions (mean = 0.8 ± 0.2 s) than the control subjects (mean = 1.1 ± 0.3 s; P = 0.008; Table 2.3). Moreover, they could lean further toward the eight target positions within their limits of stability (mean = 5.2 ± 0.6%) than the control subjects (mean = 4.6 ± 0.5%; P = 0.001; Table 2.3). They could also travel to the target positions through a smoother pathway (mean directional control = 75.9 ± 10.0%) than the control subjects (mean = 68.5 ± 6.9%; P = 0.008; Table 2.3). In sum, the Tai Chi practitioners attained better limits of stability balance control than the control subjects, with regard to their reaction time, maximum excursion and directional control of their normalized COP.

TABLE 2.3. Comparison of static standing and limits of stability tests between elderly Tai Chi and control subjects.

	Tai Chi subjects ($N = 21$)	**Control subjects** ($N = 21$)	P
Static standing balance test			
Normalized COP (%) in anteroposterior direction	1.6 ± 0.4	1.7 ± 0.5	0.423
Normalized COP (%) in mediolateral direction	1.4 ± 0.3	1.6 ± 0.5	0.139
Limits of stability test			
Reaction time (s)	0.8 ± 0.2	1.1 ± 0.3	0.008**
Maximum excursion (%)	5.2 ± 0.6	4.6 ± 0.5	0.001**
Direction control (%)	75.9 ±10.0	68.5 ± 6.9	0.008**

** Denotes significant difference at $P < 0.01$ using univariate tests, after multivariate tests showing an overall statistically significant difference at $P = 0.005$.

2.4.5 Correlation of the absolute angle error with the static standing and limits of stability results

Correlation between the absolute angle error in the knee joint repositioning test, and the outcome measures obtained in both elderly groups from the static standing balance test (normalized COP in anteroposterior and mediolateral directions), and from the limits of stability test (reaction time, maximum excursion and directional control) were analyzed using Pearson's product-moment coefficient of correlation. The absolute angle error was not statistically correlated with the normalized COP in anteroposterior and mediolateral directions in the static standing balance test (normalized COP in anteroposterior direction: r = -0.083, P = 0.604; normalized COP in mediolateral direction: r = -0.059, P = 0.710; Table 2.4). However, it was correlated with the reaction time (r = 0.572; P < 0.001; Table 2.4 and Fig. 2.3a). Subjects who exhibited larger knee joint repositioning errors required more time, on average, to initiate a voluntary response in moving their body toward the eight spatial targets. Furthermore, the absolute angle error was inversely correlated with the averaged value of the maximum excursion of the normalized COP to the eight target positions (r = -0.340; P = 0.034; Table 2.4 and Fig. 2.3b). That is to say, subjects exhibiting larger joint repositioning errors, on average, displayed smaller averaged maximum excursions to the eight test positions. No statistically significant correlation was found between the absolute angle error and directional control of the normalized COP as measured by the averaged value of the eight target directions (r = -0.253; P = 0.119; Table 2.4). Subsequent correlation analysis was performed for each of the eight target directions individually. The results showed a significant inverse correlation between the absolute angle error and directional control in the front direction (r = -0.495; P = 0.001) and the left front direction (r = -0.388; P = 0.011). In other words, subjects with larger absolute angle error showed less control, on average, in shifting their COM to the front and left front target positions.

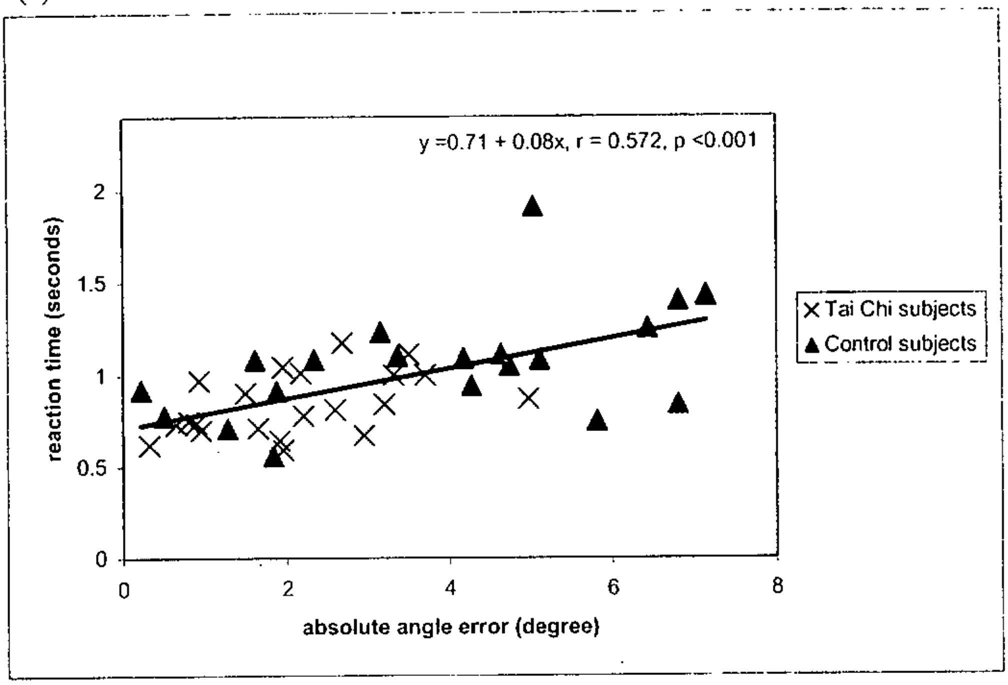
TABLE 2.4. Pearson product-moment coefficient of correlation between the absolute angle error and the outcome measures of the static standing and limits of stability test.

	Correlation coefficients ($N = 42$)	***P***
Static standing balance test		
Normalized COP in anteroposterior direction	-0.083	0.604
Normalized COP in mediolateral direction	-0.059	0.710
Limits of stability test		
Reaction time	0.572	0.000†
Maximum excursion	-0.340	0.034*
Directional control	-0.253	0.119

* Denotes significant difference at $P < 0.05$ using Pearson product-moment coefficient of correlation.

† Denotes significant difference at $P < 0.001$ using Pearson product-moment coefficient of correlation.

(a) Reaction time



(b) Maximum excursion

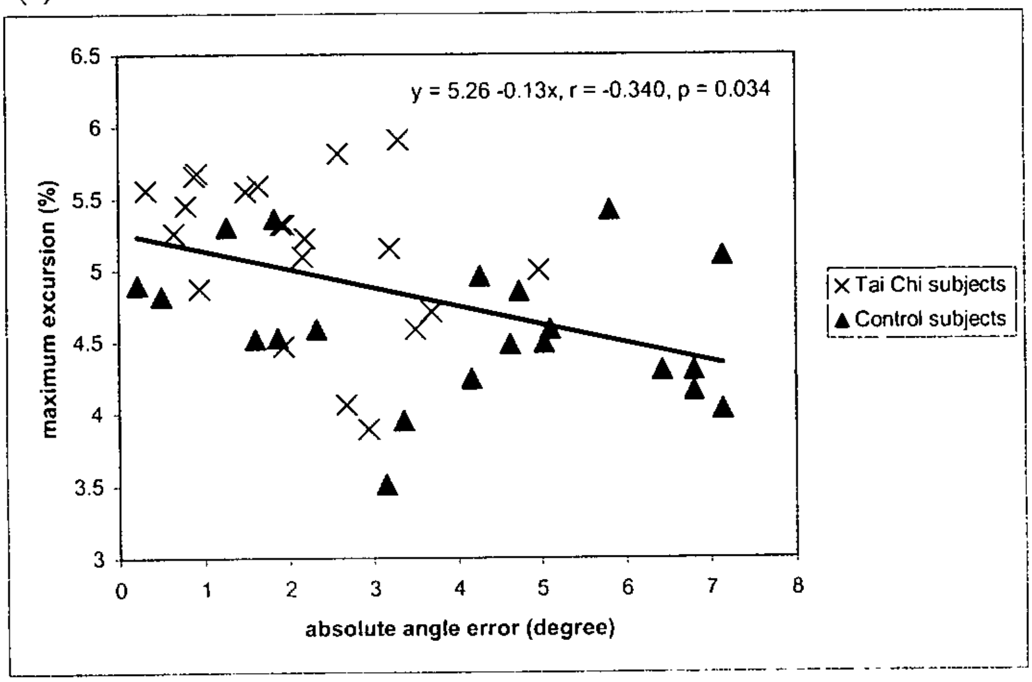


FIGURE 2.3 – Diagrams plotting (a) reaction time and (b) maximum excursion of the normalized COP against absolute angle error obtained from the passive knee joint repositioning test.

2.5 Discussion

2.5.1 Reliability of the knee joint repositioning test and the two standing balance tests

The reliability study showed that the knee joint repositioning test was highly repeatable when the same 11 subjects were tested 1 week apart (ICC = 0.90; confidence intervals 0.64 to 0.97). Kramer and colleagues (1997) conducted a reliability study on a group of young subjects, mean age of 25 years, using a nonweight-bearing knee proprioception test. They found that the test-retest reliability correlation coefficients ranged from 0.17 to 0.79 and the between-session measurement of joint angle error varied widely even in young subjects. In their protocol, subjects were asked to read the knee angle of the target position as shown by a goniometer meter, and to replicate the same knee angle with their eyes closed. The difficulty in mental transfer of the visual reading to joint repositioning may explain the low repeatability obtained in that study. Petrella and colleagues (1997) studied the reliability of the knee joint repositioning test with subjects in a standing position. The test-retest reliability correlation coefficients (r) for sedentary older subjects (r = 0.50) were lower than those of active older (r = 0.79) and young subjects (r = 0.89). The comparatively lower reliability scores obtained by the sedentary older subjects may be explained by their postural stability being poorer than that of the young subjects, when they had to perform the joint repositioning test in a standing position (Shumway-Cook and Woollacott 2001). The high reliability of the knee joint repositioning test achieved in our study can be attributed to the well-controlled test parameters with the methodology used. This included keeping the initial joint position, as well as the amount, speed and direction of joint movement constant. All these parameters are known to modulate the discharges of the joint proprioceptors, which will in turn influence the accuracy of joint repositioning (Gardner et al. 2000).

The ICC for the static standing and the dynamic limits of stability balance tests ranged from 0.82 to 0.93, which were considered satisfactory. The reliability results for the limits of stability test were similar to those of Clark and colleagues (1997), who had examined data repeatability in a group of healthy older subjects with no recent history of falls.

2.5.2 Effect of Tai Chi practice on knee joint repositioning sense

The elderly Tai Chi practitioners achieved a statistically significantly smaller knee angle error (mean = 2.1 ± 1.2°) when compared with the control subjects (mean = 4.0 ± 3.4°; P = 0.023). This result demonstrated that Tai Chi practitioners had indeed developed a heightened sense of knee joint proprioception.

Tai Chi practice consists of slow movements performed sequentially, which requires the body and limb joints to be placed in specific positions relative to each other and to space (Tsao 1995). The need for exact joint position and movement direction during repeated Tai Chi practice could have improved knee joint position sense in the elderly practitioners with mean Tai Chi experience of 10.1 ± 9.5 years in our study. Such positive findings in the knee joint proprioception acuity of elderly Tai Chi practitioners are in accord with those of Jacobson and colleagues (1997), who found an improvement in the accuracy of glenohumeral joint repositioning in younger subjects after 12 weeks of Tai Chi training.

Previous investigations have shown that exercise can improve joint proprioception sense in the young (Jacobson et al. 1997) and in older subjects (Petrella et al. 1997), but the exact mechanism through which exercise can improve joint proprioception is still unclear (Ashton-Miller et al. 2001). Petrella and colleagues (1997) postulated that the improvement in muscle strength with exercise might yield better control of movement, which, as a consequence, could enhance joint proprioception under weight bearing conditions. However, improved muscle strength cannot explain our findings, since a "passive" joint repositioning test was adopted in this study, which required no active muscle contraction.

A proposed mechanism for the improvement of joint proprioception by long-term Tai Chi practice could be the plastic changes induced in the cortex, by repeated positioning of body and limb joints in specific spatial positions as demanded by the various Tai Chi forms. Repetitive afferent inputs from the cutaneous receptors in the skin and the limb proprioceptors including muscle spindles could modify the cortical maps of the body over time. More specifically, studies in both monkeys and man have demonstrated that the internal representation of cortical maps of the body surface are modifiable by experience and training (Jenkins et al. 1990; Mogilner et al. 1993). As reviewed in Chapter 1 (section 1.5.2), Jenkins and colleagues (1990) showed that several months of practice with a repeated touch task, in which monkeys used their middle fingers to obtain food, could greatly expanded the middle finger's representation in the cortex, as measured by evoked potentials. Mogilner and colleagues (1993) employed magnetoencephalography and found that the cortical representation of the human hand area can be modified after surgical separation in subjects with congenital fusion of the fingers. For example, the distance between sites of cortical representation of the thumb and little finger had increased significantly 26 days after their surgical separation. Along a similar line of thought, repeated practice of Tai Chi over time could have increased cortical representation of the knee joints leading to enhanced knee joint proprioception.

A second possible mechanism for the improvement of joint proprioception by Tai Chi could be through increased output of the muscle spindles through the so-called γ route during voluntary movement (Ashton-Miller et al. 2001; Granit 1970). Muscle spindle activities can be increased during activities such as the Jendrassic maneuver, mental computation and the sound of hand clapping, as shown by direct measurement of fusimotor (termed also gamma) neuronal activity in human subjects (Ribot et al. 1986). Increased muscle spindle output through the γ route may occur during the voluntary movements of Tai Chi (Granit 1970), to enhance knee joint proprioception by facilitating its cortical projection. In this connection, repeated practice of a motor skill is thought to increase muscle spindle output, which could bring about plastic changes in the central nervous system, such as an increased strength of synaptic connections and/or structural changes in the organization and numbers of connections among neurons (Shumway-Cook and Woollacott 2001). This may explain why the acuity of passive knee joint repositioning was greater in the elderly Tai Chi practitioners.

2.5.3 Static standing and the limits of stability balance control

The static standing balance test showed that balance performance was similar between the elderly Tai Chi and control subjects, as evidenced by the lack of significant difference in the normalized COP in anteroposterior and mediolateral directions between groups, being $P = 0.423$ and $P = 0.139$ respectively (Table 2.3).

In contrast, in the limits of stability test, the elderly Tai Chi practitioners were able to achieve significantly better reaction times (*P* = 0.008; Table 2.3), as well as maximum excursions (*P* = 0.001) and directional control (*P* = 0.008) of their normalized COP. The results were similar to those of our previous study in which healthy elderly subjects stood under reduced or conflicting somatosensory, visual and vestibular conditions (Tsang et al. 2001). In that study, no significant difference in the maximum anteroposterior body sway was found between elderly Tai Chi and control subjects, when somatosensory and vestibular inputs were available. However, when the subjects had to increase their reliance on the visual and vestibular systems to maintain their standing balance, the Tai Chi practitioners showed significantly less anteroposterior body sway than the control subjects (Tsang et al. 2001). In the present study, the dynamic balance test required the elderly subjects to lean as fast, as smoothly, and as far possible to the eight targets located at 100% of their LOS. The better balance performance of the Tai Chi practitioners in three outcome measures from the limits of stability balance test reveals that repeated Tai Chi practice could improve dynamic balance control, under self-initiated shifting of the COM to different spatial targets within their base of support.

In Tai Chi practice, the practitioners are required to shift their body weight to different target positions in a smooth and coordinated manner. This requirement constantly challenges the balance control system to maintain the subject's COM within the base of support, when it is being shifted to the subjects' limits of stability. Such a repetitive demand for balance control during Tai Chi practice for a mean of 10.1 (± 9.5) years probably explains why the Tai Chi practitioners attained better maximum excursion and directional control than the control subjects. The reaction time in initiating movement depends on both neuromuscular control and cognitive factors (Shumway-Cook and Woollacott 2001). Improved muscle strength (Lan et al. 2002) and better balance control to stabilize the body in advance of potentially destabilizing movements (Tsang et al. 2001) might explain why the Tai Chi practitioners had a shorter reaction time in the voluntary leaning of their body to the eight target positions.

Studies have shown that the limits of stability can be used as a significant predictor of performance in functional activities, such as crossing a street, getting onto a bus and climbing a flight of 27 stairs (Topp et al. 1998). It also plays a significant role in indicating susceptibility to falls (Girardi et al. 2001). Since our study showed that long-term Tai Chi practitioners achieved greater limits of stability, they are likely to have relevant functional activities enhanced and/or possible occurrence of falls minimized. Indeed, Wolf and colleagues (1996) found that the risk of multiple falls was reduced by 47.5% in the elderly Tai Chi practitioners.

2.5.4 Correlation between knee joint position sense and balance control

The absolute angle errors in the knee repositioning test were not correlated with body sway measures in the static standing balance test. However, larger absolute angle errors were associated with slower reaction time and smaller movement of the normalized COP in the LOS test (Table 2.4). Lord and colleagues (1999) correlated the mediolateral body sway in a near-tandem stability test with the eyes open, with the knee angle error in a limb matching test, and found the correlation to be low ($r = 0.19$, $P < 0.05$). When using more dynamic balance tests, Hurley and colleagues (1998) found a higher correlation ($r = -0.535$; $P < 0.001$), in which the time to complete several functional tasks (such as walking, get-up-and-go, ascending and descending stairs) increased as the acuity of joint position sense decreased. These findings and those of the present study suggest that knee joint proprioception is more important in the control of dynamic than static standing balance, as required in some functional activities involving weight shifting, than in static standing balance.

The positive correlation (r = 0.572, $P < 0.001$; Table 2.4 and Fig. 2.3a) between the absolute angle error and the reaction time indicates that the elderly subjects produced quicker postural responses to a visual stimulus, if they had a greater acuity of knee proprioception. Lord and Fitzpatrick (2001) measured the reaction times of a group of older subjects, aged from 62 to 95 years, by asking the subjects to step on one of four targets as quickly as possible when it was illuminated. They found that subjects with a history of falls had significantly increased reaction time when compared with non-fallers. The present study demonstrated that the improved knee joint proprioception of the Tai Chi practitioners was associated with a shorter reaction time in the limits of stability test. The latter could explain the reduction in the risk of multiple falls by 47.5% in the elderly Tai Chi practitioners, as reported earlier to be shown by Wolf and colleagues (1996).

Our results further demonstrated that the absolute angle error of knee joint repositioning was inversely correlated with the maximum excursion of the normalized COP in the LOS test (r = -0.340, $P = 0.034$, Table 2.4 and Fig. 2.3b). In other words, subjects who had better acuity of the knee joint position sense were able to expand their limits of stability. Previous studies have shown that the limits of stability decreased with age (King et al. 1994) and played a significant role in predicting multiple falls (Girardi et al. 2001). Our finding of a significant correlation between the improved knee joint proprioception (reduced repositioning error) and increased excursion of the normalized COP in the LOS test, may explain why Tai

Chi practice has been shown to reduce the fear of falling and the risk of multiple falls in the elderly population (Wolf et al. 1996).

2.6 Conclusions

In conclusion, our present study provides evidence that elderly subjects, who have practiced Tai Chi for 10.1 (± 9.5) years, have better knee joint proprioception and greater limits of stability than age-, gender- and physical activity level-matched control subjects. Our finding of a positive correlation between the absolute angle error in the knee joint repositioning test and reaction time and a negative correlation with maximum excursion of the normalized COP in the limits of stability test reveals the potential importance of the accuracy of knee position sense in functional activities involving leaning or weight shifting during upright stance. We hereby propose to confirm these findings by conducting prospective intervention studies.

CHAPTER 3

EFFECTS OF TAI CHI ON STANDING BALANCE CONTROL UNDER REDUCED OR CONFLICTING SENSORY CONDITIONS

Publication

TSANG, W. W. N., V. S. W. WONG, S. N. FU, and C. W. Y. HUI-CHAN. Tai Chi improves standing balance control under reduced or conflicting sensory conditions. *Arch. Phys. Med. Rehabil.* 85:129-137, 2004.

Monograph

TSANG, W. W. N., V. WONG, and C. W. Y. HUI-CHAN. A comparison of balance control under different sensory conditions between elderly Tai Chi and non-Tai Chi practitioners. In: *Control of Posture and Gait.* J. Duysens, B. C. M. Smits-Engelsman, and H. Kingma. (Eds.). Maastricht, Netherlands: International Society for Postural and Gait Research, 2001, pp. 382-387.

3.1 Abstract

Purpose: To investigate the effects of long-term Tai Chi practice on balance control when healthy elderly Tai Chi practitioners stood under reduced or conflicting somatosensory, visual, and vestibular conditions, as compared with healthy elderly non-Tai Chi practitioners and young subjects.

Methods: Twenty elderly Tai Chi practitioners (mean experience ± standard deviation, 7.2 ± 7.2 years) were compared with 20 elderly non-Tai Chi practitioners similar in age, gender and physical activity level, as well as 20 young, healthy university students. The amplitude of anteroposterior body sway under different somatosensory, visual, and vestibular conditions was measured using computerized dynamic posturography, whereby subjects underwent 6 combinations of visual and support surface conditions.

Results: The Tai Chi practitioners had significantly better balance control than the non-Tai Chi subjects in the visual and vestibular ratios, but not in the somatosensory ratio. Furthermore, there were no significant differences in any of these 3 sensory ratios when the Tai Chi practitioners were compared with those of the young, healthy subjects.

Conclusions: Long-term Tai Chi practice improved balance control in the elderly population when there was an increased reliance on the visual and vestibular systems during stance. Of particular interest is that our elderly Tai Chi practitioners attained the same level of balance control performance as did young, healthy subjects when standing under reduced or conflicting somatosensory, visual, and vestibular conditions.

Key Words: BALALNCE, REHABILITATION, TAI CHI

3.2 Introduction

Falls are a major cause of morbidity and mortality in the elderly population (Wolter and Studenski 1996). In fact, 30% of community-dwelling older subjects over the age of 65 were reported to have fallen at least once a year (Tinetti et al. 1988). Studies have suggested that deterioration in balance control in the elderly can affect both static postural and dynamic movement equilibrium, which may lead to falls (Horak et al. 1989; Patla et al. 1990; Wolfson et al. 1996). Preventive measures to improve balance control are therefore needed to minimize falls among the elderly population.

Tai Chi has been practiced by millions of elderly Chinese for the past 300 years. Initially, it was practiced as a fighting form that emphasized strength, balance, flexibility, and speed. Over time, it evolved into a soft, slow, and gentle form of exercise that is practiced by people of all ages (Tsao 1995). It is a common belief that practicing Tai Chi can improve a person's mental and physical status (Jin 1992; Kutner et al. 1997). Some qualitative reports on the benefits of Tai Chi began to be published in China in the mid 1970s and in the Western literature in the 1980s (Van Deusen and Harlowe 1987; Zhuo et al. 1984). These initial investigations focused on joint range, cardiorespiratory, and metabolic responses (Lan et al. 1996; Van Deusen and Harlowe 1987; Zhuo et al. 1984).

Studies of Tai Chi and balance control began in the 1990s. In 1992, Tse and Bailey were the first to evaluate the influence of Tai Chi on balance control. In a cross-sectional study, they found that elderly people with more than 1 year of Tai Chi practice had better balance control than their sedentary counterparts in right and left leg standing with the eyes open. In 2000, Hong et al. found that practitioners with more than 10 years of Tai Chi experience could maintain single-leg standing with their eyes closed for a significantly longer period than non-Tai Chi practitioners.

In 1993, the Atlanta Frailty and Injuries: Cooperative Studies of Intervention Techniques (FICSIT) group evaluated 2 types of interventions, namely, Tai Chi and computerized balance training, with an education group serving as the control (Wolf et al. 1993). After 15 weeks of intervention, subjects in the Tai Chi group only had reduced their fear of falling and the risk of multiple falls by 47.5%, when compared with the education group (Wolf et al. 1996). However, these findings contradicted the objective balance measurements of the FICSIT group's subsequent study in 1997 (Wolf et al. 1997b), which showed a significantly reduced maximum sway amplitude after toe-up perturbations in the computerized balance training group, but not in the Tai Chi group. The use of toe-up perturbation as an outcome in a Tai Chi study was criticized by other researchers as being either inappropriate (Horak 1997) or not challenging enough to the balance control system (Wong et al. 2001).

In 2001, Wong et al. compared the sway amplitude of elderly Tai Chi practitioners with an active elderly group, when standing under 6 combinations of conditions: visual (eyes open, eyes closed, sway-referenced) and support surface (fixed, sway-referenced). They found that the Tai Chi practitioners swayed significantly less than did the control group in the more challenged conditions, when the somatosensory input was offset by absent or conflicting visual input. However, it is not known whether the improved performance is comparable to that found in young, healthy subjects standing under similar conditions.

Therefore, in this study, we investigated the effect of Tai Chi on balance control in people standing under reduced or conflicting somatosensory, visual, and vestibular conditions. Using computerized dynamic posturography (CDP), we compared the balance control of young, healthy subjects with that of 2 groups of elderly (aged ≥60 years) who were or were not Tai Chi practitioners.

3.3 Methods

3.3.1 Subjects and study design

Twenty young healthy subjects (12 men, 8 women; mean age = 21.5 ± 1.6 years) were recruited. All were university students who had exercised regularly for at least 2 hour·week^{-1}. Exclusion criteria were the presence of inner ear problems, dizziness, long-term medication, a history of injury within 1 year before the study, and a history of an orthopedic operation or a neurologic disease.

Forty community-dwelling elderly subjects (20 per group), aged 60 or older, participated in the study. Twenty Tai Chi practitioners (10 men, 10 women; mean age = 70.7 ± 5.1 years) were recruited from the Tai Chi clubs of 3 Hong Kong social centers for the elderly. All had practiced Tai Chi (Ng style) at least 3x week^{-1} (each session was ≈1 hour) for more than 1 year (mean Tai Chi experience, 7.2 ± 7.2 years). The non-Tai Chi subjects (8 men, 12 women; mean age = 67.8 ± 4.5 years) were recruited from several community centers for the elderly. They had no experience with Tai Chi, although some took morning walks or did stretching exercises. All 40 elderly subjects were ambulatory, independent in their activities of daily living, and could communicate and follow the testing procedures. Exclusion criteria were the presence of symptomatic cardiovascular diseases at a moderate exertion level, poorly controlled hypertension or symptomatic orthostatic hypotension, a stroke diagnosis, Parkinson's disease, or other neurologic disorder, peripheral neuropathy of the lower extremities, crippling arthritis, and metastatic cancer. In addition, subjects with a history of falls in the past 12 months were excluded.

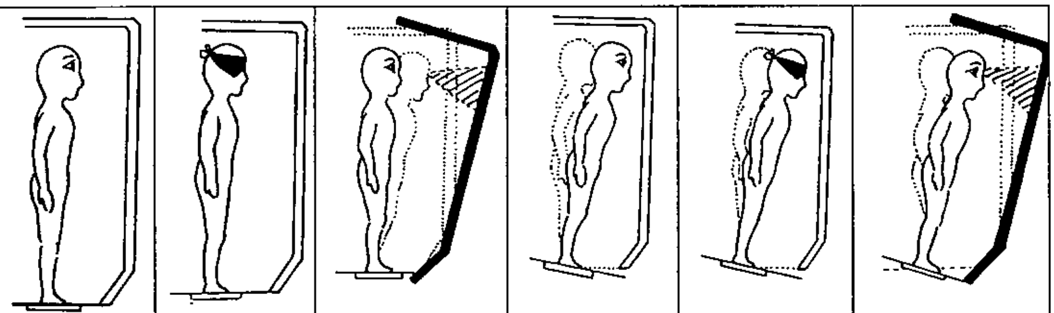
Clinical evaluation of the elderly subjects included 1) a general health questionnaire, 2) Mini-Mental Status Examination (MMSE) (Folstein et al. 1975), 3) a physical activity level questionnaire, and 4) assessment of handgrip strength. The Guttman Health Scale (Rosow and Breslau 1966) was used as a general health questionnaire to screen out subjects according to the exclusion criteria. The questionnaire has 3 sections, from which the functional health status can be assessed. The MMSE is a measure of cognitive ability developed by Folstein et al. in 1975. The Chinese version of the test was validated (Chiu et al. 1994) and used in the present study. The scale ranges from 0 to 30, with a score below 24 suggesting cognitive dysfunction (Folstein et al. 1975). Elderly subjects who scored below 24 were excluded from this study. The physical activity level questionnaire was a modified version of the Minnesota Leisure Time Physical Activity Questionnaire (Taylor et al. 1978; Van Heuvelen et al. 1998). As described in Chapter 2, it categorized physical activities into 3 levels according to their metabolic equivalents (METs) status: light (intensity $\leq$ 4.0 METs), moderate (intensity from 4.0 METs to $\leq$ 5.5 METs), and heavy activities (intensity > 5.5 METs). Handgrip strength provides an objective assessment of the subjects' general level of muscle strength (Maki et al. 1994). It is statistically significantly associated with the scores achieved on the physical activity questionnaire (Cooper et al. 1988; Rantanen et al. 1992; Sandler et al. 1991). Its measurement has the advantage of avoiding recall bias that might occur from the questionnaire (Rantanen et al. 1992). A Jamar hydraulic dynamometer (Sammons Preston Rolyan, 4 Sammons Ct, Bolingbrook, IL 60440) was used to test the maximum handgrip strength of both hands of each subject. The second handle position of the dynamometer was chosen, as recommended by the American Society of Hand Therapists. In other words, we used both subjective and objective methods (Sandler et al. 1991) to compare the physical activity levels of the Tai Chi and non-Tai Chi practitioners.

The project was approved by the ethics committee of the Hong Kong Polytechnic University, and written informed consent was obtained from all subjects.

3.3.2 Posturography test procedures

Proper integration of the information from somatosensory, visual, and vestibular receptors is necessary to generate appropriate balance responses (Anacker and DiFabio 1992; Wolfson et al. 1992). In this connection, computerized dynamic posturography (CDP) is a clinical tool used to measure a subject's ability to use somatosensory, visual and vestibular inputs to coordinate the motor responses that are necessary to maintain standing balance (Camicioli et al. 1997; Hamid et al. 1991; Wolfson et al. 1992).

We used a SMART EquiTest® CDP machine (NeuroCom International Inc, 9570 SE Lawnfield Rd, Clackamas, OR 97015-9943) in this study. The sensory organization test (SOT) was conducted to assess the balance control of the elderly subjects. A detailed description of the testing procedure has been published (Lepers et al. 1997; Nashner 1993a) and is therefore only highlighted here. Subjects stood without shoes on the support platform, while wearing a security harness to prevent falls. They were instructed to stand quietly with their arms at their sides with their eyes looking forward. During the SOT, subjects were exposed to 6 combinations of visual and support surface conditions. Each subject underwent 3 consecutive trials for each of the 6 conditions (illustrated in Fig. 3.1). In conditions 1, 2, and 3, subjects stood on a fixed platform under 3 visual conditions—eyes open, eyes closed, and eyes open in a sway-referenced visual surround. In conditions 4, 5, and 6, subjects stood on a sway-referenced platform under the same 3 visual conditions.



Condition	1	2	3	4	5	6
Vision	Normal	Absent	Sway Referenced	Normal	Absent	Sway Referenced
Support	Fixed	Fixed	Fixed	Sway Referenced	Sway Referenced	Sway Referenced

FIGURE 3.1 - The SOT for 6 different sensory conditions. Modified from Nashner (1993a).

3.3.3 Data recording and analysis

The dual force plates of the EquiTest have 4 build-in force transducers. The vertical forces captured by the transducers were used to calculate the center of pressure (COP) of the standing subject. We used an equilibrium quotient to compare the 3 groups (Camicioli et al. 1997; Nashner 1993a; Wolfson et al. 1993). The equilibrium quotient is a percentage that compares the maximum anteroposterior extent of a subject's sway to theoretical limits of stability (maximum peak-to-peak = 12.5°) (Nashner 1993b; Nashner and McCollum 1985).

An equilibrium quotient of 100 is equivalent to "no sway," while a score of 0 represents a loss of balance, that is, exceeding the 12.5° estimated maximum range of sway. The equilibrium quotient data were used to analyze the balance control under different somatosensory, visual, and vestibular conditions. We used the three sensory ratios proposed by Nashner (1993a) (Fig. 3.2).

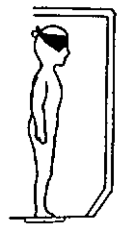
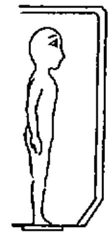
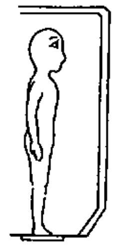
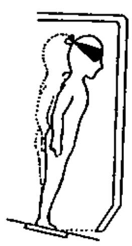
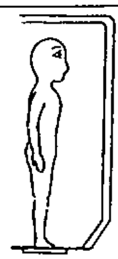
SENSORY ANALYSIS		
Sensory Ratios Equilibrium Quotient (EQ)	**Test Conditions**	
$\textit{Somatosensory ratio} = \frac{EQ\ of\ Condition\ 2}{EQ\ of\ Condition\ 1}$	 2	 1
$\textit{Visual ratio} = \frac{EQ\ of\ Condition\ 4}{EQ\ of\ Condition\ 1}$	 4	 1
$\textit{Vestibular ratio} = \frac{EQ\ of\ Condition\ 5}{EQ\ of\ Condition\ 1}$	 5	 1

FIGURE 3.2. - Sensory analysis ratios. Modified from Nashner (1993a).

The somatosensory ratio compared the equilibrium quotients of condition 2 with those of condition 1. It quantified the extent of stability loss when the subjects closed their eyes while standing on a fixed support platform. The visual ratio compared the equilibrium quotients of condition 4 with those of condition 1. This ratio quantified the extent of stability loss when the normally dominant somatosensory input was disrupted by sway referencing of the support surface with subjects' eyes open. The vestibular ratio compared the equilibrium quotients of condition 5 with those of condition 1. This ratio reflected the relative reduction in stability when absent visual and inaccurate somatosensory inputs occurred simultaneously, forcing subjects to rely primarily on vestibular input for balance control.

3.3.4 Statistical analysis

To ensure data reliability, the intraclass correlation coefficient, $ICC_{3,3}$, was used to assess the test-retest reliability of the SOT in the elderly subjects. Paired *t* tests were used to compare the equilibrium quotient of condition 1 with those of the subsequent conditions, that is, condition 2 to 6 in session 1, to assess the standing balance control under reduced or conflicting sensory conditions. One-way analysis of variance (ANOVA) was used to compare the age, height, and weight among the 3 groups, while gender was compared using chi-square test. ANCOVA model with gender and group as fixed factors was also used to investigate the effect of gender on the outcome measure and across the three groups. For the comparison between the 2 elderly groups, independent *t* tests were conducted for the MMSE and the handgrip strength test, while chi-square test was used for the comparisons of physical activity level and hand dominance.

Because there was 1 independent variable – subject group (young subjects, elderly Tai Chi, non-Tai Chi practitioners) and 3 dependent variables – somatosensory, visual, and vestibular ratios, we used multivariate analysis of variance (MANOVA) to compare the balance control among the 3 groups. If we found a statistically significant difference in the multivariate tests, univariate tests were conducted for each of the sensory ratios. Post hoc analysis using Bonferroni adjustment was conducted if a significant difference was found in the univariate test of the sensory ratios. The significance level (α) in all the statistical analyses was set at 0.05.

3.4 Results

3.4.1 Test-retest reliability of the SOT

Twelve elderly subjects (4 men, 8 women, mean age 68 ± 7.4 years) participated in the test-retest reliability study. After measuring their equilibrium quotients in each of the 6 conditions of the SOT, the testing procedures were repeated 1 week after the first testing session. The $ICC_{3,3}$ was calculated for all 6 conditions (Table 3.1). These values ranged from 0.72 (condition 3) to 0.93 (condition 5), which indicated moderate to good correlation (Portney and Watkins 1993). The lower bound value of the 95% confidence interval (CI) of the ICC for condition 3 was considered low. This might be a result of the small sample size in the reliability test. Because this particular score was not used in the calculation of the 3 sensory ratios we used, the result of the test-retest reliability with CI ranging from 0.37 to 0.98 was acceptable.

Data from the reliability test showed that the equilibrium quotients of conditions 2 to 6 were statistically significantly lower than the equilibrium quotient in condition 1 (all $P < 0.01$ after Bonferroni adjustment; Table 3.1). Note that the decrease in the equilibrium quotient was very small when the elderly subjects stood on a fixed support platform with their eyes closed, and with sway-referenced visual surround. However, the equilibrium quotients all decreased substantially when the subjects stood on a sway-referenced support for the 3 visual conditions.

TABLE 3.1. Test-retest reliability of the SOT in elderly subjects.

SOT Conditions	EQ (%) Session 1 (N=12)	EQ (%) Session 2 (N=12)	$ICC_{3,3}$	95% CI	Decrease of EQ (%) in Session 1 vs Condition 1	***P***
Condition 1	94.3±1.6	93.8±1.5	0.81	0.37–0.95	0.0	
Condition 2	92.5±1.5	92.4±2.1	0.84	0.47–0.95	1.9	0.001*
Condition 3	90.4±4.1	90.6±2.9	0.72	0.08–0.92	4.1	0.005*
Condition 4	69.0±16.9	73.4±16.5	0.90	0.66–0.97	26.8	0.000*
Condition 5	54.2±16.6	58.0±16.2	0.93	0.77–0.98	42.5	0.000*
Condition 6	44.9±21.7	51.0±16.9	0.87	0.56–0.96	52.4	0.000*

Abbreviation: CI, confidence interval; EQ, equilibrium quotient.

* Denotes significant difference at $P < 0.05/5$ or $P < 0.01$ using Bonferroni adjustment.

3.4.2 Differences among subject groups

Table 3.2 shows a comparison of age, height, weight, and gender among the

3 groups. One-way ANOVA showed statistically significant differences between the young subjects and the 2 elderly groups in age and height, but no significant differences between the practitioners and nonpractitioners of Tai Chi. The difference in height between the young and the elderly did not affect comparisons of the equilibrium quotients and the sensory ratios because the sway angle was used in their calculation. There were no statistically significant differences in weight and gender among the 3 groups. Also, the ANCOVA model showed no gender difference in the sensory organization test and no interaction between gender and group ($P > 0.05$; Table 3.3). Therefore, data from the male and female subjects in each group were combined for among-group comparison.

TABLE 3.2. Comparison of age, height and weight among young, elderly Tai Chi, and non-Tai Chi subjects.

	Young Subjects ($N = 20$)	**Tai Chi Subjects** ($N = 20$)	**Non-Tai Chi Subjects** ($N = 20$)	***P***
Age (years)	21.5±1.6	70.7±5.1†	67.8±4.5†	0.000*
Height (m)	1.66±0.09	1.54±0.08†	1.59±0.09‡	0.000*
Weight (kg)	54.8±10.3	56.2±10.7	61.1±8.7	0.122
Gender (M/F)	12/8	10/10	8/12	0.449

Abbreviations: F, female; M, male.

* Denotes significant difference at $P < 0.001$ using 1-way ANOVA.

† Denotes significant difference at $P < 0.001$ between young and elderly subjects by post hoc analysis using Bonferroni adjustment.

‡ Denotes significant difference at $P < 0.05$ between young and elderly non-Tai Chi subjects by post hoc analysis using Bonferroni adjustment.

TABLE 3.3. Compare the effect of gender on the outcome measures and across the 3 groups.

	Gender *P*	Gender x group *P*
Sensory organization test	0.187	0.132

"x" Denotes interaction between gender and group variables.

Table 3.4 provides further comparisons of the demographic data of the 2 elderly groups. Independent *t* tests showed that the 2 groups were comparable in the MMSE score and handgrip strength. All 40 subjects had MMSE scores above 24, indicating that they had no cognitive impairment (Chiu et al. 1994; Folstein et al. 1975). Physical activity levels and hand dominance were also found to be similar, by using chi-square test and the Fisher exact test, respectively. As determined by the Guttman questionnaire, none of the elderly were limited in any of their activities. The similarities in these variables did not confound any differences between the 2 groups.

TABLE 3.4. Characteristics of Tai Chi and non-Tai Chi subjects.

	Tai Chi Subjects (N = 20)	**Non-Tai Chi Subjects** (N = 20)	***P***
MMSE score	28.3±1.8	28.1±2.0	0.681
Handgrip			
Left (kg)	24.6±7.0	24.2±7.2	0.877
Right (kg)	26.5±7.8	27.2±8.7	0.790
Physical activity levels			0.574
Light (≤4 METs)	1	0	
Moderate (≤5.5 METs)	15	15	
Heavy (>5.5 METs)	4	5	
Hand dominance			1.0*
Left	2	1	
Right	18	19	

NOTE. Values are mean ± SD or n.

Abbreviations: MMSE, Mini-Mental Status Examination; METs, metabolic equivalents.

* Determined by the Fisher exact test, because the 2 cells had an expected count of less than 5.

3.4.3 Comparison of balance control using the SOT

The multivariate tests indicated an overall statistically significant effect across the 3 sensory ratios for the 3 groups (P = 0.041). The univariate tests showed that there were statistically significant differences in the visual and vestibular ratios, but not in the somatosensory ratio (Table 3.5).

TABLE 3.5. SOT: Comparison of balance control under different sensory conditions among young, elderly Tai Chi, and non-Tai Chi subjects.

	Young Subjects ($N = 20$)	**Tai Chi Subjects** ($N = 20$)	**Non-Tai Chi Subjects** ($N = 20$)	***P***
Somatosensory ratio	0.98 ± 0.03 (2%)	0.98 ± 0.02 (2%)	0.98 ± 0.03 (2%)	0.827
Visual ratio	0.85 ± 0.16 (15%)	0.82 ± 0.11‡ (18%)	0.73 ± 0.14† (27%)	0.015*
Vestibular ratio	0.67 ± 0.15 (33%)	0.67 ± 0.09‖ (33%)	0.58 ± 0.17‖ (42%)	0.049*

NOTE. Values are mean ± SD. The figures in parentheses denote the decrease of sensory ratio in percentage when compared with condition 1.

* Denotes significant difference at $P < 0.05$ between the young and the elderly subjects by using univariate tests.

† Denotes significant difference at $P < 0.01$ between young and elderly non-Tai Chi subjects by post hoc analysis using Bonferroni adjustment.

‡ Denotes significant difference at $P < 0.05$ between elderly Tai Chi and elderly non-Tai Chi subjects by post hoc analysis using Bonferroni adjustment.

‖ Denotes significant difference at $P < 0.05$ between elderly non-Tai Chi subjects with young and elderly Tai Chi subjects by post hoc analysis using Bonferroni adjustment.

Post hoc analysis was not conducted for the somatosensory ratio because no statistically significant difference was found in the univariate test (Table 3.5). Both the young and the elderly subjects achieved similar somatosensory ratios (Table 3.5) when the equilibrium quotients of condition 2 were compared with those of condition 1 (Fig. 3.2).

For the visual ratio, post hoc analysis using Bonferroni adjustment tests were conducted because a statistically significant difference was found in the univariate test (Table 3.5). The non-Tai Chi practitioners scored a statistically significantly lower visual ratio (mean ratio, 0.73 ± 0.14) than the young subjects (mean ratio, 0.85 ± 0.16; $P = 0.005$) and the Tai Chi practitioners (mean ratio, 0.82 ± 0.11; $P = 0.049$). However, no statistically significant difference was found between the young subjects and the Tai Chi practitioners ($P = 0.361$). The decrease in the visual ratios for the young, the Tai Chi, and the non-Tai Chi subjects were 15%, 18%, and 27%, respectively, when the equilibrium quotients of condition 4 were compared with those of condition 1 (Table 3.5, Fig. 3.2).

Similarly, post hoc tests were conducted by using Bonferroni adjustment when a statistically significant difference was found in the univariate test for the vestibular ratio (Table 3.5). The non-Tai Chi practitioners scored a statistically significantly lower vestibular ratio (mean ratio, 0.58 ± 0.17) than the young subjects (mean ratio, 0.67 ± 0.15; $P = 0.033$) and the Tai Chi practitioners (mean ratio, 0.67 ± 0.09; $P = 0.033$). However, no statistically significant difference was found between the young subjects and the Tai Chi practitioners ($P = 0.996$). The decrease in the vestibular ratios for the young, the Tai Chi, and the non-Tai Chi subjects were 33%, 33%, and 42%, respectively, when the equilibrium quotients of condition 5 were compared with those of condition 1 (Table 3.5, Fig 3.2).

3.5 Discussion

3.5.1 Sensory organization test (SOT)

Quantitative posturography has been used by several researchers to study the ability of elderly subjects to use somatosensory, visual, and vestibular information to control their body sway when standing under reduced or conflicting sensory conditions (Camicioli et al. 1997; Whipple et al. 1993; Wolfson et al. 1992). Results from our reliability study showed that the data obtained under the 6 sensory conditions were repeatable when the same elderly subjects were tested 1 week apart, with ICCs ranging from 0.72 to 0.93 (Table 3.1).

In this study, the COP data, as captured by the force platform, were used to estimate the center of gravity (COG) from which the equilibrium quotient was obtained. Benda et al. (1994) investigated the biomechanical relation between the COP and COG, and pointed out that these 2 parameters are not dynamically, but only statically, interchangeable. The group recommended that the COG position, as estimated from COP data, should be interpreted with caution when unstable patients are tested (Benda et al. 1994). Although we recruited young university students and healthy elderly subjects, precaution is advised in the interpretation of our results.

Studies have shown that the SOT can differentiate between elderly fallers from nonfallers. In 1997, Ho found that among 15 elderly fallers and 15 nonfallers, the fallers exhibited significantly greater sway in conditions 4 to 6. In 2001, Wallmann used the SOT to compare 10 elderly fallers and 15 nonfallers (age > 60 years) and found that the fallers swayed significantly greater in condition 4. In the same year, Girardi et al. used both dynamic posturography and electronystagmography tests to predict the risk of falls in an elderly population. Both the SOT and limits of stability test proved to be more sensitive than the electronystagmography test for predicting falls in elderly subjects.

3.5.2 Differences among groups: Effects of aging and of Tai Chi practice

Our study revealed statistically significant differences in the visual and vestibular ratios (Table 3.5) among the different groups. Three main findings emerged when all study subjects were tested while standing under reduced or conflicting sensory conditions.

First, the non-Tai Chi practitioners exhibited more sway and attained statistically significantly lower visual and vestibular ratios than did the young subjects ($P = 0.005$, $P = 0.033$, respectively). This agrees with previous findings that older subjects sway significantly more than young subjects, when there is an increased reliance on the visual and vestibular inputs, with the other sensory inputs reduced and/or distorted (Ledin et al. 1991; Shepard et al. 1993; Wolfson et al. 1992). Such increase in sway is thought to be attributable to the different degrees of deterioration that can occur with aging in the somatosensory, visual, and vestibular systems responsible for balance control (Alexander 1994; Hageman et al. 1995; Horak et al. 1989).

Second, the Tai Chi practitioners swayed significantly less and achieved significantly higher visual and vestibular ratios than did the non-Tai Chi practitioners ($P = 0.049$, $P = 0.033$, respectively). These results suggest that practicing Tai Chi for 7.2 ± 7.2 years improved balance control in the elderly population. Such positive findings when subjects stood under more functional contexts with moving visual surround and support platform might explain why the Tai Chi practitioners studied by Wolf et al. (1996) had decreased fears of falling and a decreased risk of multiple falls. Our results are similar to those of Wong et al. (2001), who also showed that elderly Tai Chi practitioners achieved a better equilibrium score under conditions 5 and 6 (Fig. 3.1); however, we provide new information on the visual and vestibular ratios. Note also that the preliminary findings were published in the same year (Tsang et al. 2001) as those of Wong et al. Thus, 2 independent studies from 2 different regions produced similar results in the same year.

Third, our findings further demonstrate that the elderly Tai Chi practitioners achieved the same level of balance performance as the young healthy subjects (P = 0.361 for visual ratio, P = 0.996 for vestibular ratio). In other words, these findings suggest that practicing Tai Chi for 7.2 ± 7.2 years enabled the elderly subjects to achieve performance in balance control similar to that of the young control subjects.

How is Tai Chi related to balance control? The practice of Tai Chi requires constant shifting between double-stance and single-stance, a requirement that constantly challenges the balance control system to maintain the subject's center of mass within the base of support (Winter 1995). Such a repetitive demand for balance control during Tai Chi practice of more than 1 year probably explains why our Tai Chi practitioners attained better visual and vestibular ratios than did our non-Tai Chi elderly subjects.

3.5.3 Balance control and the visual system

The contribution of vision to balance control has been well documented. The Romberg quotient, often used to describe the visual contribution to stabilizing posture, is a ratio between body sway values recorded during standing with the eyes open and closed. The lower the quotient, the more effect vision has on postural stabilization. Pyykkö et al. (1990) reported that, in old age groups (age > 80 years), the Romberg quotient was 0.48, while the value at ages ranging from 50 to 60 years was 0.78. This finding suggests that vision is important in maintaining balance in elderly subjects.

However, with aging, there is a decrease in visual acuity, restriction of the visual field, increased susceptibility to glare, and poorer depth perception (Horak et al. 1989; Stelmach and Worringham 1985; Woollacott 1993). As discussed in Chapter 1 (section 1.3.1), these deficiencies may result in a longer delay before the visual system alerts the central nervous system to a potential fall. They could also affect the visual sampling necessary to accurately assess the rate and direction of the falls and the time to landing (Stelmach and Worringham 1985). As a result, an older person's use of visual information for balance control could be diminished, thus increasing his/her chances of falling.

As aforementioned, investigators (Ledin et al. 1991; Shepard et al. 1993; Wolfson et al. 1992; Woollacott et al. 1986) using the SOT, have found that elderly subjects swayed more than younger subjects under conditions of reduced or conflicting sensory information. Elderly subjects also had greater difficulty when the visual input was manipulated to make it inappropriate to the postural task, and when both proprioception and visual inputs were reduced or absent. We found that Tai Chi practitioners had a significantly higher visual ratio (mean ratio, 0.82 ± 0.11) than the nonpractitioners (mean ratio, 0.73 ± 0.14; $P = 0.049$). This was denoted by less sway of the Tai Chi practitioners when there were error signals arising from the somatosensory system in condition 4 (eye open with sway-referenced support; Fig. 3.1). Even more interesting is that the visual ratio attained by the Tai Chi practitioners was comparable to that of the young healthy subjects (mean ratio, 0.85 ± 0.16; $P = 0.361$). As reported by Ho (1997), the mean visual ratio of the elderly fallers was 0.65, which was lower than those of our elderly Tai Chi and non-Tai Chi practitioners (respectively, 26% and 12% lower). Thus, subjects who sway more when there are error signals arising from the somatosensory system may have a higher tendency to fall.

Many Tai Chi forms require practitioners to focus their eyes on their hand movement through head and/or trunk rotation. In this connection, Szturm et al.

(1994) found that the left-right differences in the vestibulo-ocular reflex gain of patients with chronic peripheral vestibular dysfunction could be reduced by an exercise program of eye and head movements. Some components of this exercise program, such as focusing on a stationary visual target and tracking a moving visual target with the head either fixed or moving, were similar to those that occur during Tai Chi practice. However, the mechanism through which Tai Chi practice can improve balance control through the visual system is not known, and further investigation is needed.

3.5.4 Balance control and the vestibular system

Practicing Tai Chi involves head movements that will stimulate the vestibular system, and repeated vestibular stimulation over time may facilitate balance control in the practitioners. In this study, the Tai Chi practitioners attained a higher vestibular ratio than the non-Tai Chi elderly under condition 5 ($P = 0.033$), when the subjects stood with their eyes closed on a sway-referenced support surface. Condition 5 was designed so that subjects had to rely more heavily on the vestibular system to maintain balance (Nashner 1993b; Shepard 1989). Interestingly, the vestibular ratio achieved by the elderly Tai Chi practitioners was similar to that of the young adult subjects, and no statistically significant difference was found between them ($P = 0.996$). In this connection, the mean vestibular ratio of the elderly fallers was 0.51 in Ho's study (1997), which was 31% lower than that of our Tai Chi practitioners and 14% lower when compared with our non-Tai Chi practitioners (Table 3.5).

The effect of aging on the vestibular system has been investigated in posturography studies (Camicioli et al. 1997; Whipple et al. 1993; Wolfson et al.

1992), in which the elderly subjects tested swayed significantly more in conditions 5 and 6 than did the young subjects (Fig. 3.1). Poorer balance control in the elderly subjects could be attributed to age-related structural degeneration. For example, Rosenhall and Rubin (1975) reported a 40% reduction in the sensory cells of the vestibular apparatus in subjects more than 70 years of age.

As review in Chapter 1 (section 1.4), studies on the rehabilitation outcome of peripheral vestibular disorders have shown that specific vestibular exercises produced better balance performance than nonspecific general conditioning exercises. Horak et al. (1992) examined the effectiveness of a specific vestibular rehabilitation program, a general conditioning exercise program, and a vestibular suppressant medication in reducing symptoms in patients with chronic peripheral vestibular disorders. Although their sample size was small and the age range was wide (18–60 years), patients in the vestibular rehabilitation groups showed improvement in their equilibrium quotients, especially in conditions 5 and 6. The vestibular rehabilitation program included practicing balance during functional activities such as walking with head turns and pivot turning, or with altered surface or visual inputs. Horak et al. suggested that these activities may improve patients' ability to use the remaining vestibular inputs to achieve better balance control.

Exercise used in vestibular rehabilitation emphasizes head and trunk rotations, changes in the base of support, and fixation of the eyes on a target. It also involves turning while walking, making large circles, and gradually making smaller and smaller turns. It is well known that adaptation of the vestibulo-ocular system is context-specific, and that adaptation of the vestibular system is frequency dependent. Thus, during vestibular rehabilitation, patients are instructed to perform head movement exercises at different frequencies and with different head positions to achieve optimal effects (Herdman 1993). This is similar to Tai Chi, which also involves many head and body rotations, changes in the base of support, and fixation of the eyes on the hand during its practice.

Vestibular adaptation is affected by voluntary motor control. Mental effort will help to improve the gains (Herdman 1993). Patients in vestibular rehabilitation are encouraged to concentrate on the task and not to be distracted by conversation and other activities (Herdman 1998). Tai Chi also requires the subject to practice with a relaxed body and a calm but concentrated mind (Tsao 1995). Last, balance exercises for vestibular adaptation emphasize progression by decreasing the base of support, changing the head or arm position, manipulating sensory cues, and moving from static to dynamic activities. Tai Chi also starts with a simple and stable posture, then gradually progresses to more difficult trunk and head rotations, and from weight shifting during double-leg stance to single-leg stance. The base of support keeps changing, and different arm movements are also involved (Tsao 1995; Wolf et al. 1997a). All these motions show similarities to the vestibular rehabilitation protocols recommended by various investigators. This may explain why the Tai Chi practitioners had better balance performance than the non-Tai Chi group when there was an increased reliance on the vestibular system. Further investigation of the relation between Tai Chi practice and vestibular function is warranted.

3.5.5 Other considerations for future studies

Because we used an observational, cross-sectional study design, we cannot establish a causal relation between the practice of Tai Chi and the improvement of balance control when standing under changing sensory conditions. Prospective, randomized control studies should be conducted to delineate the training effect of

Tai Chi on the somatosensory, visual, and vestibular systems that are responsible for balance control. Indeed, using a prospective study as described later in Chapter 5, we had demonstrated that 2 months of intensive Tai Chi training was sufficient to improve the balance control of the elderly subjects, in terms of 1) less body sway when standing under conditions requiring an increased reliance on the vestibular system, and 2) more smooth movement to different targeted positions when standing with subjects' limits of stability (Hui-Chan and Tsang 2001).

We used the SOT in the present study to compare only 1 perspective of balance control among the 3 groups. It focuses on subjects' ability to utilize somatosensory, visual, and vestibular inputs in coordinating motor responses that are necessary to maintain standing balance; it does not reflect the full complexity of balance control required during the performance of functional tasks. More specifically, research findings from Krebs and colleagues (Evans and Krebs 1999; O'Neill et al. 1998) have shown that posturography findings do not necessarily correlate with the more commonly used functional tests. Krebs et al. investigated the correlation between the SOT with gait and clinical tests of timed gait and standing in patients with peripheral vestibular hypotension, and found only 7 of 18 comparisons to be statistically significant (Evans and Krebs 1999). In another study, Krebs et al. (1998) correlated the SOT with 88 functional performance tests to monitor the change of balance control in patients with peripheral vestibular hypofunction who had received 6 to 8 weeks of vestibular rehabilitation. Only 7 statistically significant correlations were detected. It should be noted that, although the SOT examines the control of standing balance under reduced or conflicting sensory conditions, functional tests often require voluntary control of movement with time and speed control demands that are beyond the control of standing balance alone. Furthermore, functional tests are conducted under normal sensory conditions, whereas the SOT requires a subject to retain standing balance despite conflicting sensory conditions (e.g., to rely on the vestibular system when vision is absent, despite receiving error signals from the somatosensory system, as in condition 5). Therefore, our findings in this study on standing balance should not be generalized to functional performance. Along this line of thought, we are studying the motor control of elderly Tai Chi practitioners in stair descent, as Tai Chi practice involves a lot of eccentric leg muscle work that is required to control the body with respect to gravity force.

In this study, we investigated only 1 type of exercise, Tai Chi. Other exercises, such as a balance training program, have been documented by others to have an effect on balance control (Ledin et al. 1991; Rose and Clark 2000). We had also conducted a study to compare the specificity of Tai Chi training in improving balance control with an equivalent active exercise group of golfers. These findings will be presented in Chapter 6.

3.6 Conclusions

We investigated possible effects of Tai Chi on balance control by examining subject's ability to use somatosensory, visual, and vestibular information to control their body sway while standing under 6 different sensory conditions when somatosensory or visual inputs were either absent or inaccurate. Our results indicate that practicing Tai Chi for 7.2 ± 7.2 years improved the control of stance under reduced or conflicting sensory conditions in an elderly population. Elderly Tai Chi practitioners showed better balance performance than non-Tai Chi practitioners who were similar in age, gender, and physical activity level when there was an increased reliance on the visual and vestibular systems. An important finding is that practicing

Tai Chi for 7.2 ± 7.2 years enabled the elderly subjects to achieve a level of balance performance comparable to that of young healthy subjects under our present experimental paradigm.

CHAPTER 4

EFFECTS OF TAI CHI ON KNEE MUSCLES, PERTURBED STANCE AND BALANCE CONFIDENCE IN ELDERLY

Publication

TSANG, W. W. N., and C. W. Y. HUI-CHAN. Comparison of muscle torque, balance & confidence in older Tai Chi and healthy adults. *Med. Sci. Sports Exerc.* 2005 (In press).

Conference abstract

TSANG, W. W. N., and C. W. Y. HUI-CHAN. Tai Chi can improve balance control in perturbed single-leg stance. In *The Third Pan-Pacific Conference on Rehabilitation.* Hong Kong, p.19, 2002.

4.1 Abstract

Purpose: The objectives of this study were to examine whether elderly Tai Chi practitioners had developed better knee muscle strength, less body sway in perturbed single-leg stance, and greater balance confidence than healthy elderly subjects.

Methods: Tai Chi and control subjects ($N = 24$ each, aged 69.3 ± SD 5.0 years and 71.6 ± 6.1 years respectively) were matched with respect to age, gender, height, weight and physical activity level. Concentric and eccentric isokinetic tests of the subjects' dominant knee extensors and flexors were conducted at angular velocity of $30°\cdot s^{-1}$. Control of body sway was assessed in static double-leg stance and in single-leg stance perturbed by forward or backward platform perturbations. The Activities-specific Balance Confidence (ABC) scale was used to investigate subjects' balance confidence in daily activities.

Results: Tai Chi practitioners developed higher peak torque-to-body weight ratios in concentric and eccentric isokinetic contractions of their knee extensors and flexors ($P = 0.044$). They manifested less anteroposterior body sway in perturbed single-leg but not static double-leg stance than did control subjects ($P < 0.001$). Tai Chi practitioners also reported significantly higher balance confidence score ratios ($P = 0.001$). Their knee muscle strengths showed negative correlations with body sway angles in perturbed single-leg stance and positive correlations with ABC score ratios. Moreover, their body sway angles in perturbed single-leg stance were negatively correlated with their ABC score ratios (all $P < 0.05$).

Conclusion: Our results demonstrate that long-term Tai Chi practitioners had better knee muscle strength, less body sway in perturbed single-leg stance, and greater balance confidence. Significant correlations among these three measures uncover the importance of knee muscle strength and balance control during perturbed single-leg stance in the elderly balance confidence in daily activities.

Key Words: AGING, FALLS, EXERCISE, ISOKINETIC TESTING, BALANCE

4.2 Introduction

According to the World Health Organization, there will be more than 1,000 million people aged 60 and older in 2020. Falls have been identified as a major cause of injury and death in the elderly (Wolter and Studenski 1996). Decrease in muscle strength is one of the intrinsic factors that cause these falls (Carter et al. 2001). As discussed in Chapter 1 (section 1.3.2), muscle size and related neuromuscular functions are known to decrease with aging (Vandervoort 2002). The decline in muscle strength is minor until about the sixth decade of life (Vandervoort 2002). Investigations conducted on older subjects reveal that resistance training can improve their leg muscle strength (LaStayo et al. 2003).

Tai Chi is a Chinese mind-body exercise, which has been practiced by millions of Chinese elderly for the past 300 years. Recent studies have demonstrated that the practice of Tai Chi can reduce anxiety, improve mood and self-esteem, and be beneficial to the cardiorespiratory system and balance control. As detailed in the previous Chapter, we compared the sway amplitude of elderly Tai Chi practitioners to that of an elderly healthy control group, when they stood under 6 combinations of visual (eyes open, eye closed, sway-referenced) and support surface (fixed, sway-referenced) conditions in the sensory organization test (Tsang et al. 2001, 2004). Our findings demonstrated that the elderly Tai Chi practitioners swayed significantly less when they stood under sensory conditions that demanded an increased reliance on the visual and vestibular systems than the healthy control group similar in age, sex and physical activity level. Of particular interest is that the elderly Tai Chi practitioners attained the same level of balance control performance in the sensory organization test as the young, healthy subjects when standing under reduced or conflicting somatosensory, visual and vestibular conditions (Tsang et al. 2004).

Using the limits of stability test, Tsang and Hui-Chan (2003) further showed that the Tai Chi practitioners initiated voluntary shifting of their weight to different spatial positions within their base of support more quickly, leaned further without losing their stability, and showed better control of their leaning trajectory than those of the control subjects.

Good balance control during functional activities requires sufficient strength of the agonist and antagonist muscles across the related joints (Wolfson et al. 1995). Tai Chi is performed with the knees bent most of the time, and it requires both concentric and eccentric contractions of the leg muscles, especially those of the knee. For instance, in one of the Tai Chi forms "part the wild horse's mane (野馬分鬃)", the practitioner semi-squats both her knees (Figure 4.1a).

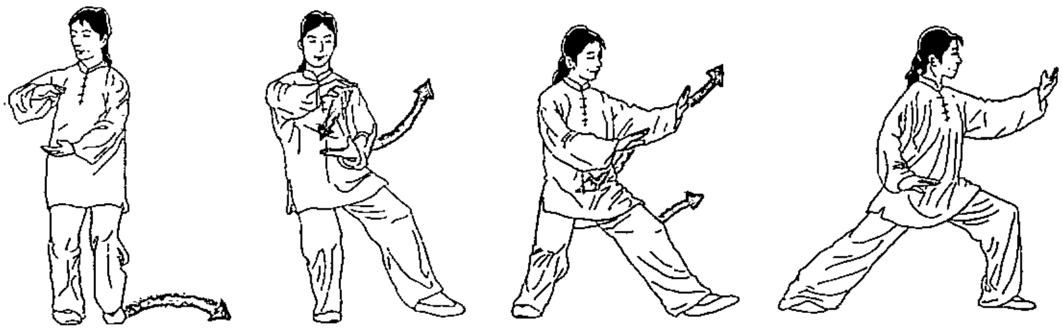


FIGURE 4.1a - A Tai Chi master illustrating "part the wild horse's mane, 野馬分鬃" maneuver.

She then transfers her whole body weight to her right leg and lifts her left leg forward. This form is completed when she extends her right knee and at the same time transfers her weight to her left leg which is bent about 90° at the knee. Her arms accompany the legs' movements with an initial ball-holding posture and then spread apart (Tsao 1995). So practicing Tai Chi could be expected to increase strength in the knee muscles, and the resultant muscle strength may produce significantly augmented functional stability in certain daily activities (Vandervoort 2002). Furthermore, Tai Chi is performed in a closed kinetic chain position in which the knee extensors and flexors co-contract to stabilize and control knee movements (Kannus 1994). Therefore, long-term practice of Tai Chi may enhance the strength of both knee agonist and antagonist muscles.

Wolfson et al. (1996) conducted a 3-month intervention study on the effects of a balance and strength training program in healthy community dwellers (mean age = 80 years). All the subjects were then required to practice Tai Chi over the subsequent 6 months to maintain the gain in their balance and muscle strength. Significant gains were found to have persisted after the study period. Regrettably, the study did not include a control group. Lan et al. (1998) investigated the effectiveness of a 12-month Tai Chi training program on knee muscle strength in older subjects aged 58 to 70 years. They demonstrated that subjects who voluntarily participated in the Tai Chi group had significantly improved concentric isokinetic strength of the knee extensors and flexors (by 19.2% and 15.7% respectively), while the control group showed no significant change in these variables. However, eccentric knee muscle strength was not investigated in this study.

Wu et al. (2002) compared the concentric and eccentric strength of the knee muscles between Tai Chi practitioners with mean experience of 21 years and control subjects, both groups aged > 55 years. They found that the Tai Chi practitioners had higher concentric and eccentric strength in their knee extensors at $60°\cdot s^{-1}$ and $120°\cdot s^{-1}$, but observed no difference in their knee flexor strength from that of the control group. These findings pose questions about possible muscle imbalance, as knee extensor strength was increased but not knee flexor strength. However, their finding of insignificant changes in concentric and eccentric knee flexor strength may be due to the higher isokinetic testing speed used (Wu et al. 2002). Since Tai Chi practice involves slow rather than fast movements, low isokinetic testing speed may better detect the effect of Tai Chi practice on knee muscle strength, especially knee flexor strength (Cronin et al. 2002; Morrissey et al. 1995). Therefore, the first objective of this study was to examine whether, at low isokinetic movement speed, elderly Tai Chi practitioners had developed better concentric and eccentric knee extensor and flexor strength than elderly control subjects, and whether the strength increase in the agonist/antagonist pair was to a similar or different extent.

Falls seldom occur during double-leg stance, as the center of mass is well within the base of support. Thus, evaluation of balance control confined to double-leg stance may not reflect the functional capability required of elderly people in certain activities of daily living. Often, their support surface is not stationary, such as when they step onto a moving escalator or walk along a moving bus. This will demand greater balance control and may pose particular problems to them. Tai Chi practice requires constant weight shifting between double-leg and single-leg stance (Tsao 1995). This requirement could improve balance control in single-leg stance under less stable conditions, such as when stepping onto a moving support platform. Consequently, the second objective of this study was to compare the control of body sway between the elderly Tai Chi practitioners and control subjects during both static double-leg stance and single-leg stance subjected to anteroposterior platform perturbations.

Better knee muscle strength and balance control during perturbed single-leg stance may enhance elderly subjects' balance confidence, which has been shown to be an important indicator of functional mobility and independence in older adults

(Myers et al. 1998). Therefore, the third objective of this study was to investigate whether repeated practice of Tai Chi could improve the elderly practitioners' subjective report of balance confidence. If the answer was positive, our final objective was to determine whether any relationship existed between knee muscle strength on the one hand, and control of body sway in static double-leg stance and perturbed single-leg stance as well as balance confidence on the other.

4.3 Methods

4.3.1 Subjects and study design

Forty-eight community-dwelling elderly subjects, aged 60 or older participated in this study. Twenty-four Tai Chi practitioners (12 males and 12 females, mean age = 69.3 ± 5.0 years) were recruited from local Tai Chi clubs. All of them had practiced Tai Chi for a minimum of 1.5 $hour \cdot week^{-1}$ for at least 3 years (mean Tai Chi experience = 8.5 ± 7.6 years). Twenty-four elderly control subjects (12 males and 12 females, mean age = 71.6 ± 6.1 years) were recruited from several community elderly centers. They had no previous experience in practicing Tai Chi, though some took morning walks or did stretching exercises. All the subjects were independent in their activities of daily living and none required walking aids. They were able to communicate and follow the testing procedures. Candidates showing symptomatic cardiovascular diseases when subjected to moderate exertion were excluded. Also excluded were people with poorly controlled hypertension or symptomatic orthostatic hypotension, those showing severe cognitive impairment or having diagnosed with Parkinson's disease, stroke or any other neurologic disorder. Peripheral neuropathy of the lower extremities was also considered grounds for exclusion, as was disabling arthritis or metastatic cancer. In addition, subjects who reported a history of falls in the past 12 months were excluded.

The elderly candidates were first screened using a general health questionnaire and a physical activity questionnaire. The validated Chinese version of the Mini-Mental Status Examination of Folstein et al. was then administered (Chiu et al. 1994). The scale ranges from 0 to 30. A score below 24 was considered indicative of cognitive dysfunction, and such subjects were excluded from this study. A modified version of the Minnesota Leisure Time Physical Activity Questionnaire (Van Heuvelen et al. 1998) was used to compare the physical levels of the elderly Tai Chi practitioners with those of the control subjects, as described in the previous two chapters. The project was approved by the Ethics Committee of the Hong Kong Polytechnic University, and written informed consent was obtained from all subjects.

4.3.2 Knee joint muscle strength test

The concentric and eccentric isokinetic strength of the knee extensors and flexors of the subject's dominant leg were tested using the Cybex Norm dynamometer (Cybex International Inc., Ronkonkome, NY, USA). The leg that the subject used to kick a ball was considered the dominant leg. The subject sat on the chair of the dynamometer, with the hips kept at 70° of flexion. The leg was attached to the knee adaptor of the dynamometer with the rotation axis in line with that of the knee joint, defined using the lateral femoral epicondyle. The subject's trunk and thigh of the dominant leg were stabilized with straps. The starting position was 90° of knee flexion, and the endpoint was full knee extension. Knee muscle strength was measured at an angular velocity of $30°\cdot s^{-1}$. Familiarization trials were performed with

3 submaximal and 3 maximal repetitions for both concentric and eccentric contractions, to ensure reliable data in the isokinetic muscle testing (Chan et al. 1996). After correction for the gravitational effect on the knee torque, 5 maximal contractions of the concentric knee extensors and flexors were recorded as a test ensemble. This was followed after a 1-minute rest by an eccentric test of both muscle groups (Chan et al. 1996). A 10-minute warm-up, including stretching of the knee muscle groups and 3-minutes of static bicycling at the subject's comfortable speed, was performed before the familiarization trials and the actual muscle strength testing.

The average of the 3 highest peak torques from the 5 repetitions was normalized to subject's body weight, termed "peak torque-to-body weight" ratio, and was used as an outcome measure to compare the muscle strength of the 2 elderly groups (Urquhart et al. 1995). The hamstrings to quadriceps (H/Q) strength ratio was employed to evaluate whether the strength increase in the agonist/antagonist pair was to a similar or different extent (Chan et al. 1996).

4.3.3 Static standing balance test

The elderly subjects underwent a static standing balance test by standing quietly with the feet together on a force platform (Kistler, model 9286AA, Switzerland) for 30s, with their eyes open. The maximum body sway in the anteroposterior and mediolateral directions during the 30s stance was calculated, using a method which will be described in the section on data recording and analysis.

4.3.4 Perturbed single-leg stance test

After the static standing balance test, the elderly subjects underwent a dynamic single-leg standing balance test. Subjects stood without shoes using only their dominant leg on a movable platform of a computerized dynamic posturography machine (NeuroCom International Inc., type Smart EquiTest®, Portland, USA), while wearing a security harness to prevent falls. The wearing of harness will provide touch as well as pressure stimulation to the subjects which may affect their balance control. However, this possible confounding effect has been controlled by the inclusion of a control group similar in weight and height and wearing the same harness. Subjects were instructed to stand on their dominant leg as still as possible, with their arms by their sides, their eyes looking forward, and their non-dominant leg off the ground and flexed 90° at the knee. They were then perturbed with either forward or backward platform translation in a random order. In order to minimize subject's anticipation, perturbations were initiated after a random delay of 2 to 7s. The computerized dynamic posturography equipment scaled the platform translation amplitudes according to the subject's height, to give an anteroposterior body sway of 3.2° (NeuroCom 2000). The translation lasted for 400ms. The center of pressure (COP) measured by 4 sensors mounted on the support surface was used to estimate the anteroposterior body sway of subjects undergoing the perturbations. The average of the maximum anteroposterior body sways recorded over 3 trials was used to compare the balance control of the 2 elderly groups for each perturbation direction.

4.3.5 Activities-specific balance confidence (ABC) scale

The Activities-specific Balance Confidence (ABC) scale was used to investigate the elderly subjects' perception of their balance confidence in daily activities (Powell and Myers 1995). The scale consisted of 16 items describing daily living tasks. The subjects were asked to rate the 16 items using a 0–100 response continuum, with 0 representing no confidence and 100 complete confidence. The items included: walk around the house, climb up and down stairs, pick up a slipper from the floor, reach an object at eye level, reach an object on tiptoes, stand on a chair to reach, sweep the floor, walk outside to a nearby bus stop, get in and out of a bus, walk across a parking lot, walk up and down a ramp, walk in a crowded mall, being bumped while walking in a crowd, use an escalator while holding rail, use an escalator without holding the rail, and walk in a wet market. Any reference to a "car" in the original scale was replaced by "bus" in this study, as it is not common for the elderly subjects in Hong Kong to use a car. In addition, the last item of the original scale was changed from "walk on icy sidewalks" to "walk in a wet market" so as to suit the local situation. A wet market is an indoor market with meat, vegetables and other goods laid out in the style of a bazaar, where the floors are often wet and slightly slippery. The ABC score ratio was presented as a percentage of the total score of 1600 (a maximum of 100 for each of the 16 items) for comparison between the 2 elderly groups (Powell and Myers 1995).

4.3.6 Data recording and analysis

4.3.6.1 Static standing balance

The COP, as measured by 4 sensors attached to the force platform, was recorded and used to estimate the amount of body sway during the 30s of quiet stance with the eyes open. This was expressed as the *sway angle*, a term commonly used to measure the control of body sway as explained in Chapter 1 (section 1.2.5.3) (Shepard et al. 1993).

4.3.6.2 Perturbed single-leg stance

All the posturography data were smoothed using a second order Butterworth low pass filter with a cutoff frequency of 0.85 Hz. They were then used to estimate the body sway in the perturbed single-leg stance tests. The body sway was first recorded for 2 seconds before the platform translation. The average value of the body sway angle during the 2 seconds served as the baseline. After the platform pertubation, the maximum sway angle was estimated and the difference from the baseline value, termed the *perturbed sway angle*, was calculated. A total of 3 trials for each perturbation direction were performed, and the average value was used to compare the 2 elderly groups. An amount of 12.5°, the theoretical anteroposterior sway stability limit, was assigned as the perturbed sway angle if any subject fell during the platform perturbation (NeuroCom 2000). A "fall" in the perturbed single-leg stance test was recorded when the subject began to fall and touched the visual surround for support, or gained support by using the non-dominant leg (NeuroCom 2000).

4.3.7 Statistical analysis

Age, weight and height were compared between the 2 elderly groups using independent t-tests. Because of the categorical nature of the variables, a chi-square test was considered more appropriate for between-group comparison of the gender distribution and physical activity levels. ANCOVA model with gender and group as fixed factors was used to investigate the effect of gender on the outcome measures and across the two groups. An (3,k) intraclass correlation coefficient (ICC) model was applied to assess the test-retest reliability of the knee muscle strength, the body sway angle during static standing and perturbed single-leg stance, and the ABC score ratio. The ICC model 3 was used for assessing intra-rater reliability, with "k" denoting the number of trials used in the different tests. Multivariate analysis of variance was used to compare the outcome measures recorded during muscle strength test, as well as static standing and perturbed single-leg stance tests between the elderly Tai Chi and control subjects. If statistically significant differences were found in the multivariate tests, univariate tests were conducted for each of the outcome measures. For between-group comparison of the hamstrings to quadriceps (H/Q) muscle strength and ABC score ratio, an independent t-test was employed. A Pearson product-moment coefficient of correlation was used to correlate the outcome measures obtained in the knee muscle strength test, with 1) maximum anteroposterior and mediolateral body sway angles in the static standing balance test, 2) anteroposterior body sway angles in perturbed single-leg stance in forward and backward platform translations, and 3) the ABC score ratio. A significance level (α) of 0.05 was chosen for the statistical comparisons.

4.4 Results

4.4.1 Subjects

Forty-eight community-dwelling elderly subjects, 24 Tai Chi practitioners and 24 controls, all aged 60 or older, participated in this study. Independent t-tests showed that there was no statistically significant difference in age, height, or weight between the elderly Tai Chi and control subjects ($P > 0.05$; Table 4.1). Chi-square tests found no statistically significant difference between the groups in either gender distribution or physical activity level ($P > 0.05$; Table 4.1). The Tai Chi and control subjects were thus similar with respect to age, height, weight, gender, and physical activity levels. All the subjects had scored at least 24 on the Mini-Mental Status Examination. The ANCOVA model showed a gender difference in the knee muscle strength test (P = 0.003; Table 4.2) but not in body sway during static standing, perturbed single-leg stance test and ABC score ratio (P > 0.05; Table 4.2). Since gender distribution was the same in the two groups (N = 12 each of female and male), and since there was no interaction between gender and group, data from male and female subjects were grouped together for statistical analysis in this study.

TABLE 4.1. Comparison of age, height, body weight, gender and physical activity level between elderly Tai Chi and control subjects.

	Tai Chi subjects (*N* = 24)	**Control subjects (*N* = 24)**	***P***
Age (years)	69.3 ± 5.0	71.6 ± 6.1	0.148
Height (cm)	156.5 ± 8.8	154.5 ± 8.7	0.432
Body Weight (kg)	58.2 ± 8.5	58.0 ± 9.0	0.963
Gender (male, female)	12M, 12F	12M, 12F	1.0
Physical activity level			0.232
Light ≤ 4 METs	*N* = 17	*N* = 21	
Moderate ≤ 5.5 METs	*N* = 5	*N* = 3	
Heavy > 5.5 METs	*N* = 2	*N* = 0	

NOTE: Values are mean ± SD for this and all subsequent tables.

TABLE 4.2. Compare the effect of gender on the measures and across the two older adult groups.

	Gender P	Gender x group P
Knee muscle strength	0.003†	0.540
Static standing	0.578	0.245
Perturbed single-leg stance	0.110	0.832
ABC scale	0.150	0.720

"x" Denotes interaction between gender and group variables.

† Denotes significant difference at $P < 0.01$

4.4.2 Test-retest reliability of knee muscle strength, body sway angles during the two standing balance tests and Activities-specific Balance Confidence (ABC) score ratio

Four males and 7 females with a mean age of 70.8 years (± SD 4.0 years) were recruited for the test-retest reliability study. The knee muscle strength test, the two standing balance tests and the ABC scale were re-administered to these subjects 1 week afterwards. For the isokinetic knee muscle strength test, the ICC(3,3) values for the concentric knee extensors, concentric knee flexors, eccentric knee extensors and eccentric knee flexors were 0.97 (confidence intervals 0.89–0.99), 0.86 (confidence intervals 0.43–0.97), 0.97 (confidence intervals 0.89–0.99) and 0.95 (confidence intervals 0.81–0.99) respectively. For the static standing balance test, the ICC(3,3) values for the maximum anteroposterior and mediolateral body sway angles were 0.82 (confidence intervals 0.21–0.96) and 0.85 (confidence intervals 0.23–0.97) respectively. For the perturbed single-leg stance test, the ICC(3,3) values for the maximum anteroposterior body sway angles in forward translation and backward translation were 0.81 (confidence intervals 0.51–0.93), 0.74 (confidence intervals 0.35–0.90) respectively. The ICC(3,1) value for the ABC score ratio was found to be 0.91 (confidence intervals 0.71–0.98). In other words, all the tests used in this study were found to produce reliable outcome measures.

4.4.3 Knee muscle strength

The multivariate tests of the knee strength results indicated an overall statistically significant effect across the 4 outcome measures between the Tai Chi and control subjects (P = 0.044). The univariate tests showed that there were statistically significant differences in the muscle strength of concentric knee extensors (P = 0.004; Table 4.3), concentric knee flexors (P = 0.021), eccentric knee extensors (P = 0.049), and eccentric knee flexors (P = 0.007) between the 2 elderly groups. The Tai Chi practitioners achieved significantly higher peak torque-to-body weight ratios with both their knee extensors and flexors in both concentric and eccentric isokinetic testing at $30° \cdot s^{-1}$. An examination of the concentric H/Q strength ratios for the elderly Tai Chi and control subjects yielded 0.49 and 0.50 respectively (P = 0.764 in the independent t-test), whereas the eccentric H/Q strength ratios were

0.67 and 0.61 respectively (P = 0.131). In other words, our findings show that the elderly Tai Chi practitioners had strength increase to a similar extent in their agonist/antagonist pairs in both concentric and eccentric muscle contractions.

4.4.4 Static standing and perturbed single-leg stance

The Tai Chi and control subjects performed equally well in terms of their anteroposterior and mediolateral body sway angles during the static standing test. Multivariate tests of the results showed no significant difference between the Tai Chi and control subjects (P = 0.498). The mean maximum anteroposterior body sway angles for the Tai Chi and control subjects were 1.6 ± 0.4° and 1.8 ± 0.5° respectively (P = 0.411; Table 4.3). The mean maximum mediolateral body sway angles were 1.5 ± 0.3° and 1.6 ± 0.5° respectively (P = 0.235; Table 4.3).

However, multivariate tests of the perturbed single-leg stance results indicated an overall statistically significant effect across these 2 outcome measures between the Tai Chi and control subjects (P < 0.001). The univariate tests showed that the Tai Chi practitioners achieved less body sway during forward platform translation (mean = 7.2 ± 2.1°) than did the control subjects (mean = 10.0 ± 2.9°; P < 0.001; Table 4.3), as well as during backward platform translation (mean = 6.2 ± 2.1° and 9.7 ± 3.2° respectively; P < 0.001).

4.4.5 Activities-specific balance confidence (ABC) scale

The Tai Chi practitioners reported having more balance confidence as assessed by the ABC scale than did the elderly control subjects, with score ratios being 98.0 ± 3.0% and 90.7 ± 9.5% respectively (P = 0.001; Table 4.3). In other words, the Tai Chi practitioners had more balance confidence in performing their daily tasks than did the elderly control subjects.

TABLE 4.3. Comparison of knee muscle strength, body sway angle in static standing and perturbed single-leg stance, and ABC score ratios between elderly Tai Chi and control subjects.

	Tai Chi subjects (N = 24)	**Control subjects (N = 24)**	***P***
Knee muscle strength – Peak torque-to-body weight ratio in $N{\cdot}m{\cdot}kg^{-1}$			
Concentric knee extensors	1.5 ± 0.4	1.1 ± 0.4	0.004**
knee flexors	0.7 ± 0.3	0.5 ± 0.3	0.021*
Eccentric knee extensors	1.7 ± 0.6	1.4 ± 0.4	0.049*
knee flexors	1.1 ± 0.3	0.8 ± 0.3	0.007**
Static standing balance – Maximum body sway angle (°)			
Anteroposterior	1.6 ± 0.4	1.8 ± 0.5	0.411
Mediolateral	1.5 ± 0.3	1.6 ± 0.5	0.235
Perturbed single-leg stance – Maximum anteroposterior body sway angle (°)			
Forward platform translation	7.2 ± 2.1	10.0 ± 2.9	0.000**
Backward platform translation	6.2 ± 2.1	9.7 ± 3.2	0.000**
ABC score ratio (%)	98.0 ± 3.0	90.7 ± 9.5	0.001†

* and ** denote significant difference at $P < 0.05$ and $P < 0.01$ respectively using univariate tests, after multivariate analysis of variance tests showing an overall statistically significant difference at $P = 0.044$ for the isokinetic knee muscle strength test and $P < 0.001$ for the perturbed single-leg stance test.

† Denotes significant difference at $P < 0.01$ after an independent t-test.

4.4.6 Correlation of knee muscle strength with outcome measures of static standing, perturbed single-leg stance and ABC tests

Correlations among the 4 outcome measures from the knee muscle strength test on the one hand, and the outcome measures from the static standing test (maximum anteroposterior and mediolateral body sway angles), the perturbed single-leg stance test (maximum anteroposterior body sway in forward and backward platform translations) and the ABC score ratio on the other hand, were analyzed using Pearson's product-moment coefficient of correlation. Table 4.4 shows that the 4 outcome measures from the knee muscle strength tests were not statistically correlated with the maximum body sway angles in the static standing balance test (all $P > 0.05$). However, they were all inversely correlated with the body sway angles obtained from forward and backward platform perturbations during the single-leg stance test (all $P < 0.05$; Table 4.4). In other words, subjects who exhibited higher peak torque-to-body weight ratios swayed less during platform perturbations in either a forward or backward direction. Also, all the outcome measures of knee muscle strength were correlated with the ABC score ratios (all $P < 0.05$; Table 4.4). This finding shows that subjects who had stronger knee muscles reported more balance confidence in their daily activities. On performing further correlation analysis, we discovered that the body sway angles during single-leg stance subjected to forward and backward platform perturbations were in fact negatively correlated with the ABC score ratio (-0.383 and -0.432 respectively, all $P < 0.05$). In other words, subjects who swayed less during perturbed single-leg stance reported better balance confidence.

TABLE 4.4. Pearson product-moment coefficient of correlation between the outcome measures of the knee muscle strength test and those of the static standing, perturbed single-leg stance and ABC tests.

	Knee extensor strength ($N = 48$)		**Knee flexor strength** ($N = 48$)	
	Concentric	Eccentric	Concentric	Eccentric
Static standing				
Maximum anteroposterior body sway angle	0.021 (0.889)	0.022 (0.884)	-0.039 (0.794)	-0.075 (0.616)
Maximum mediolateral body sway angle	-0.082 (0.585)	-0.095 (0.524)	-0.069 (0.644)	-0.117 (0.434)
Perturbed single-leg stance				
Maximum anteroposterior body sway angle				
Forward platform perturbation	-0.529 (0.000)**	-0.496 (0.000)**	-0.335 (0.023)*	-0.440 (0.002)**
Backward platform perturbation	-0.441 (0.002)**	-0.468 (0.001)**	-0.413 (0.004)**	-0.371 (0.011)*
ABC score ratio	0.405 (0.005)**	0.318 (0.030)*	0.446 (0.002)**	0.394 (0.006)**

* and ** denote significant difference at $P < 0.05$ and $P < 0.01$ respectively using the Pearson product-moment coefficient of correlation.

4.5 Discussion

4.5.1 Effect of Tai Chi practice on knee muscle strength

The elderly Tai Chi practitioners demonstrated significantly greater knee extensor and flexor muscle strength in both concentric and eccentric contractions when compared with those of control subjects ($P = 0.044$; Table 4.3). They were 36% stronger in concentric knee extensor contraction (mean = 1.5 ± 0.4 $N \cdot m \cdot kg^{-1}$ for Tai Chi practitioners and 1.1 ± 0.4 $N \cdot m \cdot kg^{-1}$ for control subjects; $P = 0.004$; Table 4.3), and 40% greater in concentric knee flexor contraction (mean = 0.7 ± 0.3 $N \cdot m \cdot kg^{-1}$ and 0.5 ± 0.3 $N \cdot m \cdot kg^{-1}$ respectively; $P = 0.021$; Table 4.3). These results are in agreement with those of Lan et al. (1998), who showed that elderly participants had significant strength improvement in both concentric knee extension and flexion after 12-months of Tai Chi training. However, the respective increases of 19.2% and 15.7% found by these investigators were comparatively less than those found in our present study (36% and 40%). Our having adopted a slower isokinetic testing speed of $30° \cdot s^{-1}$, their having analyzed only the highest peak torque among the 5 maximal extension-flexion contractions, and/or the longer experience of our Tai Chi subjects (mean = 8.5 ± 7.6 years) versus theirs of 1 year may explain the difference between our findings and theirs.

Our results also demonstrate that elderly Tai Chi practitioners had higher eccentric contraction strength in their knee extensors (21% increase, mean = 1.7 ± 0.6 $N \cdot m \cdot kg^{-1}$ for Tai Chi practitioners and 1.4 ± 0.4 $N \cdot m \cdot kg^{-1}$ for control subjects; $P = 0.049$; Table 4.3) and knee flexors (37.5% increase, mean = 1.1 ± 0.3 $N \cdot m \cdot kg^{-1}$ and 0.8 ± 0.3 $N \cdot m \cdot kg^{-1}$ respectively; $P = 0.007$). Our findings of significantly higher knee flexor muscle strength in both concentric and eccentric contractions among the elderly Tai Chi practitioners were different from those observed by Wu et al. (2002). These investigators found no significant difference in knee flexor strength between Tai Chi practitioners and control elderly subjects. Since the experimental set-up was similar in terms of the functional range of muscle testing, the reason might be the lower isokinetic testing speed adopted in our study ($30°\cdot s^{-1}$) versus theirs ($60°\cdot s^{-1}$ and $120°\cdot s^{-1}$). Note that Tai Chi practice involves mainly slow movements (Tsao 1995). Various studies have shown that muscle strength gains are consistently greatest at the training velocity, termed "velocity specificity" (Cronin et al. 2002; Morrissey et al. 1995). Therefore, the lower isokinetic testing speed employed in the present study may be able to reflect the improved muscle strength of the elderly Tai Chi practitioners, especially for the knee flexor muscles, which was not found by Wu et al. at higher isokinetic testing speed.

The frequent knee bending involved in performing various Tai Chi forms may explain the greater knee extensor strength of the Tai Chi practitioners (Flanagan et al. 2003). The increased knee flexor strength may be due to the training in the closed kinetic chain position adopted during Tai Chi practice. In this connection, the primary knee flexors are the hamstrings and gastrocnemius muscles. Both muscle groups are two-jointed muscles, with the hamstrings crossing the hip and knee joints and the gastrocnemius crossing the knee and ankle joints. Bending the knees in a closed kinetic chain standing position requires hip flexion with simultaneous ankle dorsiflexion (Flanagan et al. 2003). Hence, both the hamstrings and gastrocnemius are required to contract with their origin and insertion reversed. EMG studies have shown that the hamstrings and gastrocnemius contracted at 20% to 60% of their maximum isometric voluntary contractions in different phases during double-leg squatting (Flanagan et al. 2003). In a single-leg stance squatting protocol, the maximum hamstrings activation was found to be 81% of the maximum isometric voluntary contraction (Beutler et al. 2003). As Tai Chi practice involves a lot of squatting in double-leg and single-leg stance, it could explain why experienced Tai Chi practitioners had improved knee flexor muscle strength. However, further investigation of the muscle work during different Tai Chi forms is warranted.

Elderly Tai Chi practitioners not only did have greater knee muscle strength, our findings further show that the extent of their strength increase was similar in both the agonists and antagonists. Briefly, the concentric H/Q strength ratio was 0.49 and the eccentric H/Q strength ratio was 0.67, which was no different from the respective value of 0.51 and 0.61 found in elderly control subjects (all $P > 0.05$). This may be due to the closed kinetic chain positioning adopted during Tai Chi practice, as it requires co-contraction of the agonist-antagonist muscles, which controls joint movement in three-dimensions (Kannus 1994). Exercises only targeting at the agonists may cause muscle imbalance, which will predispose the participants to injury. Muscle imbalance between the agonist and antagonist muscles may cause joint instability, as often seen in sports activities (Söderman et al. 2001). Closed kinetic chain exercise like Tai Chi may have the advantage of improving the muscle strength of agonists and antagonists to a similar extent.

As discussed in Chapter 1 (section 1.3.2), muscle strength has been shown to decline with age. This is due to an overall loss of type I and type II muscle fibers, with a significant atrophy of the latter (Vandervoort 2002). Recent investigation has revealed that eccentric muscle training may provide an effective stimulus for adaptive changes in muscle tissues. Hortobágyi et al. (2000) conducted a study in which 48 men and women (mean age = 22 years) had their knees immobilized for 3 weeks. After 12 weeks of training involving eccentric, concentric or combined contractions, the investigators found that both the eccentric and combined training protocols could achieve faster strength recovery and greater eccentric and isometric strength gains, when compared with the subjects receiving only concentric training. In another study, LaStayo et al. (2003) administered eccentric training to 21 frail elderly subjects (mean age = 80 years) for 11 weeks. They found that the experimental group had significantly more improvements in knee extension isometric strength when compared those receiving a traditional weight training program.

Administering eccentric training to the elderly subjects may not be easy (Vandervoort 2002). LaStayo et al. (2003) tried to overcome this by designing an eccentric ergometer powered by a motor driving the pedals in a backward direction. However, the applicability of this technique is limited by the fact that the intensity of the ergometer must be individually designed and monitored, and by the need for having such a special equipment to undergo the training. Tai Chi practice does not require equipment or large space. Using one's body weight for resistance training is safe and cost-effective, and practitioners can vary the degree of knee bending according to their ability and comfort. There has been no known report of adverse effects from long-term Tai Chi practice. The eccentric training components of Tai Chi can thus become an effective and easy means of eccentric muscle strength training to the elderly subjects.

4.5.2 Static standing and perturbed single-leg stance

The static standing balance test did not reveal any difference in balance performance between the Tai Chi practitioners and the control subjects. More specifically, no significant difference in the maximum anteroposterior and mediolateral body sway angles was found between the 2 groups ($P = 0.411$ and $P = 0.235$ respectively; Table 4.3). In contrast, during the perturbed single-leg stance test, the elderly Tai Chi practitioners demonstrated significantly less body sway during both forward ($P < 0.001$; Table 4.3) and backward platform translations ($P < 0.001$).

The results of our static standing tests differ from those of Wu et al. (2002) in that their elderly Tai Chi subjects had significantly less body displacement in both the anteroposterior and mediolateral directions than their control subjects. This may be due to the more stringent inclusion criteria adopted in the present study, such as recruitment of control subjects with similar physical activity level ($P = 0.232$; Table 4.1), as well as the absence of a history of falls over the past 12 months.

The practice of Tai Chi requires constant weight shifting between double-leg and single-leg stance, and execution of various arm and leg movements during single-leg stance such as in a form called "golden hen single-leg stance, 金鷄獨立). Such weight shifting demands a higher degree of balance control from the Tai Chi practitioners. In a cross-sectional study, Tse and Bailey (1992) found that elderly people with more than 1 year of Tai Chi practice could maintain single-leg standing longer than their sedentary counterparts in right and left leg standing with the eyes open. Later, Hong et al. (2000) found that practitioners with more than 10 years of Tai Chi experience could maintain single-leg standing with their eyes closed for a significantly longer period than non-Tai

Chi practitioners. The present study demonstrated that elderly Tai Chi practitioners had better balance control even in single-leg stance against platform perturbations. All these observations may be explained by the fact that in different Tai Chi forms, the practitioners are required to perform different movements with their other limbs during single-leg stance, which clearly demands greater balance control (Tsao 1995). For example, in one Tai Chi maneuver, termed "kick with the heel, 蹬腳", the practitioner lifts the non-weight bearing leg as high as possible while simultaneously opening and holding their arms horizontally (Fig. 4.1b). In another Tai Chi move, "repulse the monkey, 倒撵猴", once the practitioners have lifted the leg, they need to extend it backward while simultaneously pushing forward with their opposite arm (Fig. 4.1c). These two examples illustrate the demand for greater balance control during single-leg stance, when movements of both arms and the other leg are performed simultaneously in different directions.

FIGURE 4.1b - "Kick with the heel, 蹬腳" maneuver.

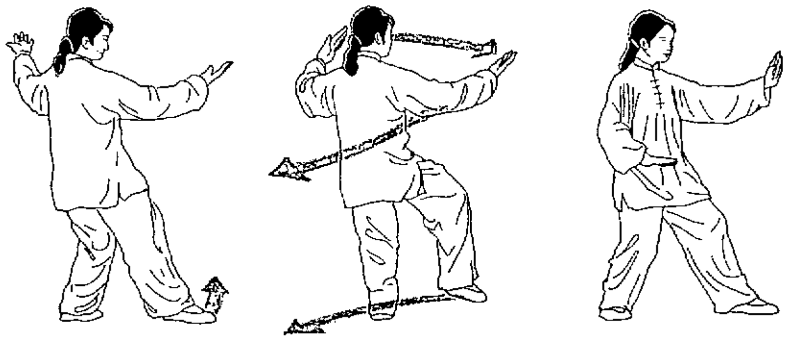


FIGURE 4.1c - "Repulse the monkey, 倒攆猴" maneuver.

Our findings thus suggest that long-term practice of Tai Chi could improve the control of body sway during perturbed single-leg stance in the elderly practitioners, who had mean Tai Chi experience of 8.5 ± 7.6 years. As falls seldom occur during double-leg stance, the improved single-leg stance during platform perturbation could explain the reduction in the risk of multiple falls by 47.5% in the elderly Tai Chi practitioners, as shown by Wolf et al. (1996).

4.5.3 Activities-specific balance confidence (ABC) scale

Both elderly groups in this study reported high ABC score ratios. With the mean ratio above 90%, they can be regarded as having good balance confidence (Powell and Myers 1995). The high ABC score ratio could be explained by the fact that our elderly participants in both groups were healthy and had no history of falls in the past 12 months. Falls can lead to fractures, soft tissue injuries, joint dislocations and mobility impairments. They may also lead to fear of falls, which can result in self-imposed activity restriction (Myers et al. 1998). This reduced activity can cause further deterioration of balance control in elderly subjects. However, such a vicious cycle can be broken by a suitable intervention program (Myers et al. 1998). In this connection, Wolf et al. (1996) conducted a 15-week Tai Chi intervention program with a group of community dwelling elderly subjects aged 70 or above. They found that the Tai Chi participants had reduced their fear of falling as compared to a control group after intervention. The Tai Chi practitioners in this study had significantly higher ABC score ratio (98.0%) than those of the control subjects (90.7%; P = 0.001; Table 4.3). The improved balance control in the Tai Chi practitioners as reported in Chapter 2 and 3 (see also Tsang et al. 2001; Tsang et al. 2004; Tsang and Hui-Chan 2003), coupled with the improved single-leg stance performance and balance confidence shown in the present study, might help to maintain their physical activity level and balance control, and reduce the risks of their falling as they age further.

4.5.4 Correlation of knee muscle strength with outcome measures of the static standing, perturbed single-leg stance and ABC tests

The 4 outcome measures from the knee muscle strength tests were not correlated with the body sway measured in the static standing balance test. However, greater muscle strength in both the knee extensors and flexors was associated with smaller body sway angles in the perturbed single-leg stance test (all $P < 0.05$; Table 4.4). These findings differ from those of Wu et al. (2002), who found a significant correlation of knee extensor but not flexor strength with body sway in static double-leg standing. The significant negative correlations observed in the present study between the strength of both the knee extensors and flexors on the one hand, and body sway in perturbed single-leg stance on the other, may be due to the need to recruit both agonists and antagonists to maintain balance control during single-leg stance. Furthermore, platform perturbations during single-leg stance would demand greater muscle contractions and even additional muscle groups to counteract the perturbations. In a forward platform translation which will induce backward body sway by virtue of inertial force, the ankle dorsiflexors, knee extensors, and abdominal muscles are recruited to maintain bipedal balance and erect standing (Shumway-Cook and Woollacott 2001). In a backward platform translation which will lead to forward body sway, the ankle plantarflexors, knee flexors, and back extensors are recruited (Shumway-Cook and Woollacott 2001). The more demanding balance control in perturbed single-leg stance is suggested by the relatively higher negative correlation coefficient values between knee extensor strength and body sway angles, ranging from -0.529 to -0.441 (all $P < 0.05$; Table 4.4), when compared with those of Wu et al. (2002) in double-leg stance (-0.37 to -0.28). Moreover, the negative correlation coefficient values between knee flexor strength and body sway angles during perturbed single-leg stance in our study were all significant, with values ranging from -0.440 to -0.335 ($P < 0.05$; Table 4.4). These findings illustrate that improved muscle strength can enhance more demanding balance control leading to less body sway during perturbed single-leg stance.

Significant positive correlations between concentric and eccentric knee extensor and flexor strength and the ABC score ratios were found, ranging from 0.318 to 0.446 (all $P < 0.05$; Table 4.4). This result indicates that greater knee muscle strength leads to more confidence in activities requiring good balance control in the elderly subjects. On further correlation analysis, we discover significant negative correlations between body sway angles during perturbed single-leg stance and ABC score ratios (all $P < 0.05$). This finding suggest that less body sway during perturbed single-leg stance was associated with better subjective report of balance confidence, when elderly people perform functional activities which could involve single-leg stance and moving support surface. A notable example is stepping onto a moving escalator without holding the rail.

4.6 Conclusions

In conclusion, our present study provides experimental evidence that experienced elderly Tai Chi practitioners have stronger knee extensor and flexor muscle strength in both concentric and eccentric contractions, less body sway in perturbed single-leg stance, and greater balance confidence than control subjects similar in age, gender, height, weight and physical activity level. Further, their knee muscle strength was negatively correlated with body sway angles in perturbed single-leg stance and positively correlated with Activities-specific Balance Confidence score ratios. This finding reveals the importance of knee muscle strength in both actual balance performance and subjective balance confidence. The finding of a negative correlation between body sway angles during perturbed single-leg stance and a subject's balance confidence points to the importance of balance control during single-leg stance against platform perturbations in the elderly balance confidence in their daily activities.

CHAPTER 5

EFFECTS OF 4- AND 8-WEEKS INTENSIVE TAI CHI TRAINING ON BALANCE CONTROL IN THE ELDERLY

Publication

TSANG, W. W. N., and C. W. Y. HUI-CHAN. Effect of 4- and 8-wk intensive Tai Chi training on balance control in the elderly. *Med. Sci. Sports Exerc.* 36:648-657, 2004.

Conference abstract

HUI-CHAN, C. W. Y., and W. W. N. TSANG. Two months of Tai Chi practice is sufficient to improve balance control in the well elderly? In *1st International Conference on Tai Chi Chuan*. Hong Kong, pp.22-23, 2001.

5.1 Abstract

Purpose: The objective of this study was to examine whether 4 and/or 8 weeks of intensive Tai Chi practice could improve balance control in the healthy elderly subjects.

Methods: Forty-nine community-dwelling elderly subjects (aged 69.1 ± SD 5.8 years) voluntarily participated in an intervention program of either supervised Tai Chi or general education for 1.5 hours, 6x week^{-1} for 8 weeks. Two balance tests were administered using computerized dynamic posturography before, at 4 and 8 weeks during training, and at 4 weeks after training ended: 1) The sensory organization test measured subjects' abilities to use somatosensory, visual and vestibular information to control their body sway during stance under 6 sensory conditions; and 2) the limits of stability test measured subjects' abilities to voluntarily weight shift to 8 spatial positions within their base of support. These outcome measures were compared between the 2 intervention groups, and with those of experienced Tai Chi practitioners having means of 7.2 and 10.1 years of practice from 2 previous studies.

Results: Statistical analysis demonstrated that, after 4 and 8 weeks of intensive Tai Chi training, the elderly subjects achieved significantly better 1) vestibular ratio in the sensory organization test (P = 0.006) and 2) directional control of their leaning trajectory in the limits of stability test (P = 0.018), when compared with those of the control group. These improvements were maintained even at follow-up 4 weeks afterwards. Furthermore, the improved balance performance from week 4 on was comparable to that of experienced Tai Chi practitioners.

Conclusions: The above findings indicated that even 4 weeks of intensive Tai Chi training are sufficient to improve balance control in the elderly subjects.

Key Words: AGING, FALLS, INTERVENTION, EXERCISE, POSTURAL STABILITY

5.2 Introduction

Falls have been identified as one of the major causes of morbidity and mortality in the elderly people (Wolter and Studenski 1996). As the population ages, the incidents of falls will rise, together with associated increase in the healthcare cost. In the United States, the cost of hip fracture attributed to falls in the elderly had been reported to be about $10 billion in 2001 (Carter et al. 2001). This represents a major financial burden to society. Among the various intrinsic (within the person) and extrinsic (within the environment) causes, impaired balance control has been identified as a major intrinsic factor that causes falls in the elderly subjects (Carter et al. 2001). Effective exercise programs to improve balance control should therefore be developed, to minimize the occurrence of falls in the elderly population.

In this regard, Tai Chi is a time-honored martial art form that has been practiced by millions of elderly Chinese over the last 300 years (Tsao 1995). However, it is only since the early 1990s that researchers have started to systematically investigate the effects of Tai Chi on balance control. In 1992, Tse and Bailey (1992) conducted a cross-sectional study, and found that elderly Tai Chi practitioners with more than 1 year of Tai Chi experience had better balance control than their sedentary counterparts in right and left leg standing with eyes open. In 2000, Hong et al. reported that Tai Chi practitioners sustained significantly longer duration in single leg standing with their eyes-closed than the non-Tai Chi subjects. They attributed the better single leg stance performance in the eye-closed condition to the duration of Tai Chi experience (>10 years) in the Tai Chi practitioners.

In 2001, Wong et al. compared the sway amplitude of elderly Tai Chi practitioners with experience ranging from 2 to 35 years to that of an active elderly group, when they stood under 6 combinations of visual (eyes open, eyes closed, sway-referenced) and support surface (fixed, sway-referenced) conditions in the sensory organization test (SOT). They found that the elderly Tai Chi practitioners swayed significantly less than the control group in the more challenging conditions, when the somatosensory input was disrupted together with absent or conflicting visual input. In the same year, we demonstrated that the SOT produced reliable outcome measures, and that the elderly Tai Chi practitioners (experience ranging from 1 to 23 years) exhibited better balance control, when they stood under sensory conditions that demanded an increased reliance on the visual and vestibular systems than the non-Tai Chi practitioners similar in age, sex, and physical activity level (Tsang et al. 2001). Of particular interest, as presented in Chapter 3, is that the elderly Tai Chi practitioners attained the same level of balance control performance in the SOT as the young, healthy subjects when standing under reduced or conflicting somatosensory, visual and vestibular conditions (Tsang et al. 2004).

In Chapter 2, we presented our findings to demonstrate that the elderly Tai Chi practitioners (with mean experience of 10.1 ± SD 9.5 years) achieved significantly better knee proprioception sense, in that they showed smaller knee angle errors in the passive knee repositioning test when compared with those of the control subjects similar in age and physical activity level (Tsang and Hui-Chan 2003). Using the limits of stability (LOS) test which we demonstrated to be reliable, we further showed that these experienced Tai Chi practitioners initiated voluntary shifting of their weight to different spatial positions within the base of support more quickly, leaned further without losing their stability, and showed better control of their leaning trajectory than those of the control subjects (Tsang and Hui-Chan 2003). In this connection, the deterioration of these balance performance had been found to be related to falls in elderly subjects (Girardi et al. 2001; Ho et al. 1998). Therefore, the improved balance control in experienced Tai Chi practitioners could explain the reduction in the risk of multiple falls by 47.5% in the elderly Tai Chi practitioners, as reported by Wolf and colleagues (1996).

However, the above studies employed a cross-sectional design. As such, the improved balance control could have been attributed to factors other than long-term Tai Chi practice. For instance, it could be argued that these Tai Chi practitioners already had better balance control before they took up practicing Tai Chi. To circumvent the possibility of sample bias, a control trial with a prospective design is needed. In this context, Wolf et al. (1997b) compared the effect of 15 weeks of Tai Chi practice (2 hour·week^{-1}) with computerized balance training and education using the elderly subjects. They found that the Tai Chi practitioners did not improve their postural stability as measured by computerized dynamic posturography during quiet stance and toes-up perturbation (angular perturbation of 4° over 4 s), when compared with that of the balance training group. As discussed in Chapter 1 (section 1.6.2), such findings could be attributed to insufficient Tai Chi training in terms of the duration of each training session, the number of training sessions each week (frequency), and/or the total period of intervention. Alternatively, the use of toe-up perturbation as an outcome of balance performance in a Tai Chi study could be either inappropriate (Horak 1997), or not challenging enough to the balance control system (Wong et al. 2001).

Quite aside from the design and methodological issues mentioned above, most if not all of the cross-sectional studies (e.g., Hong et al. 2000; Tse and Bailey 1992; Wong et al. 2001), including those of ours (Tsang et al. 2001; Tsang et al. 2004; Tsang and Hui-Chan 2003) have examined Tai Chi practitioners with from 1 to over 10 years of experience. In considering Tai Chi training as a possible falls-prevention strategy, a question naturally arises. How long will it take practicing Tai Chi for the elderly subjects to achieve significantly better balance control than their sedentary counterparts? In order to determine the length of training period needed for Tai Chi practice to produce a significant improvement in balance control, we analyzed the relationship between the balance performances as assessed by the SOT and the LOS test, and the number of years of Tai Chi experience, and found a lack of relationship between the two. We therefore surmised that Tai Chi practitioners could have improved their balance control after only "weeks" rather than "years" of training. Therefore, the main objective of the present study was to investigate the effects of short-term (8 weeks of) intensive Tai Chi training on the balance performance of elderly subjects, by comparing their outcome measures with: 1) those of a control group receiving general education for a comparable time period and 2) those of practitioners who had practiced Tai Chi for a year or longer. In order to map out the time course of the effects of this intensive Tai Chi training program on balance control, we conducted assessments at 4 time intervals: before, at 4-week intervals during the 8 weeks of training, and at 4 weeks after the training had ended for follow-up that are detailed below.

5.3 Methods

5.3.1 Subjects and study design

Forty-nine community-dwelling elderly subjects (20 men and 29 women), mean age of 69.1 ± 5.8 years, participated in the present study. None of the subjects had previous experience in practicing Tai Chi. They were independent in their activities of daily living and required no walking aids. They were able to communicate and follow the testing procedures. Exclusion criteria were the presence of severe cognitive impairments, symptomatic cardiovascular diseases at moderate exertion level, poorly controlled hypertension or symptomatic orthostatic hypotension, the diagnosis of a stroke, Parkinson's disease, or other neurologic disorder, peripheral neuropathy of the lower extremities, crippling arthritis and metastatic cancer.

Participants responded to advertisements via pamphlets through several community elderly centers. Twenty-two subjects (9 men and 13 women) voluntarily participated in a Tai Chi intervention program; the other 27 (11 men and 16 women) undertook general education and served as control. This study was approved by the Ethics Committee of the Hong Kong Polytechnic University. The procedures were fully explained to all subjects, and a written informed consent was obtained from all subjects.

5.3.2 Training protocol

Subjects in the Tai Chi group undertook supervised Tai Chi training in the Ng style for 1.5 hours in the morning, 6x $week^{-1}$ for 8 weeks. The first 10 minutes were allocated for warm-up, with the rest of the time for Tai Chi practice. The Ng style is one of the 3 main popular Tai Chi styles, namely Yang, Ng and Chen. The Ng style has 108 forms and includes popular Tai Chi postures that has been published (Tsao 1995). The subjects in the control group participated in a general education program with similar contact time for 8 weeks. Their usual morning walk and gentle stretching exercise were allowed. Participants in both the Tai Chi and control groups were instructed not to take part in other vigorous exercises throughout the study period. Two groups of long-term Tai Chi practitioners were recruited and their balance performance had already been reported in Chapter 2 and 3. The first group consisted of 20 Tai Chi practitioners (10 males and 10 females, mean age = 70.7 ± 5.1 years) (Tsang et al. 2004). They were recruited from the Tai Chi clubs of 3 Hong Kong elderly social centers. All of them had practiced the Ng style of Tai Chi at least 3x week^{-1} (each session was about one hour) for more than one year (mean Tai Chi experience= 7.2 ± 7.2 years). Their balance performance in the SOT was used for comparison in the present study. The second group consisted of 21 Tai Chi practitioners (12 males and 9 females, mean age = 69.4 ± 5.5 years) who had practiced Tai Chi with a mean experience of 10.1 ± 9.5 years (Tsang and Hui-Chan 2003). Sixteen of them practiced Ng style while the remaining 5 subjects practiced Yang style. Their balance performance in the LOS was employed for comparison with the present experimental group.

5.3.3 Equipment and measurement

All the balance measurements were conducted using a computerized dynamic posturography machine (Smart EquiTest®; NeuroCom International, Inc., USA). The dual force plates of the computerized dynamic posturography have a force transducer built into the four corners. All the data were processed using a second order Butterworth low pass filter with a cutoff frequency of 0.85 Hz. The force data were used to calculate the subjects' center of pressure (COP) during balance control tests.

5.3.4 Sensory organization test (SOT)

The subjects' ability to use somatosensory, visual and vestibular information to control body sway when standing under 6 reduced or conflicting sensory conditions was investigated, using the SOT already described in Chapter 3. As previously reported, the reliability of this test was high, with intraclass correlation coefficients ranging from 0.72 to 0.93 for the 6 conditions (Tsang et al. 2004). For details, kindly refer to section 3.4.1 and Table 3.1 in Chapter 3.

5.3.5 Limits of stability test (LOS)

After the SOT, the elderly subjects underwent a more dynamic standing balance assessment using the LOS. This test measures the subjects' ability to voluntarily shift their weight to different spatial directions within their base of support, as well as their ability to briefly maintain stability in these positions. As already described in Chapter 2 (section 2.3.4), the dynamic computerized posturography was employed to record displacements of the center of pressure (COP) during this test. The COP trajectory with respect to height, termed "normalized COP" from now on, was used to estimate the sway angle of the center of mass (Shepard et al. 1993). The subject's task was to sway as fast, as smoothly and as far as possible to 1 of the 8 randomly pre-selected targets located at 100% of the LOS. For each target position, 1 trial was performed. The average value of the 8 target positions was used in the comparison between the two elderly groups. There were familiarization trials for each target position before data recording, to ensure that subjects understood how to weight shift to the different target positions.

The three outcome measures: *reaction time*, *maximum excursion* and *directional control* described in Chapter 2 (section 2.3.4) were again used to assess dynamic standing balance control in the LOS test. As reported previously, these outcome measures were found to be reliable, with intraclass correlation coefficients equal to 0.82, 0.93 and 0.83, respectively for reaction time, maximum excursion and directional control (Tsang and Hui-Chan 2003).

5.3.6 Data recording and analysis

5.3.6.1 Sensory organization test

The vertical forces captured by the force plates were used to calculate the center of pressure of the standing subject. For the sensory organization test, the equilibrium quotient developed by Nashner (1993a) was used to compare the two groups in this study. The equilibrium quotient is a percentage that compares the maximum anteroposterior extent of a subject's body sway angle to that of the theoretical limit of stability (= 12.5°). An equilibrium quotient of 100 is equivalent to "no sway", while a score of 0 represents a loss of balance, or exceeding the 12.5° estimated maximum range of sway (Nashner 1993a).

The equilibrium quotient data were used to analyze the balance control under different somatosensory, visual and vestibular conditions. As described in Chapter 3 (section 3.3.3), the 3 sensory ratios proposed by Nashner were used in the present study (Nashner 1993a). Briefly, the equilibrium quotient of condition 1 where subject stood on a fixed support with eyes open was used as the denominator for normalization. 1) The somatosensory ratio compared the equilibrium quotient of condition 2 to that of condition 1. 2) The visual ratio compared the equilibrium quotient of condition 4 to that of condition 1. 3) The vestibular ratio compared the equilibrium quotient of condition 5 to that of condition 1.

5.3.6.2 Limits of stability test

The data recording and analysis of the three outcome measures, namely reaction time, maximum excursion and directional control have been described in Chapter 2 (section 2.3.5.3).

The aforementioned balance tests were administered at 4 time intervals: before, at 4-week intervals during the 8 weeks of intervention, and at follow-up 4 weeks afterwards, for comparison purpose between the Tai Chi and control groups.

5.3.7 Statistical analysis

Independent t-tests were conducted to compare the demographic data describing the two elderly groups, namely age, weight, and height. Due to the categorical nature of the variable for gender, chi-square test was used for between-group comparison. Also ANCOVA model with gender and group as fixed factors was used to investigate the effect of gender on the outcome measures and across the two groups at the 4 time intervals. Multivariate analysis of variance was used to compare the baseline values, as participants were not randomly allocated to the two groups. If statistically significant difference was detected, the outcome measures were normalized to the baseline values at $week_0$ for subsequent between-group comparison, to ensure the same starting level. Mixed analysis of variance model with intent-to-treat design was employed to analyze the outcome measures between Tai Chi and control groups, with "group" and "time" as fixed factors and "subjects" as random factor. There were 4 "time" levels, namely: before, at 4^{th}, 8^{th} week of intervention, and at follow-up 4 weeks afterwards (abbreviated here as $week_0$, $week_4$, $week_8$ and $week_{FU}$). If statistically significant difference was found in the outcome measures, post hoc test for pairwise comparisons was conducted to investigate if there was a within-group difference in the different assessment intervals with the baseline value. Independent t-tests were conducted to compare the Tai Chi and control groups at $week_4$, $week_8$ and $week_{FU}$. Also, the balance performance of experienced Tai Chi practitioners was compared with the experimental group, to investigate the effect of 4 and 8 weeks of Tai Chi versus that of longer-term practice, using independent t-tests. A significance level (α) of 0.05 was chosen for the statistical comparisons after Bonferroni adjustment of the P values.

5.4 Results

5.4.1 Subjects

Nineteen out of 22 subjects completed the TC intervention training (86.4%), while 18 out of 27 subjects completed the general education class (66.7%). The Tai Chi group consisted of 9 men and 13 women. The average attendance for those who completed the 8 weeks Tai Chi program was 5.5 ± SD 0.7x $week^{-1}$. The control group consisted of 11 men and 16 women. Nineteen of them reported having morning walk or gentle stretching exercise in the past 1 year. Their average attendance in the general education class was 2.7 ± 0.9x $week^{-1}$. The three dropouts in the Tai Chi group were due to travel abroad (1 subject), health problem (1 subject), and loss of interest (1 subject). The 9 dropouts for the control group were due to loss of interest (5 subjects), health problem (2 subjects), travel abroad (1 subject) and no reason being given (1 subject).

Table 5.1 shows a comparison of age, height, weight, gender, and baseline values of SOT and LOS at $week_0$ between Tai Chi and control subjects. Independent t-tests showed that there was no statistically significant difference in the age, height, and weight between them ($P > 0.05$).

TABLE 5.1. Comparison of age, height, body weight, gender, and baseline values of SOT and LOS at $week_0$ between Tai Chi and control subjects.

	Tai Chi subjects (*N* = 22)	**Control subjects (*N* =27)**	***P***
Age (years)	67.6 ± 4.9	69.4 ± 6.2	0.294
Height (cm)	158.4 ± 7.0	154.5 ± 9.2	0.106
Body Weight (kg)	59.4 ± 7.9	56.6 ± 7.9	0.225
Gender (men/women)	9/13	11/16	1.000
SOT ($week_0$)			
Somatosensory ratio	0.98 ± 0.03	0.97 ± 0.03	0.066
Visual ratio	0.73 ± 0.13	0.68 ± 0.19	0.470
Vestibular ratio	0.50 ± 0.20	0.51 ± 0.20	0.553
LOS ($week_0$)			
Reaction time (s)	0.9 ± 0.3	1.0 ± 0.3	0.149
Maximum excursion (%)	81.8 ± 9.4	80.5 ± 8.6	0.622
Directional control (%)	66.6 ± 9.0	72.3 ± 6.4	0.015*

Values are mean ± SD for this and all subsequent tables.

* Denotes significant difference at $P < 0.05$ using univariate test, after multivariate analysis of variance of the 6 outcome measures with $P = 0.030$.

Although the height between the 2 groups did not achieve statistically significant difference ($P = 0.106$), the Tai Chi practitioners tended to be slightly taller than the control group subjects (a mean difference of 3.9 cm). Since the normalized COP with respect to height was used in the calculation of the equilibrium quotients, the sensory ratios in the SOT and the maximum excursion in the LOS test, a difference in the height between the 2 groups will not affect these comparisons. The Tai Chi and control subjects were thus similar with respect to age, height, and weight. Furthermore, the chi-square test found no statistically significant difference in gender ($P > 0.05$). The ANCOVA model also demonstrated no gender difference in the two balance tests across the 4 time intervals (all $P > 0.05$; Table 5.2). Therefore, data from the male and female subjects in both groups were combined for statistical analysis.

TABLE 5.2. Compare the effect of gender on the balance tests across the 4 time intervals.

	Gender *P*
Sensory organization test	0.508
Limits of stability test	0.723

A comparison of the baseline values, using the multivariate analysis of variance between the Tai Chi and control groups, showed a significant difference with an overall $P = 0.030$. Univariate analysis revealed that the control subjects had a significantly higher baseline value of the directional control in the LOS test than that of the Tai Chi group ($P = 0.015$; Table 5.1). Therefore, the outcome measures were normalized to their respective baseline values at $week_0$ for the between-group comparison, while the absolute values were used for within-group comparison.

5.4.2 Sensory organization test

The mixed analysis of variance showed no significant difference between the Tai Chi and control subjects across the 4 assessment intervals for the normalized somatosensory and visual ratios (both P = 1.000; Table 5.3). However, it showed a significant difference in the normalized vestibular ratio (P = 0.006; Table 5.3). This finding demonstrated that there were significant differences in this ratio between the 2 groups across the 4 assessment intervals. Post hoc test for pairwise comparisons, conducted within the Tai Chi group to compare the vestibular ratio obtained from the different assessment intervals with its baseline value (mean = 0.50 ± 0.20), showed that these subjects achieved a significant improvement at $week_4$ of intensive training (vestibular ratio = 0.64 ± 0.13, P < 0.001; Fig. 5.1 and Table 5.4). There was a further improvement in the vestibular ratio at $week_8$ of training (vestibular ratio = 0.69 ± 0.11, P < 0.001), which was more or less maintained at 4 weeks after Tai Chi intervention stopped (0.63 ± 0.09, P = 0.001; Fig. 5.1 and Table 5.4). In contrast, post hoc test for pairwise comparisons for the elderly control subjects showed no improvement, with the vestibular ratios equaled to 0.51 ± 0.20, 0.53 ± 0.18, 0.54 ± 0.18 and 0.53 ± 0.19 at $week_0$, $week_4$, $week_8$ and $week_{FU}$ (all P = 1.000; Table 5.4). Analysis of the normalized vestibular ratio using independent t-tests was performed to compare the two groups. We found that the Tai Chi group performed significantly better than the control subjects at $week_4$, $week_8$ and $week_{FU}$ with P < 0.001, P < 0.001 and P = 0.012 respectively (Fig. 5.2).

TABLE 5.3. Comparison of the outcome measures of SOT and LOS test (normalized to their respective baseline values at $week_0$) between Tai Chi and control subjects across the 4 assessment intervals.

	P [a]
SOT	
Somatosensory ratio	1.000
Visual ratio	1.000
Vestibular ratio	0.006†
LOS test	
Reaction time	1.000
Maximum excursion	1.000
Directional control	0.018*

[a] Bonferroni adjustment: each P value of the 6 outcome measures was multiplied by 6.

*Denotes significant difference at $P < 0.05$ and † at $P < 0.01$ using mixed analysis of variance model.

Furthermore, when the vestibular ratio of the Tai Chi intervention group was compared to the group of experienced Tai Chi practitioners whose data were reported in Chapter 3 (N = 20, mean age = 70.7 years, mean Tai Chi experience = 7.2 years, vestibular ratio = 0.67 ± 0.09) (Tsang et al. 2004), there was a significant difference at $week_0$ before Tai Chi training ($P = 0.004$), but no significant difference was found at $week_4$, $week_8$ and $week_{FU}$ (all $P > 0.05$; Fig. 5.1).

TABLE 5.4. Within-group comparisons of the vestibular ratio of SOT and directional control of LOS measured at $week_0$, $week_4$, $week_8$ and $week_{FU}$.

	Tai Chi subjects	Control subjects
Vestibular ratio of SOT		
$Week_0$	0.50 ± 0.20	0.51 ± 0.20
$Week_4$	0.64 ± 0.13 ($P < 0.001$†)	0.53 ± 0.18 ($P = 1.000$)
$Week_8$	0.69 ± 0.11 ($P < 0.001$†)	0.54 ± 0.18 ($P = 1.000$)
$Week_{FU}$	0.63 ± 0.09 ($P = 0.001$†)	0.53 ± 0.19 ($P = 1.000$)
Directional control of LOS test		
$Week_0$	66.6 ± 9.0	72.3 ± 6.4
$Week_4$	72.1 ± 9.3 ($P = 0.004$†)	70.5 ± 8.9 ($P = 1.000$)
$Week_8$	71.4 ± 8.0 ($P = 0.013$*)	71.7 ± 10.4 ($P = 1.000$)
$Week_{FU}$	73.2 ± 4.2 ($P = 0.003$†)	72.4 ± 8.7 ($P = 1.000$)

$Week_0$, $week_4$, $week_8$ and $week_{FU}$ denote the vestibular ratio of SOT or directional control of LOS test before, at 4^{th}, 8^{th} week of intervention, and at follow-up after 4 weeks.

* Denotes significant difference at $P < 0.05$ and † at $P < 0.01$ within each group, when $week_4$, $week_8$ and $week_{FU}$ were compared with $week_0$, using post hoc test for pairwise comparisons after Bonferroni adjustment.

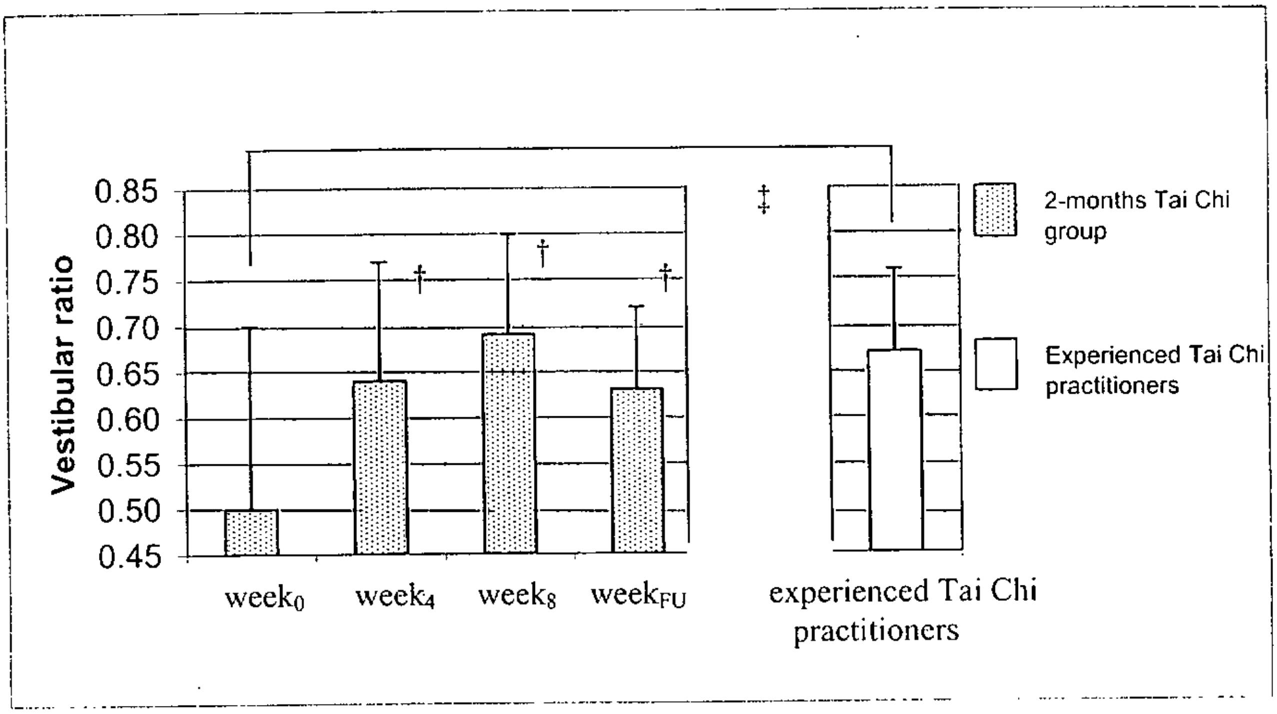


FIGURE 5.1 - Graph showing the vestibular ratios of the Tai Chi group across the 4 different assessment intervals and a comparison with experienced Tai Chi practitioners (mean experience = 7.2 years) from Table 3.5 of Chapter 3 (Tsang et al. 2004).

$Week_0$, $week_4$, $week_8$ and $week_{FU}$ denote the vestibular ratio of SOT before, at 4th, 8th week of intervention, and at follow-up 4 weeks afterwards.

† Denotes significant difference at $P < 0.01$ when the vestibular ratios of $week_4$, $week_8$, and $week_{FU}$ were compared with that of $week_0$, using post hoc test for pairwise comparisons after Bonferroni adjustment.

‡ Denotes significant difference at $P < 0.05$ when the vestibular ratios of the Tai Chi group at $week_0$ was compared with that of the experienced Tai Chi practitioners using independent t-test. Bonferroni adjustment: each P value from the 4 assessments was multiplied by 4.

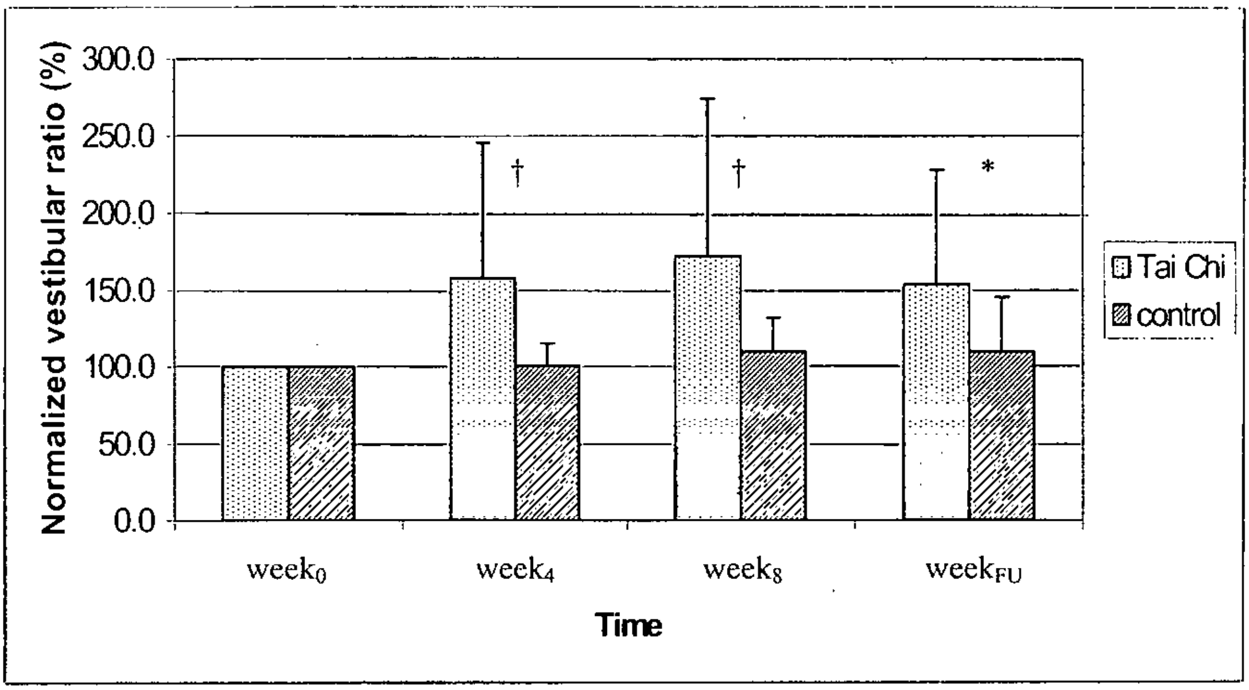


FIGURE 5.2 - Graph showing the normalized vestibular ratio (%) between Tai Chi and control groups over the 4 assessment intervals.

* Denotes significant difference at $P < 0.05$ and † at $P < 0.01$ using independent t-test. Bonferroni adjustment: each P value from the 4 assessments was multiplied by 4.

5.4.3 Limits of stability test

In the LOS test, mixed analysis of variance showed no significant difference between the 2 groups in the normalized reaction time and maximum excursion across the 4 assessment intervals (both $P = 1.000$; Table 5.3). Nevertheless, it showed a significant difference in the normalized directional control of the leaning trajectory, when subjects voluntarily shifted their weight to the different spatial target positions ($P = 0.018$; Table 5.3). Post hoc test for pairwise comparisons, conducted within the Tai Chi group to compare the directional control obtained in the different assessment intervals with the baseline value (mean = 66.6 ± 9.0%; Table 5.4), showed that the Tai Chi subjects achieved a significantly better directional control after only 4 weeks of intensive training (= 72.1 ± 9.3%, P = 0.004; Fig. 5.3 and Table 5.4). The improved directional control was maintained at $week_8$ of training (directional control = 71.4 ± 8.0%; P = 0.013), and at 4 weeks after Tai Chi intervention stopped (= 73.2 ± 4.2, P = 0.003; Fig. 5.3 and Table 5.4).

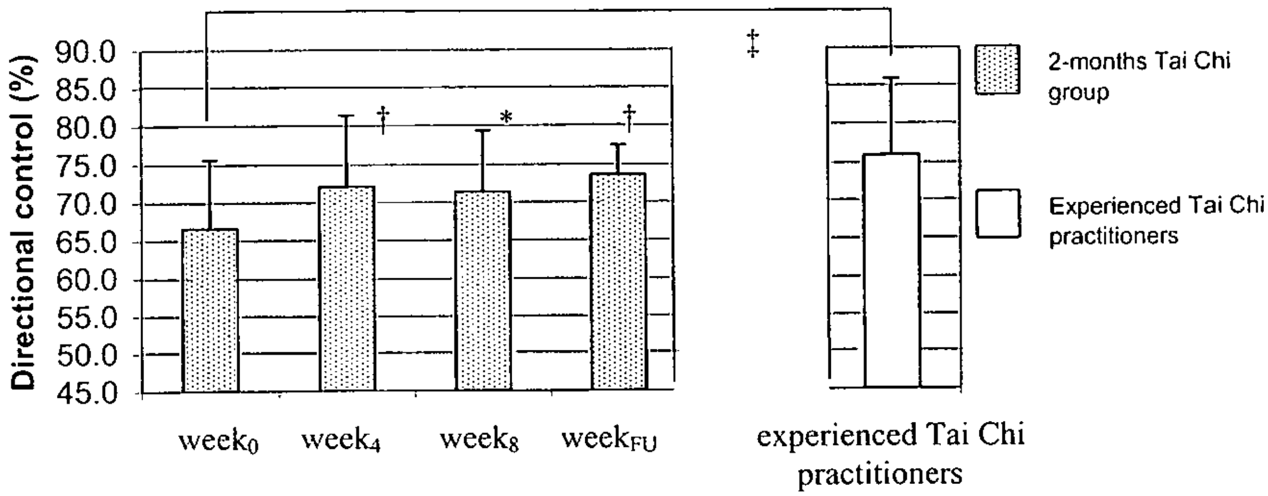


FIGURE 5.3 - Graph showing the directional control (%) of the Tai Chi group across the 4 different assessment intervals and a comparison with experienced Tai Chi practitioners (mean experience = 10.1 years) from Table 2.3 of Chapter 2 (Tsang and Hui-Chan 2003).

* Denotes significant difference at $P < 0.05$ and † at $P < 0.01$ when the directional control of $week_4$, $week_8$ and $week_{FU}$ were compared with that of $week_0$, using post hoc test for pairwise comparisons after Bonferroni adjustment.

‡ Denotes significant difference at $P < 0.05$ when the directional control ratios of the Tai Chi group at $week_0$, was compared with that of the experienced Tai Chi practitioners using independent t-test. Bonferroni adjustment: each P value from the 4 assessments was multiplied by 4.

In contrast, the control elderly subjects showed no improvement in the directional control, with values of 72.3 ± 6.4%, 70.5 ± 8.9%, 71.7 ± 10.4% and 72.4 ± 8.7% at $week_0$, $week_4$, $week_8$ and $week_{FU}$ (all $P = 1.000$; Table 5.4). Independent t-tests showed that the Tai Chi group achieved significantly higher scores in the directional control of normalized COP than those of the control group at $week_4$, $week_8$ and $week_{FU}$ (all $P < 0.001$; Fig. 5.4).

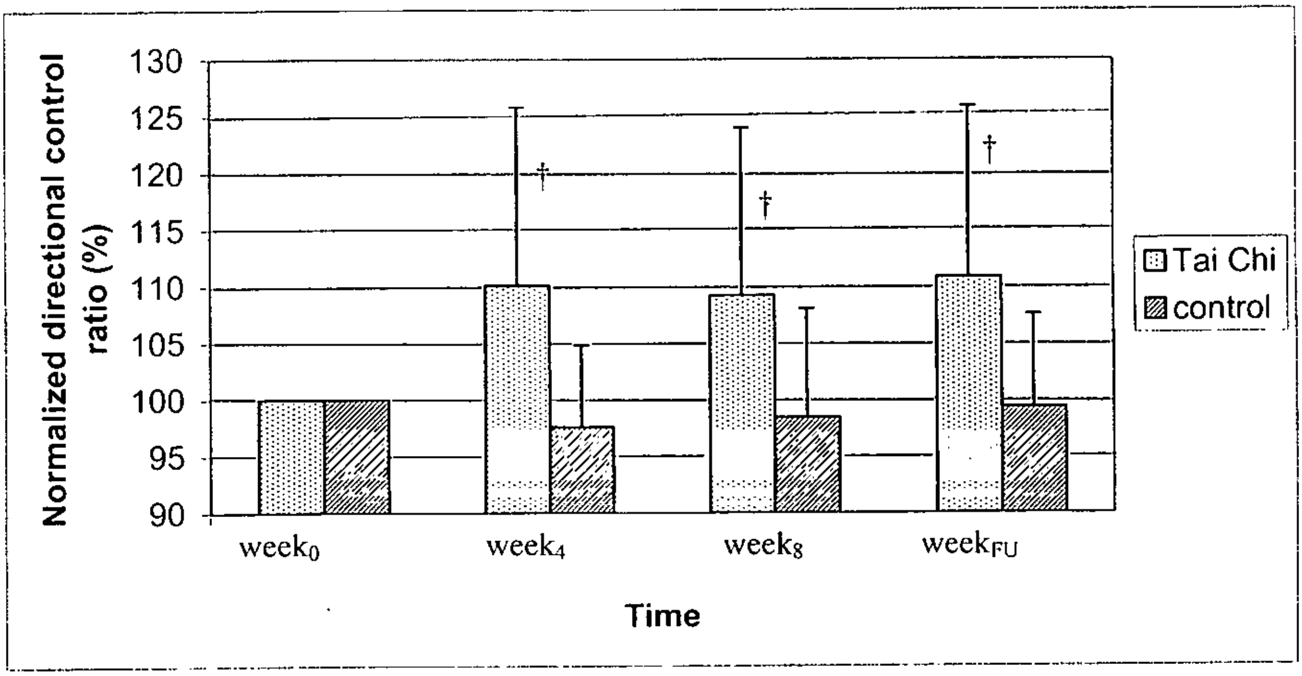


FIGURE 5.4 - Graph showing the normalized directional control ratio (%) between Tai Chi and control groups across the 4 different assessment intervals.

† Denotes significant difference at $P < 0.01$ using independent t-test. Bonferroni adjustment: each P value from the 4 assessments was multiplied by 4.

Furthermore, when the directional control of the Tai Chi training group was compared to a group of experienced Tai Chi practitioners whose data were reported in Chapter 2 (N = 21, mean age = 69.4 ± 5.5 years, mean Tai Chi experience = 10.1 ±

9.5 years, directional control = 75.9 ± 10.0%) (Tsang and Hui-Chan 2003), there was a significant difference at $week_0$ (P = 0.012), but no significant difference at $week_4$, $week_8$ and $week_{FU}$ (all $P > 0.05$; Fig. 5.3).

5.5 Discussion

The present study revealed that after only 4 weeks of intensive Tai Chi intervention, the elderly subjects achieved less body sway when they had to rely more on the vestibular system during stance with the eyes closed and with inaccurate somatosensory input (condition 5). Also, they were able to voluntarily shift their weight to the 8 target positions through a smoother trajectory. Of particular interest is that their vestibular ratio and the directional control of their leaning trajectory were similar to those of experienced Tai Chi practitioners who had practiced Tai Chi for a mean of 7.2 and 10.1 years respectively. This finding suggests that even 4 weeks of intensive Tai Chi practice was sufficient to improve the balance control of the elderly subjects. Rapid improvement in motor control after relatively short periods of training has been shown by studies on the use of constraint-induced therapy for upper extremity and of harness-assisted, partial weight bearing in gait training, as presented in Chapter 1 (section 1.5.4) and further discussed below.

Taub et al. (1993) randomly assigned patients with chronic stroke (average chronicity = 4.4 years) to either an experimental group or an attention-placebo control group. Patients in the experimental group wore a sling in their less-affected arm during waking hours for 14 days. On 10 of those days, they received 6 hours of daily supervised-practice using their more-affected arm in various activities of daily living tasks. After the short intervention period, the restraint subjects demonstrated a significant increase in motor ability as assessed by both laboratory tests and real-world arm use, whereas the control patients showed no change. Visintin et al. (1998) investigated the effect of gait training on a treadmill with body weight support on clinical outcome measures in patients with stroke. After 6 weeks of training, the body weight support group achieved significantly better balance control, motor recovery, walking speed and endurance than those of control group who were trained to walk without the body weight support. The underlying mechanism could be attributed to the ability of the brain for cortical reorganization as a result of a short period of training. For instance, Jenkins et al. (1990) showed that the cortical representation of the middle finger, as measured by evoked potentials in a monkey study, was greatly expanded after several months of practice with a repeated touch task, in which monkeys used their middle fingers to obtain food. In another study, human subjects were asked to practice a finger opposition task for about 20 minutes everyday, by touching the thumb to each fingertip in a specific repeating sequence (Karni et al. 1995). Both the speed and accuracy increased and reached plateau in just about 3 weeks. The functional magnetic resonance imaging (fMRI) scans revealed that the area of cortex activated during action of the trained sequence was larger than that activated during a novel untrained sequence. In other words, more extensive representation in the motor cortex was found in subjects after repeated practice of a single motor task for only 3 weeks. These studies demonstrate the tremendous capacity of the brain for plasticity or "rewiring" after only "weeks" of training. If these findings could be generalized to Tai Chi practice, 4 weeks of intensive training could have produced plastic changes in the cortex to improve the subjects' balance performance as assessed by the vestibular ratio and the directional control of their leaning trajectory.

5.5.1 Balance control under reduced or conflicting sensory conditions: Effects of aging

With aging, degeneration is known to occur in the different sensory systems responsible for balance control, specifically joint proprioception, visual and vestibular systems (Horak et al. 1989). In this connection, Yan and Hui-Chan (2000) showed that the joint detection threshold was 50% higher in older subjects (aged 57–77 years) than young subjects (aged 25–35 years) for both knee flexion and extension. As reported in Chapter 3, our study also showed that older subjects swayed significantly more than young subjects, when there was an increased reliance on the visual and vestibular inputs with the other sensory inputs reduced and/or distorted (Tsang et al. 2004). Such an increase in sway could be attributable to the different degrees of deterioration that can occur with aging in the somatosensory, visual and vestibular systems responsible for balance control (Horak et al. 1989).

The deterioration of balance control under reduced or conflicting sensory conditions had been found to be related to falls in elderly subjects. In 1998, Ho et al. studied 15 elderly fallers and 15 non-fallers, and found that the fallers exhibited significantly greater sway in conditions 4–6 in the sensory organization test. Our present results show that the subjects in the Tai Chi group improved their vestibular ratio from 0.50 to 0.64 after 4 weeks of intensive Tai Chi practice ($P < 0.001$), with further improvement in the ratio to 0.69 at $week_8$ ($P < 0.001$; Fig. 5.1 and Table 5.4). The improved vestibular ratio after Tai Chi training may explain in part why the risk of multiple falls was reduced by 47.5% in the elderly Tai Chi practitioners, as found by Wolf et al. (1996).

5.5.2 Standing under reduced or conflicting sensory conditions in SOT

In the previous study reported in Chapter 3, we found that elderly Tai Chi practitioners, with an average experience of 7.2 years, swayed significantly less and achieved significantly higher vestibular ratio than the control elderly, when they stood without visual input and with conflicting somatosensory input in the SOT (= 0.67 and 0.58 respectively) (Tsang et al. 2004). Practicing Tai Chi involves head movements that could stimulate the vestibular system. It involves many head and body rotations, constant weight shifting with different arm movements, changes in the base of support from double to single leg standing, and fixation of the eyes on the hand during the practice of its many forms (Tsao 1995). There are thus certain similarities between Tai Chi and vestibular rehabilitation exercise protocols. The latter exercises have been proven to be effective in the rehabilitation of patients with chronic peripheral vestibular dysfunction, by reducing the left-right differences in the vestibular-ocular reflex gain (Szturm et al. 1994) and by improving the equilibrium quotients, especially in conditions 5 and 6 of the SOT (Horak et al. 1992).

In 1999, Hain et al. investigated the training effects of Tai Chi on the balance control of 22 patients with self-perceived mild balance disorders but no definite diagnosis, with age ranged from young (20–60 years) to old (76 years and older). These patients took 8 1-hour Tai Chi classes over 2 months, at about 1 class per week. They were instructed to practice at home every day for at least 30 minutes, but no compliance record was made. The investigators found that both young and older participants improved significantly in the overall equilibrium score (8% improvement when compared to their baseline value) of the SOT. However, because no control group was incorporated into their design, the positive findings could not be attributed to the effect of Tai Chi per se.

Our present study demonstrated that intensive Tai Chi practice could improve the vestibular ratio by 21% and 28%, respectively after 4 and 8 weeks of training in a group of healthy elderly (mean age = 67.6 years), when compared with those of the control subjects (Table 5.4). Such a significant improvement over a relatively short time period (of 4 weeks) may be due to the intensive training under the close supervision of a Tai Chi master. Further comparison with experienced Tai Chi practitioners (mean experience = 7.2 years, vestibular ratio = 0.67) showed that after 4 weeks of training, elderly subjects in the Tai Chi intervention group had attained a vestibular ratio similar to that of experienced Tai Chi practitioners (0.64; Fig. 5.1). Of particular importance is that the significant improvement in the vestibular ratio was maintained in the Tai Chi group at follow-up 4 weeks afterward (Fig. 5.2).

5.5.3 Voluntary weight shifting in LOS test

Previous studies have shown that the limits of stability can predict functional performance in activities, such as crossing a street, getting onto a bus and climbing a flight of 27 stairs (Topp et al. 1998). Older subjects demonstrated a decline in all the parameters measured, such as longer movement time, shorter distance of the maximum excursion and less control of the normalized COG trajectory (Hageman et al. 1995). Decline in the limits of stability test outcome measures had also been shown to indicate a susceptibility to falls (Girardi et al. 2001).

Tai Chi practice requires the practitioners to perform the various forms in a smooth and well-controlled manner. This requirement constantly challenges the balance control system to maintain the subject's equilibrium, when their COG was being voluntarily shifted to their limits of stability within the base of support. Such a repetitive demand for balance control during Tai Chi practice probably explains our previous findings in Chapter 2, in which the experienced Tai Chi practitioners (10.1 years experience) attained faster reaction time, as well as better maximum excursion and directional control than the control subjects similar in age and physical activity level (Tsang and Hui-Chan 2003). These practitioners are likely to have relevant functional activities enhanced and/or possible occurrence of falls minimized. Indeed, Wolf et al. (1996) found that the risk of multiple falls was reduced by 47.5% in the elderly Tai Chi practitioners.

In our present study, the Tai Chi subjects achieved a significant improvement in the directional control ($P = 0.018$, Table 5.3) of the limits of stability test, but not the reaction time and maximum excursion. One possible explanation is that it may require a longer training time to improve performance in these 2 parameters. Another possible explanation is that our elderly Tai Chi participants already had reasonably good baseline values in these two parameters before Tai Chi training. In this connection, Rose and Clark (2000) detect a significant improvement in the maximum excursion of the LOS test in the elderly subjects with a history of falls, after 8 weeks of computerized balance training. Their maximum excursion improved from 74.9% to 83.8%, whereas the baseline values for our Tai Chi group was already 81.8%.

Both the improved vestibular ratio and the directional control of the leaning trajectory were maintained 4 weeks after Tai Chi training. As aforementioned, repeated Tai Chi practice could result in appropriate plastic changes in the motor cortex leading to the improved balance control. Once the plastic change is established in the cortex, the improved balance control itself could be sufficient to maintain it for the follow-up effects to be observed at 4 weeks after Tai Chi practice stopped. In this connection, Miles and Eighmy (1980) showed that monkeys wearing magnifying or minifying lenses required 1 week to augment (or diminish) the intrinsic gain of the vestibulo-ocular reflex. In other words, once the reflex was adapted, the monkeys needed a few days for readaptation of the vestibulo-ocular reflex after the lenses were off. In learning more complex motor tasks, such as rapid sequences of finger movements, after 4 weeks of training, fMRI showed that the extent of motor cortex activated by the practiced sequence was enlarged when compared with the unpracticed sequence (Karni et al. 1995). That such changes persisted for several months (not days or weeks) possibly account for the acquisition and retention of the said motor skill. This mechanism likely also underlies the carried-over effect to 4 weeks after Tai Chi training ended, as shown in our present study. The positive findings from our study are consistent with the report by Wolf et al. (1996) that, the fear of falling in elderly subjects was reduced after 15 weeks of Tai Chi intervention. Fear of falling has been found to limit the physical activities of elderly subjects (Horak et al. 1989). Once their balance control improves and their fear of falling is reduced, the elderly subjects might increase their physical activity level, thus further enhance their balance control.

5.5.4 Intensive Tai Chi training

In this study, we implemented 8 weeks of intensive Tai Chi training in healthy elderly subjects and used more challenging balance tests as outcome measures. Our positive findings with such intensive training and measurement protocols might give some clues to the negative results of Wolf et al. (1997b). More specifically, their negative findings could be due to partly a lack in sufficient Tai Chi training, or/and to an inappropriate balance test that could not reveal the more complex balance control performance achieved by the Tai Chi practitioners.

In 1999, Ross et al. conducted an 8-week Tai Chi class with 17 healthy elderly subjects aged 68 to 92 years. Each class lasted for 50 min at 3x $week^{-1}$, as opposed to the 90 min class at 6x $week^{-1}$ in our study. They observed that all participants had improved in their single-leg stance and tandem walk, but the outcome did not reach statistical significance. The insignificantly statistical result in their study could be partly attributable to the relative lighter practice in term of duration and frequency of training sessions.

5.6 Conclusions

In conclusion, our results indicate that even 4 weeks of intensive Tai Chi training can improve the balance control of the elderly subjects, in terms of (1) less body sway when standing under conditions requiring an increased reliance on the vestibular system and (2) more smooth shifting of their weight to different directions within their base of support. Even more impressive is the finding that the improved control could be equivalent to that of the experienced Tai Chi practitioners with more than 7 years of experience. Taken together with Wolf et al. (1996) showing that Tai Chi practitioners have decreased the probability of fallings, our present findings indicated that Tai Chi has the potential of being a cost-effective falls prevention program, which can easily be implemented community-wide.

CHAPTER 6

EFFECTS OF EXERCISE ON JOINT SENSE AND BALANCE IN ELDERLY MEN: TAI CHI VERSUS GOLF

Publication

TSANG, W. W. N., and C. W. Y. HUI-CHAN. Effects of exercise on joint sense and balance in elderly men: Tai Chi versus Golf. *Med. Sci. Sports Exerc.* 36:658-667, 2004.

Conference abstract

TSANG, W. W. N., and C. W. Y. HUI-CHAN. Do elderly Tai Chi practitioners have better joint proprioception and greater limits of stability than the well elderly? In *Annual meeting of the Society for Neuroscience.* New Orleans, Louisiana, p.272.4, 2003.

6.1 Abstract

Purpose: Our studies in the previous chapters showed that experienced Tai Chi practitioners had better joint proprioception and balance control during weight shifting. The objective of the present study was to examine whether experienced golfers had attained similar improvement when compared with the Tai Chi practitioners, as well as healthy elderly subjects and young university students.

Methods: We compared 12 experienced elderly Tai Chi practitioners, with 11 experienced elderly golfers, 12 healthy elderly subjects, and 12 young university students, who were all males, using: 1) passive knee joint repositioning test to assess their joint proprioceptive acuity and 2) limits of stability test to assess their ability to voluntarily weight shift within their base of support.

Results: Both Tai Chi practitioners and golfers had better knee joint proprioceptive acuity than did the elderly control subjects ($P < 0.05$). Of special interest is that their performance was similar to that of the young subjects. In the limits of stability test, Tai Chi practitioners and golfers had faster reaction time, leaned further without losing stability, and showed better control of leaning trajectory than did elderly control subjects (all $P < 0.05$). The latter 2 outcome measures were also comparable to those of the young subjects.

Conclusion: These results demonstrate that both experienced Tai Chi practitioners and golfers had improved knee joint proprioception and limits of stability, when compared with those of elderly control subjects similar in age, gender (male) and physical activity level. Such improved outcome measures were comparable to those of young male subjects. These findings suggest that experienced Tai Chi practitioners and golfers had improved joint proprioceptive acuity and dynamic standing balance control, despite the known aging effects in these specific sensori-motor functions.

Key Words: AGING, FALLS, JOINT PROPRIOCEPTION, POSTURAL CONTROL

6.2 Introduction

Information from the sensory systems is important for postural control. Normally, somatosensory, visual and vestibular inputs are available to detect a person's postural orientation and equilibrium with respect to the environment and gravity (Horak and Macpherson 1996). However, studies show that deterioration of the sensory systems affects the postural stability and the ability to recover from a loss of balance. Indeed, poor postural stability has been identified as a major intrinsic factor that causes falls in the elderly (Lord et al. 1999).

In the absence of vision, the detection of limb position and movement is termed "limb position sense" and "kinesthesia" respectively, which is known collectively as "limb proprioception" (Gardner et al. 2000). It is mediated by cutaneous receptors in the skin and proprioceptors in muscles, tendons, ligaments and joints, which signal to the central nervous system both the stationary position of a limb and the speed and direction of its movement. As detailed in Chapter 1, limb proprioception has been found to diminish with age. Hurley et al. (1998) found that elderly subjects, with a mean age of 72 years, made significantly larger errors than did young subjects in an active knee repositioning test. Yan and Hui-Chan (2000) further showed that the joint detection threshold was 50% higher in older subjects (aged 57–77 years) than in subjects aged 25–35 years, for both knee flexion and extension.

As would be expected, elderly fallers were found to have significantly reduced proprioception in their lower limbs (Lord et al. 1999). In view of the high medicare cost consequent to falls, it becomes important to determine whether exercise could help improve limb proprioception in the elderly. As reported in Chapter 2, we conducted a cross-sectional study and found that elderly practitioners of Tai Chi achieved significantly better acuity in knee proprioception sense, in that they showed smaller knee angle errors in a passive knee repositioning test when compared with those of control subjects similar in age, gender, and physical activity level (Tsang and Hui-Chan 2003). However, it is not known whether the improved joint proprioception is comparable to that in young, healthy subjects.

In terms of postural control, our findings in Chapter 3 have demonstrated that elderly Tai Chi practitioners could attain the same level of balance performance in a sensory organization test (SOT) as that of young, healthy subjects when standing under reduced or conflicting somatosensory, visual, and vestibular conditions (Tsang et al. 2004). In another study reported in Chapter 2, we chose a more dynamic standing balance assessment using the limits of stability (LOS) test, and showed that elderly Tai Chi practitioners improved their balance more than did control subjects similar in age, gender and physical activity level (Tsang and Hui-Chan 2003). Whether the improved control in the more dynamic LOS test is comparable to that of young subjects is still unknown. Therefore, the first objective in the present study was to examine whether male elderly Tai Chi practitioners have developed knee joint proprioception and control of their LOS comparable to those of young subjects.

In the aforementioned cross-sectional studies (Tsang et al. 2004; Tsang and Hui-Chan 2003), we surmised that the improved knee joint proprioception and balance performance in the SOT and LOS of elderly Tai Chi practitioners could be attributed, at least in part, to the repeated practice of Tai Chi for ≥ 1 year. This is because Tai Chi puts great emphasis on exact joint positioning and limb direction. It also involves precisely controlled weight transfer in double leg stance, and controlled weight shifting between double and single leg stance, in a smooth and coordinated manner (Tsao 1995). As reported in the previous chapter, the improvement in balance control resulting from Tai Chi practice is supported by our prospective study in which elderly subjects received 8 weeks of intensive Tai Chi training and improved significantly in balance control, in terms of: 1) less body sway when standing under conditions requiring an increased reliance on the vestibular system; and 2) smoother shifting of their weight in different directions within their base of support (Hui-Chan and Tsang 2001). However, is improvement in knee joint proprioception and LOS specific only to Tai Chi training? What about other sports such as golf? Like the practice of Tai Chi which is popular among elderly Chinese, golf is a Western sport that is also popular among elderly Westerners, and increasingly so among the Asian population. It requires concentration of mind, as well as precise and coordinated trunk and arm movements in order to hit the golf ball accurately (Selicki and Segall 1996). Consequently, experienced golfers could also have improved their joint proprioception and balance control. Thus, the second objective of the present study was to compare the knee joint proprioception and LOS of golfers with those of Tai Chi practitioners and healthy subjects matched for age, gender, and physical activity level, as well as with those of young healthy subjects. Finally, because joint afferents are known to contribute to the control of balance (Horak and Macpherson 1996), the third objective was to investigate whether any relationship exists between knee joint proprioception and limits of stability during voluntary weight shifting in these 3 groups of male elderly subjects.

6.3 Methods

6.3.1 Subjects and study design

Thirty-five male community-dwelling elderly subjects, aged 60 or older participated in this study. Twelve of them were Tai Chi practitioners (mean age =

69.6 ± SD 5.7 years) recruited from local Tai Chi clubs. All had practiced Tai Chi for a minimum of 1.5 hour·week^{-1} for at least 3 years (mean Tai Chi experience = 8.4 ± 9.1 years). Eleven were golfers (mean age = 66.2 ± 6.8 years) recruited from local golf clubs. All had practiced golf for the same minimum amount of 1.5 hour·week^{-1} and the same minimum duration of at least 3 years (mean golf experience = 15.2 ± 13.4 years). Twelve were elderly control subjects (mean age = 71.3 ± 6.6 years) recruited from several community elderly centers. They had no previous experience in either Tai Chi or golf, though some took morning walks or did stretching exercises.

All the subjects could walk without the assistance of walking aids. Those candidates reported history of falls in the previous 12 months were excluded. A fall is defined as an event resulting in a person inadvertently coming to rest on the ground or another lower level. Major intrinsic events, e.g., seizure, and overwhelming external forces, e.g., motor vehicle accident will be excluded. All subjects were able to communicate and were active enough to comply with the testing procedures. All were independent in their activities of daily living at the time of the study. Candidate subjects showing symptomatic cardiovascular diseases when subjected to moderate exertion were excluded. Also excluded were candidates with poorly controlled hypertension or symptomatic orthostatic hypotension, severe cognitive impairment, Parkinson's disease, stroke or any other neurologic disorder, peripheral neuropathy of the lower extremities, and disabling arthritis or metastatic cancer.

Twelve young healthy subjects (mean age = 20.3 ± 1.4 years) were also recruited. All were male university students who exercised regularly for at least 2 hour·week^{-1}. Exclusion criteria were the presence of inner ear problems, dizziness, long-term medication, a history of injury within 1 year before the study, prior orthopedic operation or neurologic disease.

The elderly candidates were first screened using a general health questionnaire and a physical activity questionnaire. The validated Chinese version of the Mini-Mental Status Examination of Folstein et al. was then administered (Chiu et al. 1994). As described in Chapter 2 (section 2.3.1), a score below 24 was considered indicative of cognitive dysfunction, and such subjects were excluded from this study. The physical activity level questionnaire was a modified version of the Minnesota Leisure Time Physical Activity Questionnaire (Van Heuvelen et al. 1998). It had been used in our previous studies reported in Chapter 2, 3, and 4 (Tsang et al. 2004; Tsang and Hui-Chan 2003), and was used in the present project to compare physical activity levels among the 3 elderly groups in terms of their metabolic equivalent (MET) status. These protocols were approved by the Ethics Committee of the Hong Kong Polytechnic University, and written informed consent was obtained from all subjects.

6.3.2 Passive knee joint repositioning test

General methods for testing joint proprioception include: 1) testing the threshold for detecting joint movement, 2) joint position matching with the contralateral limb, and 3) limb segment repositioning called the "joint repositioning test", all of which could be tested in either a passive or an active mode. Knee joint repositioning test was adopted because the practice of Tai Chi and golf both put great emphasis on exact joint positioning of the knee, which could have improved the acuity of knee joint repositioning, as was already demonstrated in our Tai Chi study reported in Chapter 2 (Tsang and Hui-Chan 2003). Also, some investigators noted that the knee joints are often held in some degrees of flexion during certain functional activities performed by the elderly subjects (Hurley et al. 1998). Others had chosen knee joint proprioception to correlate with selected functional activities in the elderly people (Hurley et al. 1998; Lord et al. 1999). Our test was performed passively in a non-weight-bearing condition. The reason for using a passive and nonweight-bearing protocol in the joint repositioning test was to minimize the motor contribution, which has been found to aid proprioceptive acuity (Ashton-Miller et al. 2001).

Using our particular experimental paradigm, we had reported in Chapter 2 that the passive knee joint repositioning test produced highly repeatable data, with intraclass correlation coefficients of 0.90 (Tsang and Hui-Chan 2003). This paradigm was adopted in the present study. For details, please refer to Chapter 2, section 2.3.2.

The signals from 1) the electrogoniometer attached to the lateral aspect of the knee, 2) the thumb switch pressed by the subject upon perceiving that the knee had regained the previous target position, and the EMG onset signal of the thenar eminence muscles (mainly the flexor pollicis brevis) indicating the moment when the subject perceived that the knee had regained the target position, were stored (through an A/D card, DataQ® Instruments Inc., type DI-720P, Ohio, USA) for off-line analysis. Each subject completed 3 trials. The error with which the subject reproduced the initial position was calculated. The 3 absolute error values were averaged, and the average value, termed the *absolute angle error*, was used for comparison across the 4 groups. There are 3 reasons for choosing the absolute angle error: 1) The absolute angle error can be regarded as a measure of the overall accuracy of performance. It is the average absolute deviation (regardless of the direction) between the subject's perceived position and target position of the knee. 2) The absolute angle error has the advantage of having taken into consideration both the deviation from the target position (termed as a constant variable) as well as the variability or inconsistency of subject's performance (termed as a variable error) (Schmidt and Lee 1999). 3) Consequently, this outcome measure has been commonly used by other investigators when employing joint position sense test (Barrack et al. 1983; Petrella et al. 1997) as we reported in Chapter 2 (Tsang and Hui-Chan 2003).

6.3.3 Limits of stability (LOS) test

After the knee joint repositioning test, the subjects underwent a dynamic standing balance test that involved voluntary weight shifting to determine their LOS. This test measures the subjects' ability to voluntarily shift their weight in 8 different spatial directions within their base of support. Smart EquiTest® equipment (NeuroCom International, Inc., USA) was employed to record displacements of the center of pressure (COP) during this test. A detailed description of the testing procedure has been reported in Chapter 2 (Tsang and Hui-Chan 2003) and is therefore only highlighted here. The COP trajectory with respect to height, termed the "normalized COP", was used to estimate the sway angle of the center of mass (Shepard et al. 1993). The balance measurement system consisted of dual force plates (one for each foot) and a video screen on which the subject's current normalized COP was continually displayed. There were 8 target positions on the screen, with the normalized COP during quiet stance displayed in the center. The subject was instructed to shift his weight so as to move the normalized COP trace to

1 of the 8 target positions, pre-selected in a random order, as quickly and smoothly as possible, without moving his feet.

Three outcome measures – reaction time, maximum excursion, and directional control – were used to assess dynamic balance control in the LOS test. As reported in Chapter 2 (section 2.4.2), we had found these outcome measures to be reliable in elderly subjects, with intraclass correlation coefficients equal to 0.82, 0.93 and 0.83 for reaction time, maximum excursion and direction control respectively (Tsang and Hui-Chan 2003). As previously described, *reaction time* was defined as the time from the presentation of a visual stimulus as a response signal to the initiation of voluntary shifting of the subject's center of mass (COM) toward the target location. *Maximum excursion* measured the maximum displacement of the normalized COP, within the subject's theoretical limits of stability and without the subject taking a step to recover balance. *Directional control* measured the smoothness of the displacement of the normalized COP to the target positions. It compared the amount on-target movement of the normalized COP to the amount of off-target movement (NeuroCom 2000). The subject's task was to sway as fast, as smoothly and as far as possible, to 1 of the 8 randomly preselected targets located at 100% of the LOS. For each target position, 1 trial was performed. The average value from the 8 target positions was used to compare among the participating subjects. There were familiarization trials, at least 1 for each target position before data recording, to ensure that subjects understood how to weight shift to the different target positions.

6.3.4 Data recording and analysis

6.3.4.1 Knee joint repositioning

The first appearance of an EMG signal from the thenar eminence muscles (mainly the flexor pollicis brevis) was taken to indicate the moment when the subject perceived that the joint angle had reached the target value during the repositioning test. The EMG signals were sampled at 1000Hz, filtered with a bandwidth of 10–500Hz, and amplified with a gain of 4048. They were then full-wave rectified.

The first indication of an EMG signal was taken to be the moment when EMG activity reached 3 standard deviations above the baseline, to minimize the influence of muscular activities due to anticipation and/or noise from the environment. As reported in Chapter 2 (section 2.3.5.1), EMG onset was chosen because large variations had been found in our previous study between EMG onset and the thumb switch signals (Tsang and Hui-Chan 2003). This approach served to minimize the error that could have arisen from the thumb pressing on the switch at slightly different locations and/or with slightly different forces.

6.3.4.2 Limits of stability test

All the data from the Smart EquiTest® were processed, using a second-order Butterworth low-pass filter with a cutoff frequency of 0.85 Hz. The force data were used to calculate the subjects' center of pressure (COP) during balance control tests. The data recording and analysis of the three outcome measures, namely reaction time, maximum excursion and directional control have been described in Chapter 2 (section 2.3.5.3).

6.3.5 Statistical analysis

One-way analysis of variance (ANOVA) was used to compare age, height and weight among the 4 subject groups and Kruskal-Wallis test for the Mini-Mental Status Examination results among the 3 elderly groups. A chi-square test was applied to compare the physical activity levels among the elderly groups due to its categorical nature. An independent t-test was used to compare the years of experience between the Tai Chi practitioners and the golfers. For between-group comparison of the knee joint repositioning test results, a one-way ANOVA was employed. Multivariate analysis of variance was used to compare the outcome measures recorded with the limits of stability (LOS) test among the 4 groups. If statistically significant differences were found in the multivariate tests, univariate tests were conducted for each of the outcome measures of the LOS test. Post hoc analysis using Bonferroni's adjustment was conducted, if a significant difference was found in the univariate test. A Pearson product-moment coefficient of correlation was used to correlate the absolute angle error obtained in the knee joint repositioning test, with reaction time, maximum excursion and directional control of the normalized COP in the LOS test among the 3 groups of elderly subjects. A significance level (α) of 0.05 was chosen for the statistical comparisons.

6.4 Results

6.4.1 Subjects

Table 6.1 shows a comparison of age, height and weight among the 4 male groups. One-way ANOVA showed statistically significant differences between the young subjects and the 3 elderly groups in age, with no significant differences among the 3 elderly groups of Tai Chi practitioners, golfers and control subjects in the post hoc analysis. There were also statistically significant differences in height between young subjects on the one hand, and elderly Tai Chi and elderly control subjects on the other. However, any difference in height would not have affected the comparisons of the limits of stability test among the subject groups, because "sway angle" was used to calculate the outcome measures. There were no statistically significant differences in weight among the 4 groups.

Table 6.1 provides further comparisons of the demographic data for the 3 elderly groups. Kruskal-Wallis test showed that the 3 groups were comparable in terms of Mini-Mental Status Examination (MMSE) scores (P = 0.124). All 35 subjects had MMSE scores above 24, indicating that they had no cognitive impairment (Chiu et al. 1994). Physical activity level was also found to be similar, using chi-square test (P = 0.583). As revealed by the general health questionnaire, none of the elderly were limited in any of their activities. Similarities in these variables meant that they would not have confounded any differences in the outcome measures among the 3 elderly groups. Note that although the golfers had more years of experience than the Tai Chi practitioners, the differences were not significant (P = 0.168).

6.4.2 Knee joint repositioning test

Table 6.2 shows that Tai Chi practitioners and golfers had significantly better knee joint proprioceptive acuity and made less absolute angle errors in the knee joint repositioning test than did the control elderly, being 1.7 ± 1.3°, 1.3 ± 0.7° and 3.9 ± 3.1° respectively (P = 0.001). Their proprioceptive acuity was actually comparable to that of the young control subjects, being 1.1 ± 0.5° ($P > 0.05$).

TABLE 6.1. Comparison of age, height and body weight among the elderly Tai Chi practitioners, golfers, elderly and young control subjects; Mini-Mental Status Examination and physical activity levels among the 3 elderly groups; and years of practice between the Tai Chi practitioners and golfers.

	Tai Chi subjects ($N = 12$)	**Golfers** ($N = 11$)	**Elderly control subjects** ($N = 12$)	**Young control subjects** ($N = 12$)	***P***
Age (years)	69.6 ± 5.7	66.2 ± 6.8	71.3 ± 6.6	20.3 ± 1.4†	0.000*
Height (cm)	162.8 ± 6.7	164.5 ± 7.7	160.0 ± 6.2	171.0 ± 4.3††	0.001*
Body Weight (kg)	62.9 ± 6.9	65.7 ± 7.7	62.4 ± 8.6	65.0 ± 7.9	0.695
Mini-Mental Status Examination	30 (29, 30)	30 (29, 30)	29 (27.5, 29.75)	–	0.124
Physical activity levels					0.583
Light ≤ 4 METs	$N = 7$	$N = 6$	$N = 10$	–	
Moderate ≤ 5.5 METs	$N = 4$	$N = 4$	$N = 2$	–	
Heavy > 5.5 METs	$N = 1$	$N = 1$	$N = 0$	–	
Years of practice	8.4 ± 9.1	15.2 ± 13.4			0.168

Values are mean ± S.D. for this and all subsequent tables, except the values for Mini-Mental Status Examination were median (25th, 75th percentiles).

– Denotes "not tested".

* Denotes significant difference at $P < 0.01$ using one-way ANOVA.

† Denotes significant difference at $P < 0.05$ between young subjects on the one hand, and the 3 elderly groups of Tai Chi subjects, golfers and control subjects on the other, by means of post hoc analysis using Bonferroni's adjustment.

†† Denotes significant difference at $P < 0.05$ between young subjects on the one hand, and the 2 elderly groups of Tai Chi and control subjects on the other, by means of post hoc analysis using Bonferroni's adjustment.

6.4.3 Limits of stability test (LOS)

The multivariate ANOVA indicated a statistically significant overall effect across the 3 outcome measures for the 4 subject groups ($P < 0.001$; Table 6.2). The univariate tests showed that there were statistically significant differences in the reaction time ($P < 0.001$), maximum excursion ($P < 0.001$), and directional control of the normalized COP ($P = 0.002$) among the 4 groups. Because statistically significant differences were found in all the univariate tests, post hoc analysis using Bonferroni's adjustment was conducted for the 3 outcome measures and revealed the findings below.

Both the Tai Chi practitioners and the golfers achieved faster reaction times when leaning to the different target positions (mean = 0.8 ± 0.1 s, 0.8 ± 0.2 s respectively; Table 6.2) than did the elderly control subjects (mean = 1.0 ± 0.3 s; $P < 0.05$), but their reaction times were still significant longer when compared with those of the young control subjects (mean = 0.5 ± 0.1 s; $P < 0.05$).

TABLE 6.2. Comparison of absolute angle errors and limits of stability test outcome measures among the 4 subject groups.

	Tai Chi subjects (N = 12)	**Golfers** (N = 11)	**Elderly control subjects** (N = 12)	**Young control subjects** (N = 12)	P
Knee joint repositioning test					
Absolute angle error (°)	1.7 ± 1.3	1.3 ± 0.7	3.9 ± 3.1†	1.1 ± 0.5	0.001*
Limits of stability tests					
Reaction time (s)	0.8 ± 0.1	0.8 ± 0.2	1.0 ± 0.3†	0.5 ± 0.1††	0.000**
Maximum excursion (%)	92.6 ± 5.5	92.9 ± 5.7	83.2 ± 8.2†	97.1 ± 3.3	0.000**
Directional control (%)	79.0 ± 4.1	78.3 ± 5.4	70.3 ± 7.3†	79.2 ± 7.0	0.002**

* Denotes significant difference at $P < 0.01$ using one-way ANOVA.

** Denotes significant difference at $P < 0.01$ using univariate tests, after multivariate ANOVA for limits of stability test with $P < 0.001$.

† Denotes significant difference at $P < 0.05$ between elderly control subjects on the one hand, and elderly Tai Chi subjects, golfers and young control subjects on the other, by means of post hoc analysis using Bonferroni's adjustment.

†† Denotes significant difference at $P < 0.05$ between young control subjects on the one hand, and elderly Tai Chi subjects and golfers subjects on the other, by means of post hoc analysis using Bonferroni's adjustment.

For the maximum excursion, both exercise groups were able to lean farther toward the 8 target positions within their limits of stability (mean = 92.6 ± 5.5%, 92.9 ± 5.7% respectively) than the elderly control subjects (mean = 83.2 ± 8.2%; $P < 0.05$; Table 6.2). In fact, their improved maximum excursion was comparable to that of the young control subjects (mean = 97.1 ± 3.3%; $P > 0.05$). Similarly, the Tai Chi practitioners and golfers could travel to the target positions through a smoother pathway (mean directional control = 79.0 ± 4.4%, 78.3 ± 5.4%, respectively) than the elderly control subjects (mean = 70.3 ± 7.3%; $P < 0.05$; Table 6.2). This level of improved directional control was again comparable to that of the young control subjects (mean = 79.2 ± 7.0%, $P > 0.05$). In sum, the male elderly Tai Chi practitioners and golfers attained better control when shifting weights within their limits of stability than the elderly control subjects, with regard to reaction time, maximum excursion and the directional control of normalized COP. Of interest is that improvements in the latter 2 outcome measures made their performance comparable to that of the young control subjects.

6.4.4 Correlation of the absolute angle errors with the limits of stability outcome measures

To determine possible relationship between proprioceptive input and a related output (balance control), we correlated the absolute angle errors obtained from the knee joint repositioning test with the outcome measures obtained from the limits of stability test (reaction time, maximum excursion and directional control) in the 3 elderly groups, using Pearson's product-moment coefficient of correlation. Our findings showed that the absolute angle errors were indeed correlated with the reaction times recorded in the LOS test ($r = 0.427$; $P = 0.013$; Table 6.3; Fig. 6.1a).

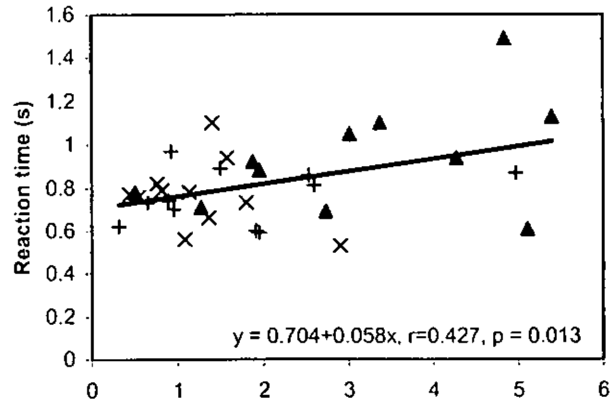
TABLE 6.3. Pearson product-moment coefficient of correlation between the absolute angle errors and the limits of stability test outcome measures among the 3 elderly groups.

	Correlation coefficient ($N = 35$)	***P***
Limits of stability test		
Reaction time (s)	0.427	0.013*
Maximum excursion (%)	-0.522	0.002†
Directional control (%)	-0.396	0.023*

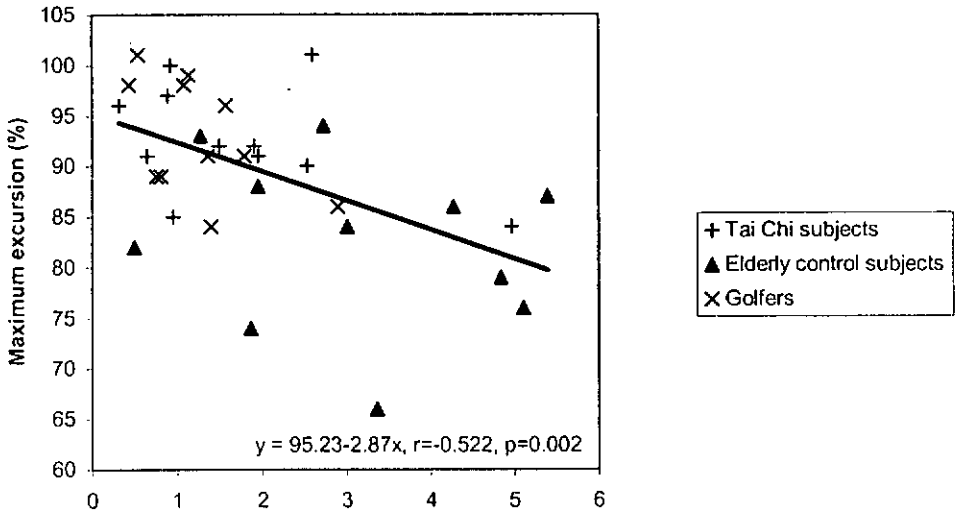
* Denotes significant difference at $P < 0.05$ using Pearson product-moment coefficient of correlation.

† Denotes significant difference at $P < 0.01$ using Pearson product-moment coefficient of correlation.

(a) Reaction time



(b) Maximum excursion



(c) Directional control

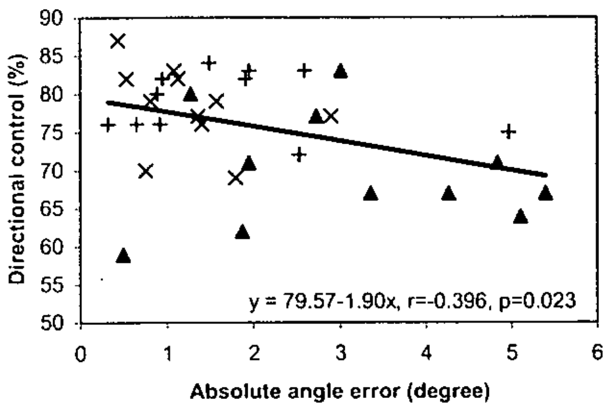


FIGURE 6.1. – Diagrams plotting (a) reaction time, (b) maximum excursion and (c) directional control of the normalized COP against absolute angle error obtained from the passive knee joint repositioning test.

Elderly subjects who exhibited larger knee joint repositioning errors required more time, on average, to initiate a voluntary response in moving their body toward the 8 spatial targets. Furthermore, the absolute angle errors were inversely correlated with the averaged values of the maximum excursion to the 8 target positions ($r = -0.522$; $P = 0.002$; Table 6.3; Fig. 6.1b). That is to say, elderly subjects exhibiting larger joint repositioning errors, on average, displayed smaller averaged maximum excursion to the 8 test directions. A significant negative correlation was also found between the absolute angle errors and directional control of the normalized COP, as measured by the averaged values in the 8 target directions ($r = -0.396$; $P = 0.023$; Table 6.3; Fig. 6.1c). In other words, elderly subjects with larger absolute angle errors showed less directional control, on average, in shifting their weight toward the 8 target positions.

6.5 Discussion

6.5.1 Joint proprioception sense and limits of stability: Effects of aging

6.5.1.1 Joint proprioception sense

Limb proprioception has been reported to decrease with age, after ligamentous injuries, and in some pathological conditions common among the elderly subjects such as stroke and osteoarthritis. Limb proprioception is known to play an important role in maintaining normal body posture, in generating smooth and coordinated movements, and in motor learning and relearning (Gardner et al. 2000). Elderly fallers showed significantly reduced proprioception of the lower limbs, when asked to match the position of the big toe on each side by extending the knee (Lord et al. 1999).

In the present study, the elderly control subjects made significantly larger angle errors in the passive knee joint repositioning test (mean = 3.9 ± 3.1°) than did the young subjects (mean = 1.1 ± 0.5°; $P < 0.05$; Table 6.2). This result agreed with previous findings that the ability to reproduce knee position deteriorated with increasing age. Barrack et al. (1983) compared healthy elderly subjects (average age = 63 years) with young subjects (25 years), using an *active* joint repositioning test with 90° of knee flexion as the starting position. The limb was passively moved at $10°\cdot s^{-1}$ to target positions ranged from 5° to 25° of knee flexion. The subjects were then asked to reposition the knee to the target positions *actively*. The absolute angle errors were 4.6° and 3.6° for the elderly and young subjects respectively, which represented an increase by 28% in the elderly subjects. Petrella et al. (1997) used an active joint repositioning test in a standing position, with target positions ranging from 10° to 60° of knee flexion. The elderly (age range, 60–86 years) and young subjects (age range, 19–27 years) attained 4.6° and 2.0° in their absolute angle errors, respectively, which represented an increase by 130% in the elderly group. Using a passive knee repositioning test protocol in this study, we detected an even more significant increase (by 255%) in the absolute angle error of elderly control subjects when compared with that of the young subjects. One possible reason for detecting such a large difference could be the *passive* protocol used by us as opposed to the *active* protocol adopted by the previous investigators cited above. It should be noted that when the brain issues a descending motor command signal to the limb muscles, corollary discharges are being sent simultaneously to relevant cortical areas, the so called "efferent copy" (Lafargue et al. 2003). In other words, the brain will receive corollary discharges from descending cortical signals, as well as ascending limb proprioceptive afferent inputs coding limb position and movement, when *active* as opposed to *passive* repositioning is employed. Hence, a *passive* joint repositioning test would produce greater angle errors than an *active* test. Also, the afferent input from the muscle spindles is relatively less in the passive repositioning test as the muscles are in a relaxed state (Vallbo 2003). Consequently, subjects have to rely more on other sources of afferent inputs, such as those from the ligaments and joints which are known to degenerate with aging (Barrack et al. 1983). The amplitude of joint movement used in this study was only 3°, which was much smaller than that used in the studies cited above. It is possible that smaller changes in knee position might demand higher proprioceptive sensitivity for the knee joint to detect. Hence, the angle errors could have been larger than the case when larger changes in knee position were used. Please note that we had already shown that the passive knee repositioning test protocol adopted by us produced highly repeatable data in Chapter 2 (Tsang and Hui-Chan 2003). This could be attributed to the well-controlled test parameters in our test protocol, which kept the initial joint position as well as the amount, speed and direction of joint movement constant. All these parameters are known to modulate the discharges of the joint proprioceptors (Gardner et al. 2000). Hence, their proper control would be expected to ensure the accuracy of joint repositioning. This was supported by our finding of high data repeatability with an intraclass correlation coefficient of 0.90 in Chapter 2 (Tsang and Hui-Chan 2003).

6.5.1.2 Limits of stability (LOS)

Studies have shown that the LOS can be used as a significant predictor of performance in functional activities, such as crossing a street, getting onto a bus and climbing a flight of 27 stairs (Topp et al. 1998). It also plays a significant role in indicating susceptibility to falls (Girardi et al. 2001).

In the present study, the elderly control subjects showed a slower reaction time (by 100%), smaller maximum excursion (by 14%) and less directional control of their leaning trajectory (by 11%) than did the young subjects (all $P < 0.05$; Table 6.2). These declines in LOS performance of elderly subjects agreed with the findings from different studies using similar outcome measures. King and colleagues (1994) found that the active older subjects (age range, 60–91 years) had a decrease of 30% in the maximum forward and backward displacement of the COP normalized with respect to foot length, when compared with that of the younger subjects (age range, 20–59 years). In another study, Hageman and colleagues (1995) measured the total time moving from center to the 8 target positions (termed as movement time), and the mean distance traveled from the center to each of 8 target positions normalized with its respective shortest distance (termed as path length). They found that older adults (mean age = 65.3 years) had longer movement time (by 49%) and path length (by 12%) when compared to those of the young adults (mean age = 25.3 years).

6.5.2 Joint proprioception sense and limits of stability: Effects of Tai Chi practice

6.5.2.1 Joint proprioception sense

Our results showed that the male elderly Tai Chi practitioners achieved significantly smaller knee angle errors (mean = 1.7 ± 1.3°), when compared with those of the elderly control subjects (mean = 3.9 ± 3.1°; $P < 0.05$). Moreover, their performance was comparable to that of young subjects (mean = 1.1 ± 0.5°; $P > 0.05$;

Table 6.2). In other words, experienced Tai Chi practitioners had developed a heightened sense of knee joint proprioception. Practicing Tai Chi involves doing a series of slow and precise movements, often repeatedly. The body and limb joints must be placed in specific positions relative to each other and in space (Tsao 1995). The subjects in our study had been practicing these slow and precise movements for 8.4 ± 9.1 years (Table 6.1). It is thus entirely plausible that repeated Tai Chi practice could have improved their knee joint position sense.

In Chapter 2, we proposed 2 mechanisms which could have given rise to the improvement of joint proprioception through long-term Tai Chi practice (Tsang and Hui-Chan 2003): 1) Plastic changes could have been induced in the cortex, by repeated positioning of body and limb joints in specific spatial positions as demanded by the various Tai Chi forms. 2) Increased output of the muscle spindles through the so-called γ route could have occurred during Tai Chi practice, which could help to bring about plastic changes in the central nervous system, such as an increased strength of synaptic connections and/or structural changes in the organization and numbers of connections among neurons (Shumway-Cook and Woollacott 2001).

6.5.2.2 Limits of stability (LOS)

Our results from the LOS test also showed that the male elderly Tai Chi practitioners achieved significantly faster reaction times (0.8 ± 0.1 s), as well as greater maximum excursions (92.6 ± 5.5%) and directional control of their normalized COP (79.0 ± 4.1%) than those of the elderly control subjects (1.0 ± 0.3 s, 83.2 ± 8.2%, 70.3 ± 7.3% respectively, $P < 0.05$; Table 6.2). The more superior performance of the Tai Chi practitioners in these 3 outcome measures revealed that repeated Tai Chi practice could have improved their dynamic balance control during self-initiated weight shifting within the subjects' base of support.

Practicing Tai Chi requires shifting the body weight to different target positions in a smooth and coordinated manner. In other words, the subjects had regularly been challenging their balance control systems to maintain their centre of mass within their base of support, when it was shifted to the limits of stability. It is hardly surprising that in our Tai Chi practitioners such a repetitive demand for proper balance control over a period of 8.4 ± 9.1 years of practice could have developed better maximum excursion and directional control of their normalized COP than those of the control subjects. Indeed, the Tai Chi practitioners were found to be comparable to the young control subjects in these 2 measures, being respectively 92.6 ± 5.5%, 79.0 ± 4.1% in the former and 97.1 ± 3.3%, 79.2 ± 7.0% in the latter subjects ($P > 0.05$; Table 6.2). As the present findings are from a cross-sectional study, an argument naturally arises that these Tai Chi practitioners already had better balance control before they took up Tai Chi practice. To circumvent the possibility of sample bias, we had conducted a control trial with a prospective design (Hui-Chan and Tsang 2001; Tsang and Hui-Chan 2004a). As reported in Chapter 5, elderly subjects (mean age = 67.6 years) who underwent Tai Chi practice for 1.5 hours, 6x week^{-1} for 8 weeks, had significantly improved the directional control of their normalized COP after 4 weeks of training, whereas the control group receiving general education for a comparable period had no improvement in their balance performance (Tsang and Hui-Chan 2004a).

The reaction time in initiating a movement depends on both neuromuscular control and cognitive factors (Shumway-Cook and Woollacott 2001). Lord and Fitzpatrick (2001) measured the reaction time of a group of older subjects, aged from 62 to 95 years, by instructing them to step on 1 of 4 targets with either leg as quickly as possible when it was illuminated. They found that leg muscle weakness, slow decision time as reflected by finger-press reaction time test, and poor leaning balance impaired the reaction time of their stepping on the illuminated target. Better balance control to stabilize the body in advance of potentially destabilizing movements (Tsang et al. 2004), and further leaning distance and smoother control of leaning trajectory as shown in our present study, might explain why the elderly Tai Chi practitioners had shorter reaction times than those of the elderly control subjects, when shifting their weight to the 8 target positions. Despite these improvements, we found that the reaction times of the elderly Tai Chi practitioners (mean = 0.8 ± 0.1 s) were still significantly slower than those of the young control subjects (mean = 0.5 ± 0.1 s, $P < 0.05$; Table 6.2). The finding of slower reaction times in the elderly subjects had also been demonstrated by Patla et al. (1993). These investigators compared a group of healthy elderly subjects (mean age = 69 years) with young subjects (mean age = 20 years), by asking them to step in 1 of 3 directions, namely forward, sideways and backwards with the designated leg, after a light response signal. They found that the reaction time increased significantly in the elderly subjects. Further analysis using the vertical force component of forceplate revealed that elderly subjects took longer time to reach peak force in all 3 stepping directions, as well as lower peak force for forward stepping. The peak force was required to transfer body weight to the nonstepping leg.

Tai Chi exercise is regarded as a moderate form of exercise. Although its practice has been found to improve knee muscle strength in the older subjects (Lan et al. 1998), its training intensity on the leg muscle may not have produced sufficient increase in muscle strength, to help the elderly subjects to generate as fast a reaction time as that of the young subjects. Another contributing factor to the slower reaction time is the known decrease in conduction velocity in the elderly subjects. In this connection, using magnetic stimulation of the brain, Tobimatsu et al. (1998) found that aging had a significant effect on prolonging the descending motor evoked potential latencies in the leg abductor hallucis muscles of the foot. In our study, the subjects had to recruit postural muscles including those of the lower legs to shift their weight to the target positions as fast as possible. The slower conduction velocity of the elderly subjects may thus explain in part or whole why the elderly Tai Chi practitioners still showed slower reaction times, when compared with those of young control subjects.

6.5.3 Joint proprioception sense and limits of stability: Comparison of Tai Chi practitioners versus golfers

Our findings further demonstrated that the male elderly golfers achieved levels of knee joint proprioceptive acuity similar to those of the elderly Tai Chi practitioners, with absolute angle errors equal to 1.3 ± 0.7° and 1.7 ± 1.3° respectively ($P > 0.05$; Table 6.2). In addition, the elderly golfers achieved a similar level of balance performance as the Tai Chi practitioners, in terms of reaction times (golfers = 0.8 ± 0.2 s; Tai Chi practitioners = 0.8 ± 0.1 s), maximum excursion (golfers = 92.9 ± 5.7%; Tai Chi practitioners = 92.6 ± 5.5%) and directional control of their normalized COP (golfers = 78.3 ± 5.4%; Tai Chi practitioners = 79.0 ± 4.1%) (all $P > 0.05$, Table 6.2). As with the Tai Chi practitioners, the elderly golfers achieved a performance level in the joint repositioning and LOS test comparable to that of the young subjects, except for the reaction time in the LOS test.

In a well-executed golf swing, golfers must maintain good balance and precise control of the posture of the head and body in relation to space and to the limb, as well as timely co-ordination of their muscle activities (Selicki and Segall 1996). As with Tai Chi, these requirements might explain the improved joint proprioception sense and balance control with repeated practice of golf over time. There has been a lack of research studies on the effect of golfing on joint proprioception and balance control. The present results thus add new and original knowledge to the benefits of golfing. Furthermore, our findings in both experienced Tai Chi practitioners and golfers suggest that exercise which demands accurate positioning of the body and limbs in space and in relation to each other is likely to improve joint proprioception sense. A similar line of thought may apply to the improvement in balance control found in these 2 groups of elderly subjects, in that both Tai Chi and golfing demand precise postural orientation of the head and body with respect to their limbs, as well as controlled weight shifting in single and/or double leg stand with various arm movements. In sum, the positive findings from our study provide potentially scientific support of the benefits of the 2 exercises, Tai Chi and golf, for the elderly subjects in the 2 functions that are known to decrease with aging, namely joint proprioception and balance control when subjects voluntarily shift weight within their base of support.

6.5.4 Correlation between knee joint position sense and LOS measures

Subjects who had more acute knee proprioception responded more quickly in shifting their weight toward 1 of the 8 target position, when it was lit up during the LOS test. This is clearly shown by the positive correlation between the absolute angle errors and the reaction times in moving the normalized COP during the test (r = 0.427, P = 0.013; Table 6.3; Fig. 6.1a), plotted with the data from all 3 elderly groups. This result further elaborated on the finding of Lord and Fitzpatrick (2001), who showed that subjects with a history of falls had 13% longer reaction time than that of non-fallers (1.32 s and 1.17 s). Lord's group measured the reaction time by asking the elderly subjects to step on one of 4 targets as quickly as possible when it was illuminated. The elderly Tai Chi practitioners and golfers in the present study had significantly shorter reaction times (0.8 s in both groups; Table 6.2), when compared with that of elderly control subjects (1.0 s, $P < 0.05$). Table 6.3 and Figure 6.1a further showed that improved knee joint proprioception, as shown by smaller angle errors in the passive knee repositioning test was correlated with shorter reaction times in the LOS test. The finding of a faster reaction time in voluntary weight shifting helped to explain the report by Wolf et al. (1996) of a reduced risk of multiple falls (by 47.5%) among elderly Tai Chi practitioners.

Our finding showed that the absolute angle error in the passive knee joint repositioning test was also inversely correlated with the maximum excursion in the LOS test (r = -0.522, P = 0.002; Table 6.3; Fig. 6.1b). In other words, subjects with more acute knee joint position sense had more extensive limits of stability. Previous studies have shown that the limits of stability decrease with age (Hageman et al. 1995) and that this is a significant predictor of multiple falls (Girardi et al. 2001). Our present finding may help to explain why Tai Chi practice has been shown to reduce the fear of falling and the risk of multiple falls among the elderly subjects (Wolf et al. 1996).

Our results further demonstrated that the absolute angle of error in the passive knee joint repositioning test was inversely correlated with the directional control of the subject's normalized COP in the LOS test (r = -0.396, P = 0.023; Table 6.3; Fig. 6.1c). In other words, elderly subjects who had better acuity of the knee joint position sense were able to maintain better directional control of their leaning trajectory to the specified target positions. The concept of directional control is based on the assumption that straight-line movements to the target positions are the most efficient and therefore better coordinated (NeuroCom 2000). Both Tai Chi and golfing require the practitioners to shift their body weight in a smooth and coordinated manner (Selicki and Segall 1996; Tsao 1995), which may enhance the directional control of their leaning trajectory. How the quality of directional control is related to daily activities has not yet been delineated, and further research is warranted in this area.

As aforementioned, the correlations between the absolute angle errors and the 3 LOS measures were statistically significant, with degrees of association ranged from -0.522 to 0.427 (all $P < 0.05$; Table 6.3). However, in one of our previous studies, we could not find any significant correlation between the absolute angle errors and the body sway in both anteroposterior and mediolateral directions, when 42 elderly subjects (mean age = 71 years) stood quietly with feet together for 30 s with their eyes open (Tsang and Hui-Chan 2003). In this connection, Lord and colleagues (1999) correlated the knee angle error in a limb matching test, with the mediolateral body sway in a near-tandem stability test with the eyes open, and found a statistically significant but low correlation (r = 0.19). Taken together, these findings suggest that knee joint proprioception is more important in the control of dynamic balance involving voluntary weight shifting than static standing balance. Though statistically significant, the correlation values were small. This finding could be attributed to the fact that postural control requires both sensory input (the information to detect the position and movement of the body in space) and motor output (the ability to generate forces for movement of the body) (Shumway-Cook and Woollacott 2001). Furthermore, the sensory input includes all the information from the somatosensory, visual and vestibular systems, and somatosensory information consists of proprioceptive inputs from the neck, body and limbs (Gardner et al. 2000). In other words, knee joint position sense is only one of the many sensory inputs that the brain can use for postural control. This would explain why there were only fair to moderate degrees of association between the knee joint position sense and LOS measures in the present study.

6.6 Conclusions

In conclusion, our study has provided evidence that male elderly subjects who had practiced Tai Chi or golf on average for more than 8 years had better knee joint proprioception and greater limits of stability significantly beyond those of the control subjects similar in age, gender and physical activity level. Of particular interest were the results showing that their knee joint proprioceptive acuity, as well as the maximum excursion and directional control of their normalized COP during weight shifting within their base of support, were even comparable to those of the young subjects. These findings suggest that long-term practice of Tai Chi and golf may improve joint proprioceptive acuity and dynamic standing balance control within the limits of stability in the elderly subjects, despite the known aging effects in these specific sensori-motor functions. The significant correlations found between the absolute angle errors in passive knee joint repositioning on the one hand, and the reaction time, maximum excursion and directional control of the normalized COP in the LOS test on the other, highlight the importance of knee position sense in functional activities involving leaning or weight shifting. Nevertheless, because a cross-sectional design was employed in the present study, the findings should be confirmed in prospective intervention studies.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Introduction

7.1.1 Rationale of the study

The world population is aging (Fries 1980; Kalache et al. 2002). Among the problems of aging, falls have been identified as one of the major causes of injury in elderly people (Wolter and Studenski 1996). Falls cause most hip fractures in older people, and is the leading cause of accidental death in people more than 65 years old (Sattin 1992). In the United States, the cost of hip fractures attributed to falls in the elderly has been reported to be about $10 billion in 2001 (Carter et al. 2001).

Impaired postural control causes falls in the elderly (Berg and Kairy 2002; Lin and Woollacott 2002). The postural control system controls both postural orientation and postural equilibrium (Melville-Jones 2000; Shumway-Cook and Woollacott 2001). Postural orientation is the alignment of the various parts of the body in specific orientations with respect to one another, and orientating the body in the environment, whereas postural equilibrium is the ability to maintain body stability (Horak and Macpherson 1996). Postural control in standing involves sensory, central integrative and motor mechanisms.

With aging, deficits in the sensori-motor systems and neural mechanisms, as well as deterioration in postural control have been shown to contribute to an increased likelihood of falls (Berg and Kairy 2002; Clark and Rose 2001). However, interventions such as exercise have been shown to maintain and/or improve postural control in the elderly and decrease the likelihood of falls (Carter et al. 2001; Province et al. 1995).

Indeed, increasing evidence has shown that the central nervous system is flexible and dynamic (Stein et al. 1995). Neural plasticity can be found in both intact and lesioned brains responding not just to changes in the environment, but also to training and rehabilitation programs (Gordon 2000).

In this context, Tai Chi is a Chinese mind-body exercise which requires practitioners to establish precise postural orientation of the head and body with respect to their limbs, as well as to coordinate controlled weight shifting in single and/or double leg stance with various arm movements (Tsao 1995; Wolf et al. 1997; Yu 2002). Repeated practice of Tai Chi might, therefore, be expected to improve the sensori-motor and postural control of elderly practitioners. Preliminary findings from studies of Tai Chi have shown that it could improve balance control in the elderly subjects (Lan et al. 2002). However, evidence for the therapeutic value of Tai Chi for the sensori-motor system is either lacking or inconclusive (Jacobson et al. 1997; Wu et al. 2002). Also, the balance measures used in Tai Ch studies have often been static tests, which may not reflect the beneficial effects of Tai Chi on more dynamic postural control under more complex moving conditions than mere relaxed standing still (Li et al. 2001; Wolf et al. 1997; Wu 2002).

If improvement were found in the sensori-motor and postural control of elderly Tai Chi practitioners, we wanted to determine whether any improvement, for example, in joint proprioception was comparable to that in young, healthy subjects. In considering Tai Chi training as a possible falls-prevention strategy, how long will it take to practice Tai Chi for the elderly subjects to achieve significantly better balance control than their sedentary counterparts? To determine the specificity of Tai Chi in improving sensori-motor and postural control, elderly golfers were selected as a comparison group. The studies reported in this thesis were designed to answer all these questions. It is hoped that the results might contribute to solving the growing falling problem associated with the rapidly aging world population.

7.1.2 Study design

Studies 1, 2, 3, and 5 were cross-sectional in nature, conducted to investigate the efficacy of Tai Chi in improving knee proprioception, knee muscle strength and postural control in elderly subjects. Depending on the particular study, either the knee proprioceptive acuity, isokinetic knee extensor and flexor muscle strength, and/or postural control assessments (assessed through a static standing test, a limits of stability test, a sensory organization test, and/or a perturbed single-leg standing test) of elderly Tai Chi practitioners were compared with those of the healthy elderly control subjects, elderly golfers and/or young university students. Study 4 was a prospective test to determine whether 4 or 8 weeks of intensive Tai Chi practice could improve balance control in the healthy elderly subjects.

Elderly Tai Chi practitioners were recruited from local Tai Chi clubs. All had practiced Tai Chi for a minimum of 1.5 hour·week^{-1} for at least 1 year. Golfers were recruited from local golf clubs. Non-Tai Chi elderly subjects were recruited from several community centers for the elderly. They had no experience with Tai Chi, although some took morning walks or did stretching exercises. All the elderly subjects were ambulatory, independent in their activities of daily living, and could communicate and follow the testing procedures. All had Mini-Mental Status Examination scores of 24 or above. The young healthy subjects were all university students who exercised regularly for at least 2 hours a week. The elderly subjects participated in the prospective intervention study had no previous experience with Tai Chi. The inclusion and exclusion criteria for those subjects were similar to those of the cross-sectional study.

The experiments were conducted at the Center of East-meets-West in Rehabilitation Sciences at the Hong Kong Polytechnic University. The sensori-motor assessments consisted of passive knee joint repositioning and knee muscle strength tests. A passive joint repositioning test with an average speed of $3°\cdot s^{-1}$ was used to assess knee joint proprioceptive acuity. The absolute angle error with which the subject reproduced the initial position was used to compare the different groups. Concentric and eccentric isokinetic tests of subjects' dominant knee extensors and flexors were conducted at an angular velocity of $30°\cdot s^{-1}$. Peak torque-to-body weight ratios in concentric and eccentric isokinetic muscle contractions were measured, as well as the hamstrings to quadriceps (H/Q) muscle strength ratio.

Depending on the study, postural control assessments comprised either a static standing test, a limits of stability test, a sensory organization test, and/or a perturbed single-leg standing test. Control of body sway during static standing was measured using a force platform. Excursions of the center of pressure (COP) in the anteroposterior and mediolateral directions during 30 s of standing were recorded. The COP trajectory with respect to height (termed normalized COP) was used to compare subjects' balance performance. In the limits of stability test, subjects' intentional weight shifting to eight different spatial positions within their base of support was captured using force platform measurements. Reaction time, maximum excursion and directional control of the leaning trajectory were the outcome measures. For the sensory organization test, subjects stood under reduced or conflicting somatosensory, visual and vestibular conditions. The amplitude of anteroposterior body sway was measured using dynamic posturography. Subjects were tested in 6 combinations of visual and support surface conditions. Lastly, subjects stood using only their dominant leg on the moving platform of a dynamic posturography machine in the perturbed single-leg stance test. They were then perturbed with forward or backward platform horizontal translations in random order. The maximum anteroposterior body sway was used to compare their balance performance. The reproducibility of all measurement protocols was tested in a pilot study as summarized below.

7.2 Reproducibility of measurement protocols in the pilot study

The reproducibility of the measurement protocols used in the main study was tested 1) to assess the feasibility of the protocol and 2) to ensure that the protocol can generate reliable data. An intraclass correlation coefficient was used to analyze the test-retest reliability of the outcome measures. The data averaged between 2 assessment sessions were compared, and a 2-way mixed random model was employed (Portney and Watkins 1993).

Eleven elderly subjects, seven Tai Chi practitioners and four control subjects, were recruited for the test-retest reliability study. They were four males and seven females with a mean age of 70.8 years (± 4.0 years). After administering the measurement protocols, the same procedure was repeated 1 week later. The same group of subjects underwent all the reliability measurements except for the sensory organization test. For the latter reliability study, 12 elderly subjects (4 men, 8 women, mean age = 68 ± 7.4 years) received measurement of their equilibrium quotients in each of the 6 conditions of the sensory organization test. The testing procedures were also repeated 1 week after the first testing session.

7.2.1 Measurement of errors in the passive knee joint repositioning and knee muscle strength tests

The ICC(3,3) value for the absolute angle error in the knee joint repositioning test was found to be 0.90 (confidence intervals 0.64–0.97).

In the isokinetic knee muscle strength test, the ICC(3,3) values for the concentric knee extensors, concentric knee flexors, eccentric knee extensors and eccentric knee flexors were 0.97 (confidence intervals 0.89–0.99), 0.86 (confidence intervals 0.43–0.97), 0.97 (confidence intervals 0.89–0.99) and 0.95 (confidence intervals 0.81–0.99) respectively.

7.2.2 Measurement of postural control

In the limits of stability test, the ICC(3,8) values for the reaction time, maximum excursion, and directional control were 0.82 (confidence intervals 0.29–0.96), 0.93 (confidence intervals 0.72–0.98), and 0.83 (confidence intervals 0.30–0.96) respectively.

Results from the reliability study of the sensory organization test showed that data obtained under the 6 sensory conditions were repeatable when the same subject was retested 1 week after the initial, with ICC(3,3) ranging from 0.72 to 0.93 (Table 3.1).

In the perturbed single-leg stance test, the ICC(3,3) values for the maximum anteroposterior body sway angles in forward translation and backward translation were 0.81 (confidence intervals 0.51–0.93) and 0.74 (confidence intervals 0.35–0.90) respectively.

7.2.3 Conclusions from the pilot study

In conclusion, the reliability studies on the sensori-motor and postural control showed that all the tests used in this study produced reliable outcome measures. The measurement protocols together with their outcome measures could thus be employed for the main study.

7.3 Summary of original contributions

The studies reported in this doctoral thesis were aimed at gaining new knowledge about the effects of Tai Chi on the sensori-motor and postural control of elderly subjects in the maintenance of upright stance. The summary below will reiterate the findings regarding sensory input, motor output and various postural control tests. Findings on how many weeks of Tai Chi training were needed to improve balance control will be presented, along with conclusions about the specificity of Tai Chi training for improving knee joint proprioceptive acuity and limits of stability when compared to that of golf.

7.3.1 Sensory input

1) We are the first research group to demonstrate that elderly Tai Chi practitioners achieved significantly better knee proprioceptive acuity, in that they showed smaller knee angle errors in the passive repositioning test when compared with that of the control subjects similar in age, gender and physical activity level (Chapter 2, section 2.4.3).

2) We further show that the performance of knee proprioception of the elderly Tai Chi practitioners was comparable to that of young subjects (Table 6.2). In view of the finding that elderly fallers manifest significantly reduced proprioception

in their lower limbs, our findings suggest that Tai Chi could be used as a fall prevention and rehabilitation program for the elderly subjects.

3) The passive knee joint repositioning test developed in this thesis was highly repeatable (Chapter 2, section 2.4.2) and sensitive (Chapter 6, section 6.5.1.1) when compared with that reported in the literature. Our passive joint repositioning test protocol thus provides a reliable clinical and laboratory tool for measuring joint proprioceptive acuity.

4) We show that the absolute angle errors in the knee repositioning test were not correlated with body sway measures in the static standing balance test (Table 2.3). However, in the limits of stability test, smaller absolute angle errors were associated with faster reaction times, larger movements of the normalized center of pressure in the limits of stability test, and better directional control of the subject's leaning trajectory (Table 6.3 and Fig. 6.1). This original finding reveals the potential importance of the accuracy of knee position sense in functional activities involving leaning or weight shifting during upright stance.

7.3.2 Motor output

5) We adopted a lower isokinetic testing speed of $30°\cdot s^{-1}$ in accordance with training velocity specificity, and demonstrated that the elderly Tai Chi practitioners achieved significantly greater knee extensor and flexor muscle strength in both concentric and eccentric contractions than those of the elderly control subjects (Table 4.2).

6) Our results not only show that the elderly Tai Chi practitioners had greater knee muscle strength in both their agonists and antagonists, but that the extent of the strength increases were similar in both knee extensors and flexors (Chapter 4, section

4.4.3). We attribute the findings to the closed kinetic chain positioning adopted during Tai Chi practice, as it requires co-contraction of the agonist-antagonist muscles.

7) Our findings show for the first time significant negative correlations between the strength of both knee extensors and flexors on the one hand, and body sway angles in perturbed single-leg stance on the other. This result could be explained by the need to recruit both knee agonist and antagonist muscles to maintain balance control during single-leg stance (Table 4.3). Platform perturbations during single-leg stance would have demanded greater muscle contractions and even the recruitment of additional muscle groups to counteract the perturbations.

8) We show significant positive correlations between concentric and eccentric knee extensor and flexor strength and the Activities-specific Balance Confidence score ratios (Table 4.3). These original findings demonstrate that both knee extensor and knee flexor strength may enhance the subjective report of balance confidence in the elderly subjects.

7.3.3 Postural Control

Our findings demonstrate that static standing balance test showed no significant differences between the elderly Tai Chi practitioners and elderly control subjects in terms of control of body sway in the anteroposterior and mediolateral directions. However, Tai Chi practitioners did have better balance performance than age-, gender- and physical activity level-matched control subjects in the various balance tests as summarized below:

9) In the limits of stability test, we demonstrate that the elderly Tai Chi practitioners achieved significantly better reaction times than the elderly control

subjects, as well as greater maximum excursions and better directional control of their leaning trajectory in self-initiated shifting of the center of mass within their base of support (Table 2.2). The latter two balance control outcome measures were comparable to those of the young university students (Table 6.2).

10) We demonstrate that long-term elderly Tai Chi practitioners significantly improved their balance performance when standing under conditions that required increased reliance on the visual and vestibular systems, as compared with that of elderly healthy subjects similar in age and physical activity level (Table 3.4). We are the first research group to demonstrate that the elderly Tai Chi practitioners attained the same level of balance control performance as did young, healthy subjects when tested under the same SOT protocol.

11) In the perturbed single-leg stance test, we show that the elderly Tai Chi practitioners were able to achieve significantly less body sway during forward and backward platform translation than that of the elderly control subjects (Table 4.2).

12) The perturbed single-leg stance test designed in this thesis was reliable (Chapter 4, section 4.4.2), able to differentiate the balance performance of elderly Tai Chi and healthy elderly control subjects (Table 4.2), and significantly correlated with the knee muscle strength and subjective report of balance confidence (Table 4.3). The perturbed single-leg stance test, which resembles some of the daily function activities such as stepping onto a moving escalator or walking along a moving train or bus, could be adopted by other investigators in their assessment of elderly subjects.

13) We show that the Tai Chi practitioners reported significantly higher Activities-specific Balance Confidence score (Table 4.2) than that of the elderly control subjects.

7.3.4 Length of Tai Chi training period required to improve balance control

14) Our study establish for the first time the duration of Tai Chi practice required for the elderly subjects to achieve significantly better balance control than their sedentary counterparts. Table 5.3 and Figure 5.1 to 5.4 demonstrate that after only 4 and 8 weeks of intensive Tai Chi training, the elderly subjects achieved significantly better balance control when compared with that of the control group. These improvements were maintained even at follow-up 4 weeks afterwards. We further demonstrate that the improved control was similar to that of the experienced Tai Chi practitioners with more than 7 years of experience (Fig. 5.1 and Fig. 5.3).

7.3.5. Specificity of Tai Chi training for knee joint proprioceptive acuity and limits of stability: Tai Chi versus golf

15) Table 6.2 shows that elderly male golfers had improved their knee joint proprioceptive acuity to an extent similar to that of the elderly Tai Chi practitioners. Similar improvements were also noted in the golfers' reaction times, maximum excursions and directional control of their leaning trajectory in the limits of stability test. Like the Tai Chi practitioners, all the outcome measures recorded in the golfers were significantly better than those of the elderly control group. As with the Tai Chi practitioners, the elderly golfers achieved a performance level in the joint repositioning and limits of stability tests comparable to that of the young subjects, except for their slower reaction times in the LOS test. Our findings on the effect of golf on knee joint proprioception and limits of stability are the first being reported in the literature.

7.4 Limitations and future studies

Generalization of the results of this thesis should be confined to healthy persons aged 60 or above who met the inclusion and exclusion criteria of the thesis. Note that subjects who reported falling in the past 12 months had been excluded from our studies.

The finding of improved joint proprioception has so far been confined to the knee in our studies. Since Tai Chi puts great emphasis on exact joint positioning and direction of movement, and requires the practitioners to move their limbs in smooth coordination with their trunk movement, a study is being conducted to investigate the effect of Tai Chi on the accuracy in active repositioning of their trunk.

In the present thesis, the postural control outcome measures were recorded with subjects in upright stance. Standing does not reflect the full complexity of balance control required during the performance of more functional tasks involving movement. Therefore, we are studying the motor control of elderly Tai Chi practitioners in stair descent. This is because descending stairs involves a lot of eccentric leg muscle work, which has been shown in this thesis to be improved by Tai Chi.

Tai Chi is regarded as a mind-body exercise (Tsao 1995). It involves not only physical movements, but also makes cognitive demands such as the sequencing of movement patterns and motor planning (Wolf et al. 1997a; 2003). A study is being conducted to investigate the effects of Tai Chi on pre-landing muscle EMG of the lower limb during stepping down, with and without a concurrent cognitive task. Our preliminary findings indicate that stepping down while performing a cognitive task altered pre-landing muscle activity in the healthy elderly controls, but not in the young nor elderly Tai Chi practitioners (Lai et al. 2003).

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