

Plantar Pressure Distribution During Tai Chi Exercise

De Wei Mao, PhD, Jing Xian Li, PhD, Youlian Hong, PhD

ABSTRACT. Mao DW, Li JX, Hong Y. Plantar pressure distribution during Tai Chi exercise. *Arch Phys Med Rehabil* 2006;87:814-20.

Objectives: To describe and quantify the plantar pressure distribution characteristics during Tai Chi exercise and to explain the beneficial effect of Tai Chi on balance control and muscle strength when compared with normal walking.

Design: Description and within-subject design.

Setting: A biomechanics laboratory.

Participants: Sixteen experienced Tai Chi practitioners.

Interventions: Not applicable.

Main Outcome Measures: Pressure-time integral, ground reaction force, and displacement of center of pressure (COP).

Results: During Tai Chi movements, the loading of the first metatarsal head and the great toe were significantly greater than in other regions ($P < .05$). The ground reaction forces varied between the Tai Chi movements and normal walking. Compared with normal walking, the locations of the COP in the Tai Chi movements were significantly more medial and posterior at initial contact ($P < .05$), and were significantly more medial and anterior at the end of contact with the ground ($P < .05$). The displacements of the COP were significantly wider ($P < .05$) in the mediolateral direction in the forward, backward, and sideways Tai Chi movements. The displacement was significantly larger ($P < .05$) in the anteroposterior direction in the forward movement.

Conclusions: The plantar pressure characteristics of Tai Chi movements found in this study may be one of the important factors that Tai Chi exercise improves balance control and muscle strength.

Key Words: Balance; Center of pressure; Exercise; Muscles; Rehabilitation; Tai Chi.

© 2006 by the American Congress of Rehabilitation Medicine and the American Academy of Physical Medicine and Rehabilitation

THE FOOT IS THE DIRECT CONTACT between the body and the external environment. The central nervous system relies on sensory input from the muscles and cutaneous receptors in the lower extremities to generate effective motor patterns for human posture and locomotion. Feedback that originates from these receptors provides a constant source of information on loading, joint kinematics, and plantar pressure

distribution.¹ On the plantar surface, the toe, and the metatarsal head, tactile sensations, which convey information about the magnitude and direction of even small strains that occur on the skin, are crucial to the avoidance of falls.² A human can maintain balance by using toe pressure to correct the many postural disturbances that are experienced in everyday life.^{2,3} There is a significantly negative relation between the sensation threshold of the great toe and the peak pressure under the great toe in walking and running.³ The tactile sense of the great toe decreases with age and elderly people are often unable to sufficiently utilize the muscle of the great toe to maintain balance control when perturbation occurs.^{2,4} Therefore, the training of the activity of the toe and the somatosensory information from the sole may be more appropriate than strength training as a physical therapy treatment to rectify balance problems.^{2,5}

Numerous studies have suggested that the center of pressure (COP) on the bottom of the foot has an important biomechanical meaning.⁶ The controlled displacement of the COP has broad applications, such as the investigation of gait in amputees,⁷ vestibular deficits,⁸ and Parkinson's disease,⁹ or as an index of postural stability,¹⁰ and different designs of footwear.¹¹ McCaw and DeVita¹² suggested that shifting the COP posteriorly or anteriorly induces significant changes of torque in the ankle, knee, and hip joints of the leg during the stance phase of gait. Schmid et al⁷ reported that impaired COP displacement in amputees can lead to difficulties in the adequate control of dynamic equilibrium. In addition, a few studies have demonstrated that an increase in the displacement of the COP increases not only the intensity of electromyography,¹³ but also the number of muscles that participate in the movement of the lower extremities when disturbances occur.¹⁰

The ground reaction force is exerted on the foot during human locomotion and varies continually from the instant of initial contact until the foot leaves the supporting surface.¹⁴ There have been numerous studies on the ground reaction force during walking that have showed it is a reliable and repeatable feature of gait.^{14,15} However, there have been few studies on the ground reaction force in Tai Chi movements. Tai Chi is an ancient Chinese martial art. The broad consensus is that Tai Chi exercise improves balance control and muscle strength in the lower extremities.^{16,17} However, the mechanisms by which Tai Chi improves balance control and subsequently prevents falls in older people^{16,18} are still unclear.

According to the theory of Tai Chi, foot posture and movement are the foundation of the whole body posture, and the concept of proper position and direction are always emphasized.¹⁹ Stepping forward, backward, sideways, up and down, and fixing are the 5 fundamental movements of Tai Chi.¹⁹ Wu and Hitt¹⁸ studied the foot ground contact characteristics using force platforms and pressure plates. They found that the impact force to the foot was significantly lower and the main pressure was located in the more medial and anterior of the foot when compared with walking. Unfortunately, only the stepping forward movement was selected and analyzed. The hypotheses of this study are (1) the main plantar loadings are located on the first metatarsal head and the great toe regions during Tai Chi movements, whereas they are located on the second and third and fourth and fifth metatarsal head regions during normal

From the Department of Sports Science and Physical Education, Chinese University of Hong Kong, Shatin, Hong Kong (Mao, Hong); Shandong Institute of Physical Education and Sports, Jinan, Shandong, China (Mao); and School of Human Kinetics, University of Ottawa, ON, Canada (Li).

Supported by the Hong Kong Special Administrative Region (project no. CUHK4360/00H).

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit upon the authors or upon any organization with which the authors are associated.

Reprint requests to Youlian Hong, PhD, Dept of Sports Science and Physical Education, Chinese University of Hong Kong, Shatin, NT, Hong Kong, e-mail: youlianhong@cuhk.edu.hk.

0003-9993/06/8706-10210\$32.00/0

doi:10.1016/j.apmr.2006.02.035

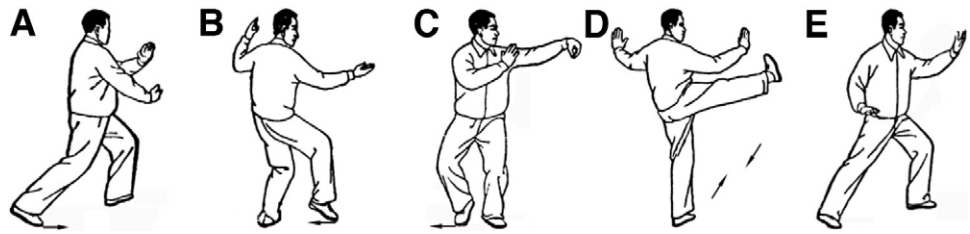


Fig 1. Foot movements during (A) forward, (B) backward, (C) side-ways, (D) up-down, and (E) fixing Tai Chi movements.

walking; (2) the impact force to the foot is lowered; and (3) the displacements of COP are wider in the mediolateral (ML) direction and longer in the anteroposterior (AP) direction during all of the 5 typical Tai Chi movements when compared with normal walking. Therefore, the objective of this study is to describe and quantify the plantar pressure distribution characteristics in the 5 fundamental Tai Chi movements, and try to illustrate why Tai Chi movements benefit balance control and muscle strength when compared with normal walking.

METHODS

We recruited 16 sex-matched elite Tai Chi masters (8 men, 8 women; age, 23.1 ± 5.5 y; height, 166.0 ± 7.6 cm; body mass, 62.2 ± 7.8 kg; experience of practicing, 8.1 ± 5.7 y) with no previous diseases or injuries in the year before the study. The 42-form Tai Chi was selected for this study because this style was designed on the bases of the Yang style and contains the most representative components of the other traditional schools.¹⁹ It is likewise the standard for national and international competitions¹⁹ and has become one of the most popular styles of Tai Chi exercise.^{16,19} Five typical movements were selected for analysis: the brush knee and twist steps, step back to repulse monkey, wave hand in cloud, kick heel to right, and grasping the bird's tail, representing stepping forward, backward, sideways, up-down, and fixing movements, respectively. We used the Pedar-X insole system^a to collect the plantar forces during performance of the movements. Each insole has 99 sensors and the sampled rate was set at 50Hz. The reliability of this system has been well documented in the previous studies.^{20,21} With the aid of the Trublu calibration device,^a all of the sensors of the system were individually calibrated before testing. Due to the quasi-identity of the left and right cycle during most Tai Chi movements,¹⁹ only the data obtained from the left foot were selected and analyzed.

The foot movements during the 5 typical Tai Chi movements are described as follows: (1) forward movement, the left foot makes contact with the ground first, the right foot then steps forward, and the left foot leaves the ground at the end; (2) backward movement, the left foot makes contact with the ground, the right foot then steps backward, and the left foot then leaves the ground; (3) sideways movement, the left foot makes contact with the ground, the right foot then steps sideways, and the left foot then leaves the ground; (4) up-down movement, the right foot leaves the ground, moves upward, kicks in the air, and then moves back down to the ground; and (5) fixing movement, the left foot makes contact with the ground, both feet then make contact with the ground, and the movement is finished (fig 1).

Each subject performed 3 trials of the 5 movements. To maintain the continuity and smoothness of each measured movement, the subject was asked to perform 3 consecutive movements that included the specific movement to be studied in the middle. After the performance of the 5 movements, each subject was asked to walk 15m 3 times at a free speed, and the plantar forces were recorded. All of the subjects wore the

identical socks and Chinese Tai Chi shoes. The sole of this kind of shoe is flat and has uniform rigidity. Before testing, the subjects completed consent forms and were given sufficient time to warm up.

For analysis, the foot was divided into 9 distinct regions: the medial heel, lateral heel, medial midfoot, lateral midfoot, first metatarsal head, second and third metatarsal heads, fourth and fifth metatarsal heads, great toe, and lesser toes, as illustrated in figure 2.

In accordance with the definitions of the Pedar-X insole coordinates system, the most medial and posterior point of the left foot was defined as the origin (zero point). The x and y coordinates of the COP were normalized to the maximum width and maximum length of the insole, respectively. The locations (x and y coordinates) of the COP at initial and end contact with the ground and the displacements in the ML and AP directions were extracted and analyzed. The total forces that were exerted on the foot were normalized to body weight and drawn against the stance time. The pressure-time integral (PTI) of each region were obtained using Novel Database Pro

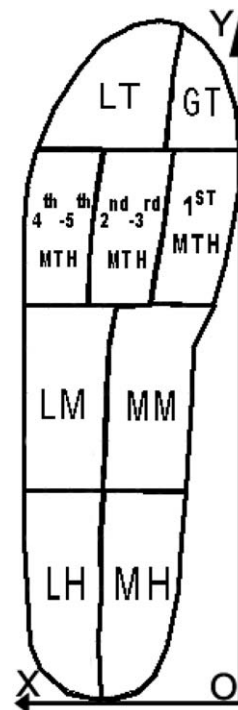


Fig 2. Divided plantar regions of the left foot and the definition of the coordinate system based on this insole system. Abbreviations: 1st MTH, first metatarsal head; 2nd-3rd MTH, 2nd-3rd metatarsal heads; 4th-5th MTH, 4th-5th metatarsal heads; GT, great toe; LH, lateral heel; LM, lateral midfoot; LT, lesser toes; MH, medial heel; MM, medial midfoot.

software.^a The PTI was defined as the amount of loading maintained through a divided plantar region when the foot comes in contact with the ground. It was calculated as the product of the pressure that was exerted multiplied by the time during which the pressure was exerted.²² PTI values reflect not only the pressure's amplitude but also the time duration. Compared with peak pressure, PTI provides more information of the plantar mechanical loading and has been shown to be a more sensitive indicator in foot function,²³ foot injury,²⁴ and foot pain.²⁵ For the Tai Chi movements, the mean of 3 trials for each parameter were calculated and analyzed. For normal walking, the mean of 3 left-foot steps in each of the 3 trials was prepared for comparison with the Tai Chi movements.

The independent *t* test was conducted to compare the differences of all dependent variables between men and women. In this study, the comparison between each of the 5 typical Tai Chi movements and normal walking is done using a within-subject design. A repeated-measures analysis of variance (ANOVA) was employed for the displacement of COP variables. After finding the significant differences among Tai Chi movements and normal walking, we used the post hoc Bonferroni adjustment to detect the differences between normal walking and each Tai Chi movement.

On the other hand, 1 hypothesis of this study is that the main plantar loadings are located on the first metatarsal head and the great toe regions during Tai Chi exercise, while they are located on the second and third and fourth and fifth metatarsal head regions during normal walking. To test the hypotheses, the comparisons of PTI among different plantar regions (see fig 2) in each specific Tai Chi movement and in normal walking were conducted respectively. The 1-way ANOVA with planned comparisons was employed to detect: (1) whether the PTIs of the first metatarsal head and the great toe regions were significantly greater than the remaining regions during each Tai Chi movement and (2) whether the PTI of the second and third and fourth and fifth metatarsal head regions were significantly greater than the remaining regions during normal walking. A significance level of .05 was chosen for all the statistical analyses.

RESULTS

No significant difference was found in any of the parameters between the male and female groups ($P > .05$), and thus the data from the 2 groups were pooled and averaged for further analysis.

Results show that the PTIs of the first metatarsal head and the great toe were the 2 largest values (fig 3, table 1) and were significantly greater ($P < .05$, Cohen $d \geq 0.7$) than those of the other regions across all 5 Tai Chi movements. However, during normal walking, the PTIs of the second and third metatarsal heads and the fourth and fifth metatarsal heads were the 2 largest values (fig 3, table 1) and were significantly greater than those of the other regions ($P < .05$, $d \geq 0.9$).

Figure 4 illustrates that the forces exerted on the foot varied between the 5 Tai Chi movements, which also shows lower magnitudes and different shapes of ground reaction forces than in normal walking.

Figures 5 and 6 and tables 2 and 3 show the statistical results of *x* and *y* coordinates of the COP at initial and end contact with the ground and the displacement during contact when compared between normal walking and each Tai Chi movement. Compared with normal walking, the *x* coordinates (see fig 5, table 2) of the COP at initial and end contact were significantly less ($P < .05$, $d \geq 0.8$) in the forward, backward, sideways, and fixing movements, which indicates a more medial position of contact. The *y* coordinates (see fig 6, table 3) of the COP at

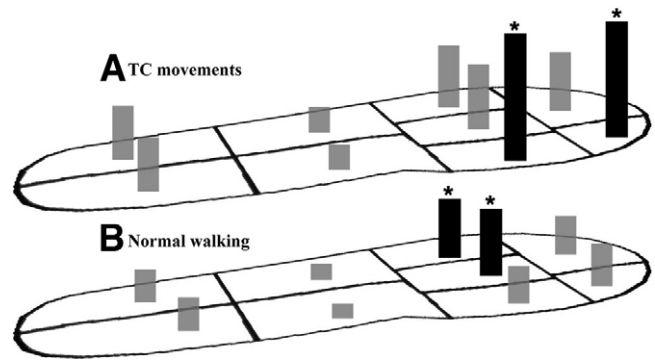


Fig 3. Comparison of PTI among 9 plantar regions during (A) Tai Chi (TC) movements and (B) normal walking. *Indicates the 2 largest regions significantly greater than the remaining regions ($P < .05$).

initial contact were significantly greater ($P < .05$, $d \geq 13.4$) in the backward and sideways movements, and the figures show that the contact positions were located in the forefoot region. The *y* coordinates (see fig 6, table 3) of the COP at initial contact were significantly less ($P < .05$, $d \geq 1.5$) in the forward and fixing movements, which indicates that the positions of contact were more posterior. The *y* coordinates (see fig 6, table 3) of the COP at end contact were significantly greater ($P < .05$, $d \geq 0.8$) in the forward, backward, and sideways movements, and the figures show that the positions were more anterior. In addition, the forward, backward and sideways movements had significantly wider ($P < .05$, $d \geq 7.4$) displacements in the ML direction (see fig 5, table 2). The forward movement had a significantly larger ($P < .05$, $d \geq 3.5$) displacement in the AP direction (see fig 6, table 3).

DISCUSSION

Generally, straight and forward walking during daily activity differs from Tai Chi exercise, which combines and repeats different support patterns and step directions.¹⁹ However, several studies have demonstrated that Tai Chi and walking are both moderate forms of exercise that are suitable for older people. Both exercises have beneficial effects on balance control, muscle strength and cardiorespiratory responses in the elderly population.^{16,17,26-28}

The main finding of this study is that plantar pressure distribution during Tai Chi movements differs when compared with normal walking.

Pressure Distribution

Figure 3 and table 1 show that in the Tai Chi movements, the 2 greatest PTIs were located in the first metatarsal head and great toe regions, whereas in normal walking, they were located in the second and third and fourth and fifth metatarsal heads regions. The results further strengthen the findings of other researchers,¹⁸ who reported that the main loading in Tai Chi movements occurs in the regions of the great toe and first metatarsal head, whereas the loading maintained in slow walking occurs in the third metatarsal head region. These results reveal that the main plantar loading shifts from the second and third and fourth and fifth metatarsal head in normal walking to the first metatarsal head and the great toe in Tai Chi movements. Some studies have demonstrated that the great toe and the forefoot play a very important role in both cutaneous feedback and the muscle activity of the toe in maintaining balance control during gait.^{2,4} Nurse and Nigg^{1,3} investigated

Table 1: Statistical Results of PTI When the 2 Largest Regions Are Compared With the Remaining Regions for the 5 Tai Chi Movements and During Normal Walking

Movement	Two Largest Regions	MH		LH		MM		LM		2nd-3rd MTH		4th-5th MTH		LT	
		t	d	t	d	t	d	t	d	t	d	t	d	t	d
Forward	1st MTH	8.3	1.8	8.2	1.7	17.2	3.8	15.9	3.5	11.8	2.5	13.8	3.0	11.2	2.4
	GT	4.4	1.0	4.3	0.9	13.8	3.2	12.5	2.8	8.1	1.8	10.3	2.3	7.5	1.6
Backward	1st MTH	8.3	1.5	8.2	1.4	17.2	2.7	18.9	1.9	11.8	1.1	13.8	1.3	11.2	1.3
	GT	6.6	1.7	6.2	1.6	12.0	3.5	8.4	2.2	4.4	1.2	5.4	1.4	5.5	1.4
Sideways	1st MTH	4.0	1.0	4.1	1.0	8.9	2.4	6.9	1.8	2.4	0.9	3.5	0.9	3.5	0.9
	GT	6.3	1.4	6.4	1.4	10.7	2.6	8.9	2.1	4.8	1.1	5.8	1.3	5.8	1.3
Up-down	1st MTH	2.3	0.7	2.4	0.8	6.6	1.5	3.7	0.8	2.8	0.9	2.8	0.8	2.3	0.7
	GT	5.5	1.4	5.7	1.4	11.1	2.8	7.5	1.9	6.5	1.5	6.6	1.6	5.2	1.2
Fixing	1st MTH	9.9	2.4	9.6	2.2	16.1	3.9	15.1	3.7	9.7	2.1	12.8	3.1	10.8	2.4
	GT	4.0	1.4	3.2	1.1	12.2	4.3	11.0	3.9	2.8	1.0	7.7	2.7	4.1	1.5
Walking															
	2nd-3rd MTH	3.0	1.1	2.7	0.9	17.2	6.1	12.4	4.4	2.6	0.9	3.8	1.3	3.9	1.4
	4th-5th MTH	2.9	1.0	2.6	0.9	14.6	5.2	10.8	3.8	2.6	0.9	3.7	1.3	3.7	1.3

Abbreviations: 1st MTH, first metatarsal head; 2nd-3rd MTH, 2nd-3rd metatarsal heads; 4th-5th MTH, 4th-5th metatarsal heads; GT, great toe; LH, lateral heel; LM, lateral midfoot; LT, lesser toes; MH, medial heel; MM, medial midfoot.

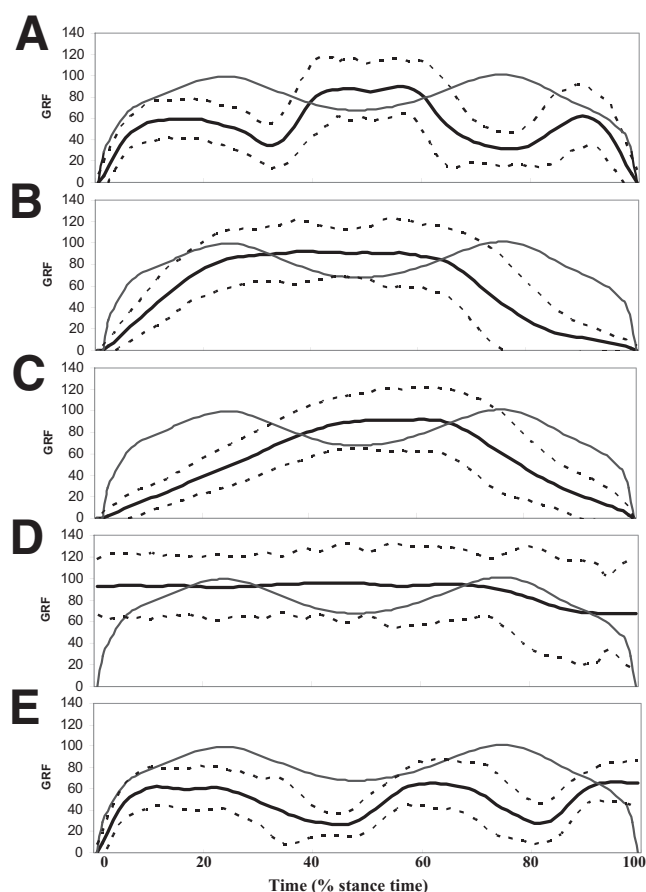


Fig 4. Normalized (percentage of body weight) ground reaction forces (GRFs) against the time during the stance phase in the Tai Chi movements and normal walking. Legend: Thick lines (—) indicate the (A) forward; (B) backward; (C) sideways; (D) up-down; and (E) fixing Tai Chi movements; dotted lines (···) indicate 1 standard deviation (SD) from the mean of the Tai Chi movements; thin lines (—) indicate normal walking.

the relation between plantar pressure and the sensation of the great toe, and found that there is a negative relation between plantar pressure and the sensation threshold under the great toe. The tactile sense of the great toe decreases with age, and elderly people are not able to sufficiently utilize the muscle of the great toe to maintain balance control when perturbations occur.^{2,4} Tanaka et al² suggested that not only the development of motor performance, but also the facilitation of sensory input, should be considered in rehabilitation programs to improve poor balance. Plantar loading is mainly located in the anterior and medial areas of the foot in Tai Chi movements, which presents a strong challenge to the exertion of the great toe, and subsequently has a training effect on the muscles controlling the great toe. Furthermore, the greater pressure in the anterior and medial regions may intensify the sensory input from the great toe^{2,4} and the first metatarsal head, because the first metatarsal head area is one of the most sensitive regions on the bottom of the foot.³ Thus, it is expected that long-term Tai Chi exercise not only enhances muscle strength, but also improves the somatosensory input and feedback of the great toe area to assist in balance control.

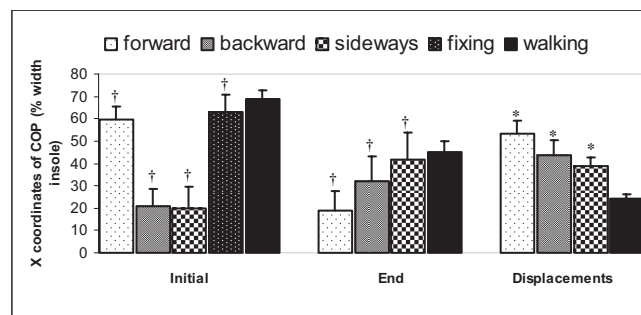


Fig 5. Comparisons of the x coordinates of the COP at initial and end contact with the ground and the displacements during contact in the Tai Chi movements and normal walking. NOTE. Values are mean ± SD. *Significantly greater than normal walking ($P < .05$); †significantly less than normal walking ($P < .05$), which were detected by 1-way ANOVA with repeated measures using a Bonferroni adjustment.

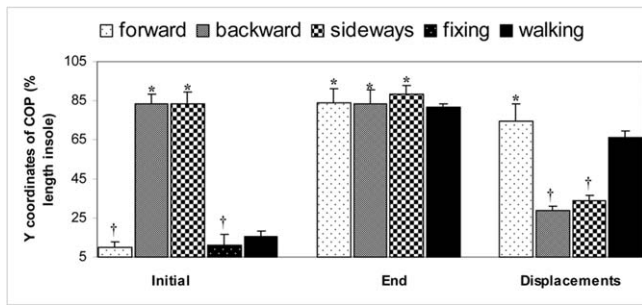


Fig 6. The comparisons of the y coordinates of the COP at initial and end contact with the ground and the displacements during contact in the Tai Chi movements and normal walking. NOTE. Values are mean ± SD. *Significantly greater than normal walking ($P < .05$); †significantly less than normal walking ($P < .05$), which were detected by 1-way ANOVA with repeated measures using a Bonferroni adjustment.

Ground Reaction Force

The shapes and amplitudes of the ground reaction forces of the 5 Tai Chi movements varied depending on the movement (see fig 4). The amplitudes of the ground reaction force during the Tai Chi movements were lower than in normal walking, which is consistent with the results of other studies¹⁸ that found that the peak vertical force is about the same as the body weight. The lower impact that is exerted on the foot may be explained by the fact that Tai Chi is characterized by slow and smooth motions, and light and steady steps.²⁹ He²⁹ stated that the steps in Tai Chi are made “as quietly as a cat walks,” and the exertion is “so mild that it looks like reeling raw silk from a cocoon.” This suggests that Tai Chi is a safe weight-bearing exercise¹⁸ and is suitable even for patients who suffer from rheumatoid arthritis.³⁰ The shapes of the ground reaction force in the Tai Chi movements were varied and different from those in normal walking, which may reflect the complex gait of Tai Chi movements, which combine various foot support patterns and step directions.¹⁹ Different support patterns and step directions may be the reason for the differences in ground reaction force between the different Tai Chi movements and normal walking.

Center of Pressure

The COP loci were significantly displaced posteriorly at initial contact in the forward and fixing movements, and were displaced anteriorly at end contact with the ground in the forward movement compared with normal walking. Mc-

Caw and DeVita¹² reported that, during stance phase of gait, shifting the COP posteriorly increases the flexor torque at the ankle, knee, and hip joints of the present leg. Conversely, shifting the COP anteriorly increases the extensor torque at the ankle, knee, and hip joints of the present leg. Further, ±0.5-cm and ±1.0-cm shifts in the location of the COP cause about a 7% and 14% change in the maximum joint torque and angular impulse values, respectively. When the location of the COP is more posterior at initial contact, the ankle posture is more dorsiflexed, and when the location of the COP is more anterior at end contact, the ankle posture is more plantarflexed. The increase in the range of motion (ROM) of the ankle in the sagittal plane in Tai Chi movements may thus be expected. Some studies^{31,32} have reported that there is a positive relation between the ROM of the ankle joint and balance control and muscle strength in the lower extremities. This may partly explain why muscle strength was improved in the lower extremities after Tai Chi exercise.^{17,26} Further kinematic investigation on the ROM of the ankle joint is required in the future.

A previous study³³ demonstrated that the base of gait and angle between the feet are significantly greater in Tai Chi movements than in normal walking. These increases may result in the more medial locations of the COP both at initial and end contact with the ground in Tai Chi movements. In addition, the results show that the forward, backward, and sideways Tai Chi movements have wider displacements in the ML direction, and the forward movement has a greater displacement in the AP direction than in normal walking. Szturm and Fallang¹³ investigated the electromyographic activity and the displacement of the COP on the bottom of the foot when disturbance occurs. They found that there is a positive relation between the displacement of the COP and the magnitude of the electromyographic activity in the lower extremities. Nakamura et al¹⁰ found that an increase in the displacement of the COP not only increases the magnitude of the electromyographic activity, but also the number of muscles that are used in the lower extremities. Thus, the larger displacement of the COP in Tai Chi movements may induce the lower extremities to recruit more muscles that contract at a higher level³⁴ than in normal walking.

It is expected that the understanding of the characteristics of Tai Chi exercise has a special clinical relevance for people who have problems maintaining balance. The findings of this study may provide useful information toward the development of strengthening programs, strategies for the prevention of falls, and the promotion of a physically active lifestyle.

Table 2: Statistical Results of the x Coordinates of the COP at Initial and End Contact With the Ground and the Displacements During Contact When Walking Normally Compared With Tai Chi Movements

Movements	Walking								
	Initial			End			Displacements		
	F	$df_A/df_S/df_{A,S}$	d	F	$df_A/df_S/df_{A,S}$	d	F	$df_A/df_S/df_{A,S}$	d
Forward	9539	4/15/60	1.5	812	3/15/45	1.6	14775	3/15/45	-14.2
Backward			7.1			1.0			-9.8
Sideways			5.8			0.8			-7.4
Up-down			—			—			—
Fixing			1.3			—			—

Abbreviations: df_A , degree of freedom for repeated-measures term; $df_{A,S}$, degree of freedom for interaction term; df_S , degree of freedom for subjects' term.

Table 3: Statistical Results of the y Coordinates of the COP at Initial and End Contact With the Ground and the Displacements During Contact When Walking Normally Compared With Tai Chi Movements

Movements	Walking								
	Initial			End			Displacements		
	F	$df_A/df_S/df_{A,S}$	d	F	$df_A/df_S/df_{A,S}$	d	F	$df_A/df_S/df_{A,S}$	d
Forward	11362	4/15/60	1.6	4905	3/15/45	0.9	8384	3/15/45	-3.5
Backward			-16.3			0.8			16.8
Sideways			-13.4			1.1			14.6
Up-down			—			—			—
Fixing			1.5			—			—

Abbreviations: df_A , degree of freedom for repeated-measures term; $df_{A,S}$, degree of freedom for interaction term; df_S , degree of freedom for subjects' term.

CONCLUSIONS

Based on the results observed from this study, the Tai Chi movements have greater anteromedial plantar loading, lower ground reaction forces, and larger COP displacements both in the direction of AP and ML when compared with normal walking. It is speculated that the plantar pressure characteristics in Tai Chi exercise may benefit to intensify the plantar cutaneous tactile sensory input from the first metatarsal head and great toe areas, increase the muscle strength of the lower extremities, and subsequently improve balance control.

References

- Nurse MA, Nigg BM. The effect of changes in foot sensation on plantar pressure and muscle activity. *Clin Biomech (Bristol, Avon)* 2001;16:719-27.
- Tanaka T, Noriyasu S, Ino S, Ifukube T, Nakata M. Objective method to determine the contribution of the great toe to standing balance and preliminary observations of age-related effects. *IEEE Trans Rehabil Eng* 1996;4:84-90.
- Nurse MA, Nigg BM. Quantifying a relationship between tactile and vibration sensitivity of the human foot with plantar pressure distributions during gait. *Clin Biomech (Bristol, Avon)* 1999;14:667-72.
- Tanaka T, Takeda H, Izumi T, Ino S, Ifukube T. Effect on the location of the centre of gravity and the foot pressure contribution to standing balance associated with ageing. *Ergonomics* 1999;42:997-1010.
- Tanaka T, Hashimoto N, Nakata M, Ito T, Ino S, Ifukube T. Analysis of toe pressure under the foot while dynamic standing on one foot in healthy subjects. *J Orthop Sports Phys Ther* 1996;23:188-93.
- Han TR, Paik NJ, Im MS. Quantification of the path of center of pressure (COP) using an F-scan in-shoe transducer. *Gait Posture* 1999;10:248-54.
- Schmid M, Beltrami G, Zambambieri D, Verni G. Centre of pressure displacement in trans-femoral amputees during gait. *Gait Posture* 2005;21:255-62.
- Allum JH, Honegger F, Schicks H. The influence of a bilateral peripheral vestibular deficit on postural synergies. *J Vestib Res* 1994;4:49-70.
- Schieppati M, Nardone A. Free and supported stance in Parkinson's disease. The effect of posture and 'postural set' on leg muscle responses to perturbation, and its relation to the severity of the disease. *Brain* 1991;114:1227-44.
- Nakamura H, Tsuchida T, Mano Y. The assessment of posture control in the elderly using the displacement of the center of pressure after forward platform translation. *J Electromyogr Kinesiol* 2001;11:395-403.
- Eisenhardt JR, Cook D, Pregler I, Foehl HC. Changes in temporal gait characteristics and pressure distribution for bare feet versus various heel heights. *Gait Posture* 1996;4:280-6.
- McCaw ST, DeVita P. Errors in alignment of center of pressure and foot coordinates after predicted lower extremity torques. *J Biomech* 1995;28:985-8.
- Szturm T, Fallang B. Effects of varying acceleration of platform translation and toes-up rotations on the pattern and magnitude of balance reaction in humans. *J Vestib Res* 1998;8:381-97.
- Cook TM, Farrell KP, Carey IA, Gibbs JM, Wiger GE. Effects of restricted knee flexion and walking speed on the vertical ground reaction force during gait. *J Orthop Sports Phys Ther* 1997;25:236-44.
- Takahashi T, Ishida K, Hirose D, et al. Vertical ground reaction force shape is associated with gait parameters, timed up and go, and functional reach in elderly female. *J Rehabil Med* 2004;36:42-5.
- Li JX, Hong Y, Chan KM. Tai Chi: physiological characteristics and beneficial effects on health. *Br J Sports Med* 2001;35:148-56.
- Hong Y, Li JX, Robinson. Balance control, flexibility, and cardiorespiratory fitness among older Tai Chi practitioners. *Br J Sports Med* 2000;34:29-34.
- Wu G, Hitt J. Ground contact characteristics of Tai Chi gait. *Gait Posture* 2005;22:32-9.
- Editor Group. *Tai Chi Chuan exercise*. Beijing: People's Sports Publishing House of China; 2000. p 347-410.
- Boyd LA, Bontrager EL, Mulroy SJ, Perry J. The reliability and validity of the Novel Pedar system of in-shoe pressure measurement during free ambulation [abstract]. *Gait Posture* 1997;5:165.
- Kernozek TW, LaMott EE, Dancisak MJ. Reliability of an in-shoe pressure measurement system during treadmill walking. *Foot Ankle Int* 1996;17:204-9.
- Soames RW. Foot pressure patterns during gait. *J Biomed Eng* 1985;7:120-6.
- Chen H, Nigg BM, Hulliger M, de Koning J. Influence of sensory input on plantar pressure distribution. *Clin Biomech (Bristol, Avon)* 1995;10:271-4.
- Stess RM, Jensen SR, Mirmiran R. The role of dynamic plantar pressures in diabetic foot ulcers. *Diabetes Care* 1997;20:855-8.
- Hodge MC, Bach TM, Carter GM. Orthotic management of plantar pressure and pain in rheumatoid arthritis. *Clin Biomech (Bristol, Avon)* 1999;14:567-75.
- Mao DW, Hong Y, Li JX. Characteristics of foot movement in Tai Chi exercise. *Phys Ther* 2006;86:215-22.
- Melzer I, Benjuya N, Kaplanski J. Effects of regular walking on postural stability in the elderly. *Gerontology* 2003;49:240-5.
- Shin Y. The effects of a walking exercise program on physical function and emotional state of elderly Korean women. *Public Health Nurs* 1999;16:146-54.
- He CF. A new type of Chinese Taijiquan. Hong Kong: Joint Publishing (H.K.); 1990. p 5-21.
- Kirsteins AE, Dietz F, Hwang SM. Evaluating the safety and potential use of a weight-bearing exercise, Tai-Chi Chuan, for rheumatoid arthritis patients. *Am J Phys Med Rehabil* 1991;70:136-41.

31. Mecagni C, Smith JP, Roberts KE, O'Sullivan SB. Balance and ankle range of motion in community-dwelling women aged 64 to 87 years: a correlation study. *Phys Ther* 2000;80:1004-11.
32. Whipple RH, Wolfson LI, Amerman PM. The relationship of knee and ankle weakness to falls in nursing home residents: an isokinetic study. *J Am Geriatr Soc* 1987; 35:13-20.
33. Mao DW, Hong Y, Li JX. The kinematical characteristics of the lower extremities during Tai Chi Chuan exercise. In: Proceedings of the XXIIInd International Society of Biomechanics of Sports; 2004 Aug 9-12; Ottawa (ON). p 597-600.
34. Wu G, Liu W, Hitt J, Millon D. Spatial, temporal and muscle action patterns of Tai Chi gait. *J Electromyogr Kinesiol* 2004;14: 343-54.

Supplier

- a. Novel Gmbh, Ismaninger Str 51, D-81675 Munich, Germany.