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The duration and plantar pressure distribution during one-leg stance in Tai Chi exercise

D.W. Mao [a], J.X. Li [b], Y. Hong [c,*]

[a] Department of Sports Science and Physical Education, Chinese University of Hong Kong, Shandong Institute of Physical Education and Sports, China
[b] School of Human Kinetics, University of Ottawa, Canada
[c] Department of Sports Science and Physical Education, Chinese University of Hong Kong, Shatin, N.T., Hong Kong

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Abstract

Background. Tai Chi exercise improved the balance control and muscle strength of the lower extremities. The aim of this study is to quantify the one-leg stance duration and plantar pressure distribution during the one-leg stance in Tai Chi and to try to elaborate on its probable effects on the ability to balance on one leg.

Methods. Sixteen experienced Tai Chi practitioners participated in this study. The Novel Pedar-X insole system was used to record the plantar forces during the execution of a set of 42-form Tai Chi movements and during normal walking. The one-leg stance duration and plantar pressure distribution during the one-leg stance were analyzed.

Findings. In Tai Chi exercise, the total duration spent in the one-leg stance was less ($p < 0.05$), the duration of each one-leg stance was longer ($p < 0.01$) and the medial–lateral displacement of the centre of pressure was greater ($p < 0.05$) than during normal walking. The peak pressure and pressure–time integral of the second and third metatarsal heads and the fourth and fifth metatarsal heads were significantly greater ($p < 0.05$) than those of other plantar regions during the one-leg stance in normal walking, whereas the peak pressure and pressure–time integral of the first metatarsal head and the great toe were significantly greater ($p < 0.05$) than those of other plantar regions during the one-leg stance in Tai Chi exercise.

Interpretation. The longer duration of each one-leg stance and the plantar pressure distribution characteristics during the one-leg stance in Tai Chi exercise may be associated with an improved ability to balance on one leg. The findings may provide useful information toward the development of strengthening programs, strategies for the prevention of falls, and the promotion of a physically active lifestyle.

Keywords: Tai Chi exercise; One-leg stance; Centre of pressure; Plantar pressure distribution; Balance control

1. Introduction

The one-leg stance is a particularly challenging part of human locomotion, because the whole weight of the body is placed on one leg and the support base is relatively narrow in the lateral direction (Mak and Ng, 2003). Balancing on one leg is fundamental to locomotion and to many of the activities of daily living (Richardson et al., 1996). The ability to maintain an one-leg stance is an important predictor of injurious falls for elderly people (Richardson et al., 1996), and has been shown to correlate strongly with falls (Richardson et al., 1996; Schaller, 1996) and age (Bohannon et al., 1984; Iverson et al., 1990; Jonsson et al., 2004). Tai Chi (TC) is a traditional Chinese martial art that has been demonstrated by numerous studies to improve the ability to balance on one leg (Bohannon et al., 1984; Iverson et al., 1990; Schaller, 1996; Hong et al., 2000; Jonsson et al., 2004). However, very few studies

* Corresponding author.
E-mail address: youlianhong@cuhk.edu.hk (Y. Hong).

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have investigated the one-leg stance duration during TC exercise or explained why TC exercise may improve balance in the one-leg stance.

There are many different schools of TC and each has its own distinctive features, but the basic principles are the same (Editor, 2000). Forty-two-form TC was selected for this study because all of the basic and typical movements from the various TC schools are combined in this form, and it is used in national and international competition (Editor, 2000; Mao et al., 2006). Walking is the most common daily activity, for both feet, 80% of a complete gait cycle is spent on one leg (Winter, 1991). Generally, walking is different from TC exercise, but several studies have demonstrated that TC and walking are both moderate forms of exercise that are suitable for elderly people (Shin, 1999; Li et al., 2001), and both exercises have been found to have beneficial effects on balance control, muscle strength, and cardio-respiratory response in the elderly (Shin, 1999; Hong et al., 2000; Li et al., 2001; Melzer et al., 2003). Several recent studies have compared TC to walking (Wu et al., 2004; Wu and Hitt, 2005). They found that the main plantar loading is located on the anterior–medial portion of the foot during one TC movement, whereas, it falls on the anterior–middle region of the foot during normal walking.

Impaired balance in the lateral direction is associated with a higher fall risk than impaired anterior–posterior balance (Tanaka et al., 1996b; Islam et al., 2004). Lateral falls are also more associated with hip fractures than falls in other directions (Mak and Ng, 2003; Islam et al., 2004). During the one-leg stance, the foot tilt strategy are employed as an adaptation of the ankle strategy for balance control on the narrow support surface (Hoogvliet et al., 1997). The medial–lateral displacements of the centre of pressure (CoP) are the result of the activity of the foot tilt strategy as a mechanism for balance control during the one-leg stance (Hoogvliet et al., 1997). To control balance, a certain amount of the CoP displacement must be attained within a certain amount of time (Hoogvliet et al., 1997). We hypothesise that the medial–lateral displacement of the plantar CoP is greater during the one-leg stance in TC exercise when compared with that in normal walking.

Numerous researches have shown that plantar afferent feedback plays an important role in postural stability during the one-leg stance (Iverson et al., 1990; Richardson et al., 1996; Jonsson et al., 2004; Meyer et al., 2004). An individual can maintain balance by using toe pressure to correct the many postural disturbances that are experienced in everyday life (Tanaka et al., 1996b; Nurse and Nigg, 1999), and indeed the functions of the great toe and fist metatarsal head are more important than that of any other toes (Tanaka et al., 1996a). The tactile sense of the great toe decreases with age, and elderly people are often unable to sufficiently utilise the muscle of the great toe to maintain balance when perturbations occur (Tanaka et al., 1996b; Tanaka et al., 1999). Therefore, the training of the activity of the toes and the somatosensory information that is gleaned from the sole may be more appropriate than strength training as a physical therapy treatment to rectify balance problems (Tanaka et al., 1996b; Tanaka et al., 1996). Therefore, the second hypotheses of this study is that the plantar loadings of the great toe and first metatarsal head regions are greater than the remaining regions during one-leg stance in TC exercise, while the plantar loadings of the third and fourth metatarsal head regions are greater than the remaining regions during one-leg stance in normal walking.

Therefore, the objective of this study is to quantify the one-leg stance duration and plantar pressure distribution during the one-leg stance in a set of 42-form TC compared to those in normal walking, and to elaborate the beneficial effect of TC on the ability to balance on one leg.

2. Methods

Sixteen gender-matched long-term TC practitioners (8 women and 8 men aged 23.07 ± 5.53 years with a body height of 166.0 ± 7.6 cm, a body weight of 62.27 ± 7.87 kg, and 8.09 ± 5.72 years of exercise experience) with no previous injuries in the year before the study were recruited. Five different insole sizes (Pedar-X Insole Model: X, Y, U, V, and W) were used and five relevant sizes of Chinese TC shoes were provided in this study. Each insole was inserted to the pairwise shoe properly. After the shoe had been carefully worn, the palpation was done manually to ensure the shoe fit the subject and no discomfort was reported by all subjects throughout the test. Before testing, the subjects completed consent forms and were given sufficient time to warm up. The subjects were then asked to perform the whole set of 42-form TC once at a self-selected training pace and to walk a 15-m pathway three times at a normal self-selected speed. The sequence of TC or normal walking was random. An insole force measurement system (Novel Pedar-X, Germany) was employed to collect the plantar force continuously, with a sampled rate of 50 Hz during the performance of TC and normal walking. Each insole contained 99 force sensors, and the recorded data were stored in the data log box that was attached to the waist of each subject. With the aid of a calibration device (Novel Trublu), all of the insole sensors were individually calibrated before testing. The reliability of this system has been well documented in the previous studies (Kernozek et al., 1996; Boyd et al., 1997). Two digital video cameras (JVC 9800) with 50-Hz frequency were used, with one camera focused on the lower extremities and the other camera focused on the whole-body movement during the continuous plantar force data collection when the 42-form TC and normal walking were being performed. At the moment when the data start to be recorded, a flash would be generated by the Pader-X Insole System. At the same time, this event was captured by the two video cameras and it was treated as the synchronized signal.

Based on the recorded TC performance and normal walking plantar force data and video picture, the one-leg stance was defined as the interval spent in a one-footed stance when the ground reaction force of the other foot is below two Newtons, which is the initial threshold of the insole system after confirming by synchronizing two video pictures. For both left and right feet, each of the specific instances of one-leg stance was extracted from the whole set of 42-form TC and normal walking plantar force data. The one-leg stance total duration was taken as the sum of all of the durations, and the duration of each one-leg stance was determined by dividing the sum of the total duration by the number of repetitions (Mao et al., 2006). These two variables represented the average values which were obtained from the whole set 42-form TC and 15 completed gait cycles normal walking. Using Novel Database-Pro software, the medial–lateral displacement of the CoP was calculated by subtracting the lateral maximum by the minimum coordinates of the CoP during the one-leg stance. To identify the pressure distribution of the specific area under the foot, the foot was divided into nine distinct regions, as illustrated in Fig. 1. The nine plantar regions were created by the Pedar-X Insole Software automatically, and were consistent for all the different insole sizes. The peak pressure and pressure–time integral of each of the regions were calculated using Novel Database-Pro software. For analysis, the total one-leg stance duration of the TC exercise was normalized to the whole period of the 42-form TC performance (Mao et al., 2006), and the total one-leg stance duration of normal walking was normalized to a completed gait cycle (Winter, 1991). The medial–lateral displacement of the CoP was normalized to the maximum width of the insole. For the TC movements, each variable was taken as the average of all of the instances of one-leg stance during the whole set of 42-form TC exercise, and for the normal walking each variable was taken as the average of the three trails, each of which included five completed gait cycles. All variables were calculated and prepared for both left and right feet, respectively.

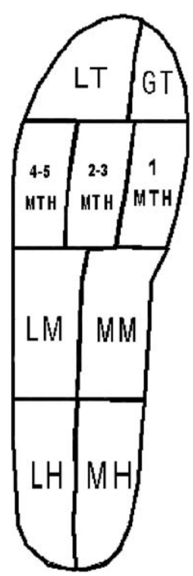

Fig. 1. The nine regions on the plantar surface MH: medial heel; LH: lateral heel; MM: medial midfoot; LM: lateral midfoot; 1 MTH: first metatarsal head; 2–3 MTH: second and third metatarsal heads; 4–5 MTH: fourth and fifth metatarsal heads; GT: great toe; LT: lesser toes.

All of the dependent variables were statistically analyzed using an independent-T test to detect any differences between the left and right foot and between the male and female groups (Mao et al., 2006). In this study, the comparison between TC exercise and normal walking is done using a within-subject design. A paired-T test was employed to detect the differences between the normal walking and 42-form TC in the variables of total one-leg stance duration, duration of each one-leg stance, and the medial–lateral displacement of the CoP. However, for the peak pressure and pressure–time integral, the direct comparisons using paired-T test between one-leg stance in normal walking and in TC movements may be not appropriate because these two variables are speed- and time-dependent (Soames, 1985; Chen et al., 1995). Our previous study showed that the stepping speed and support pattern differ in TC exercise and normal walking (Mao et al., 2006). As mentioned above, one hypothesis of this study is that the plantar loadings of the great toe and first metatarsal head regions are greater than the remaining regions during one-leg stance in TC exercise, while the plantar loadings of the third and fourth metatarsal head regions are greater than the remaining regions during one-leg stance in normal walking. Therefore, one-way ANOVA with planned comparisons was employed. The differences between the great toe and first metatarsal head regions and the remaining regions during one-leg stance in TC exercise, and the differences between the third and fourth metatarsal head regions and the remaining regions during one-leg stance in normal walking were contrasted, in terms of peak pressure and pressure–time integral, respectively. A significance level of 0.05 was chosen for all the statistical analysis.

3. Results

No significant difference was found in any of the dependent variables between the left foot and the right foot ($p > 0.05$). For the purpose of simplification of the data, the data from both feet were averaged. No significant difference was found in any of the dependent variables between the male and female groups ($p > 0.05$), and thus the data from the two groups were pooled for further analysis.

Table 1 shows that the range of total duration spent in whole set 42-form TC is from 394 s to 267 s, and the mean is 331 s. This indicated that the performance paces selected by TC practitioners are different. The range of times with one-leg stance is from 30 to 26, and the mean is 28.3. It is means that the repeatability of one-leg stance for each subject is different. This may be affected by different exercise styles and skill levels that the subjects possessed. The range of duration of each one-leg stance is from 7.8 s to

Table 1
The descriptive statistics in total duration, times of one-leg stance, and duration of each one-leg stance in 15 completed gait cycles normal walking and in 42-form TC exercise

Movements	Total duration (s)			Times of OLS (time)			Duration of each OLS (s)		
	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean
15 Gait cycles	16.3	14.3	15.4	15	15	15	0.42	0.37	0.40
42-Form TC	394	267	331	30	26	28.3	7.8	0.5	1.95

OLS: one-leg stance; Max.: maximum; Min.: minimum.

0.5 s, and the mean is 1.95 s. This may be caused by the demand of each specific TC movement. For example, some movements need the practitioner to be supporting one's self with a one-leg stance for a longer time, and other movements may not. In addition, the results during normal walking are comparable with previous literature (Winter, 1991).

Table 2 shows that the total one-leg stance duration (35.1%) in the TC exercise was significantly less ($p < 0.05$) than in normal walking (39.9%). However, the duration of each one-leg stance in the TC movements (1.95 s) was significantly greater ($p < 0.01$) than in the normal walking (0.40 s). The medial–lateral displacement of the CoP during one-leg stance in the TC movements (25.2%) was significantly greater ($p < 0.05$) than in normal walking (21.8%).

Fig. 2(a) shows that the peak pressure and pressure–time integral of the region of the second and third metatarsal heads and the region of the fourth and fifth metatarsal heads had maximum values that were significantly greater ($p < 0.05$) than those of the other regions during the one-leg stance in normal walking. Conversely, the peak pressure and pressure–time integral of the region of the first metatarsal head and the region of the great toe had maximum values that were significantly greater ($p < 0.05$) than those of the other regions during the one-leg stance in the TC exercise (Fig. 2(b)).

Table 2
The comparisons of total one-leg stance duration, duration of each one-leg stance, and medial–lateral displacement of CoP during one-leg stance in normal walking and in TC exercise

	Normal walking	TC
	Mean (SD)	Mean (SD)
Total OLS duration (%)	39.9 (2.06)	35.1 (3.63)*
Duration of each OLS (s)	0.40 (0.04)	1.95 (0.27)**
Medial–lateral displacement of CoP (%)	21.8 (2.92)	25.2 (3.23)*

*: $p < 0.05$; **: $p < 0.01$; OLS: one-leg stance.

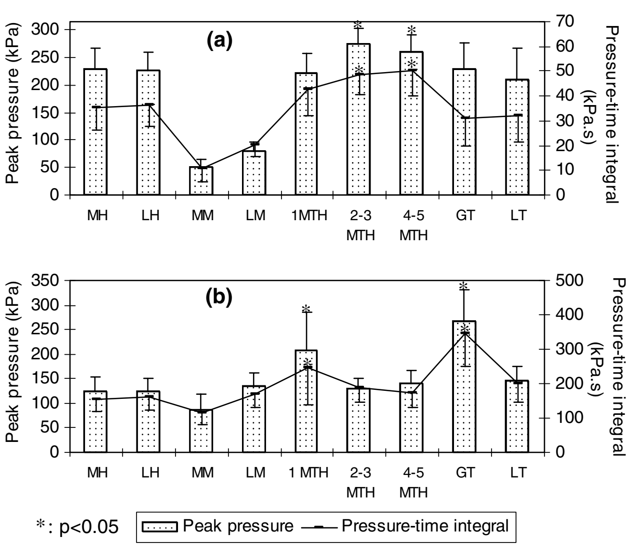

Fig. 2. Comparison of the regions of peak pressure and the pressure–time integral during the one-leg stance in (a) normal walking and (b) TC exercise.

4. Discussion

4.1. The one-leg stance duration

During normal walking, the total one-leg stance duration and the duration of each one-leg stance that were obtained from this study were 39.9% (0.40 s), which are very close to the values of 40.0% (0.40 s) that were reported by Winter (Winter, 1991). During the TC exercise, the total one-leg stance duration and the duration of each one-leg stance were 35.1% (1.95 s), which confirms the results of our previous study (Mao et al., 2006). These results also generally agree with the report of Wu et al. (2004) that suggested the duration of one-leg stance to be 1.80 s in one TC movement.

Several studies have suggested that standing on one leg induces the centre of gravity and weight line to move closer to the supporting leg (Steinberg, 1998; Mak and Ng, 2003). This causes an asymmetrical and unstable posture, which may result in awkwardness and fatigue, and become a cause of falling (Steinberg, 1998). With increased age, the muscles that are required to maintain balance in the one-leg stance become weak (Briggs et al., 1989; Iverson et al., 1990; Steinberg, 1998), and the duration that individuals are able to maintain their balance on one leg is lowered (Bohannon et al., 1984; Iverson et al., 1990; Steinberg, 1998). Jonsson et al. suggested that the elderly group could not stand on one leg for longer instances than the young group and the condition depends on decreased muscle strength and endurance (Jonsson et al., 2004). Practicing TC, which this study finds has a longer time of each one-leg stance duration, probably help the elderly to increase muscle contraction time and thus may enhance muscle strength and endurance (Mao et al., 2006). Balancing on one leg for longer periods requires conscious and precise neuromuscular control (Xu et al., 2003). This may help manage and simulate the activities that are encountered during daily activities, such as stepping over an obstacle and pulling on long trousers when dressing (Mao et al., 2006). Other studies have compared older fallers and non-fallers and found that there is a very high correlation between the number of falls and the duration of the one-leg stance (Briggs et al., 1989; Richardson et al., 1996; Steinberg, 1998). It has been speculated that engaging in the one-leg stance for a longer duration through TC exercise may contribute to improving the ability to stand on one leg, which in turn may reduce the risk of falls in the elderly.

4.2. The medial–lateral displacement of the CoP during the one-leg stance

Tropp and Odenrick (1988) found that ankle inversion–eversion is a critical mechanism in maintaining balance during the one-leg stance. Other investigators (Hoogvliet et al., 1997; King and Zatsiorsky, 2002) further examined the relationship between foot inversion–eversion and CoP displacement during the one-leg stance in healthy adults, and suggested that the tilting of the foot results in considerable changes in the pressure distribution, and is thus a major source of CoP displacement. They concluded that medial–lateral displacements of the CoP are good indicators of the tilting motions of the foot during the one-leg stance. King and Zatsiorsky (2002) suggested that balance is maintained during the one-leg stance through a relatively large displacement of the CoP that is made possible by a rocking motion of the foot. This large displacement of the CoP then in turn creates a large ankle torque and horizontal forces to restore the centre of gravity to a more balanced position. In this study, the medial–lateral displacement of the CoP in the TC movements was 25.2%, which is significantly greater than the displacement in normal walking of 21.8% (Table 2). These results reveal that the one-leg stance in TC exercise may force the ankle joint to produce more activities of motion and create more horizontal forces, while the other parts of the body are also moving, to ensure that the CoP is located within the base of support. It is likely that practicing TC may have a beneficial effect in training to maintain medial–lateral balance, which is considered to cause a higher risk of falls during the one-leg stance (Mak and Ng, 2003; Islam et al., 2004). In addition, Szturm and Fallang (1998), and Tropp and Odenrick (1988) investigated the electromyography and displacement of the CoP on the bottom of the foot during one-leg stance in a dynamic platform. They found that there is a positive relationship between the displacement of the CoP and the magnitude of the electromyography in the lower extremities. Nakamura et al. (2001) found that an increase in the displacement of the CoP not only increases the magnitude of the electromyography, but also increases the number of muscles that are used in the lower extremities. Thus, a large medial–lateral displacement of the CoP during the one-leg stance in TC exercise may induce the lower extremities to recruit more muscles that contract at a higher level (Xu et al., 2003, 2004) than in normal walking.

4.3. Pressure distribution during the one-leg stance

Fig. 2 demonstrates that during the one-leg stance, the peak plantar load is located under the second and third, and fourth and fifth metatarsal heads in normal walking, whereas it is sited under the first metatarsal head and the great toe in TC exercise. These results further strengthen the findings of other researchers on TC movement (Wu and Hitt, 2005), and are also consistent with Tanaka's report that the peak pressure under the great toe is significantly greater than the other four toes during the one-leg stance (Tanaka et al., 1996a). Several 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 during the one-leg stance in moveable or static platform and with eyes open or closed (Tanaka et al., 1996b; Tanaka et al., 1999; Meyer et al., 2004). The tactile sense of the great toe decreases with age (de Neeling et al., 1994), and elderly people are not able to sufficiently utilize the muscle of the great toe to maintain balance when perturbations occur (Tanaka et al., 1996b; Tanaka et al., 1999). Plantar loading is mainly located in the anterior–medial areas of the foot in TC movements, which probably presents a strong challenge to the exertion of the great toe, and subsequently has a training effect on the great toe muscle. Furthermore, the greater pressure on the anterior–medial region may intensify the sensory input from the great toe (Tanaka et al., 1996b; Tanaka et al., 1999) and the first metatarsal head, because this area is one of the most sensitive regions on the bottom of the foot (Nurse and Nigg, 1999). Thus, it is possible that long-term TC exercise not only enhances muscle strength, but also improves the somatosensory input in the great toe region to assist in balance control to a greater extent than would be achieved with normal walking.

4.4. Limitation of this study

The results of this study are based on the performance of a group of young experienced TC practitioners, and thus the characteristics of their one-leg stance and the plantar pressure distribution during the one-leg stance may not be the same as in other subject populations, such as elderly people or beginner TC practitioners. In addition, the previous researches which related to plantar pressure distribution and the displacement of CoP focused on the subject who balanced and stood with one leg on a dynamic or static platform. The subject, whose other parts of the body are moving continuously during one-leg stance in TC exercise and normal walking, were studied in this paper. Thirdly, although a few studies have been conducted to compare TC with walking in terms of gait and electromyography (Wu et al., 2004), ground reaction force (Wu and Hitt, 2005), and foot movement (Mao et al., 2006), there are some fundamental differences between the two types of exercise, such as activity speed and stepping direction, and thus any comparison between the two should be taken as a functional comparison only (Wu et al., 2004).

5. Conclusion

This study finds that the duration of each one-leg stance is longer and the medial–lateral displacement of the CoP during the one-leg stance is greater than in normal walking. Furthermore, the main loading of the plantar surface falls on the anterior–middle portion of the foot during the one-leg stance in normal walking, whereas it falls on the anterior–medial portion of the foot during the one-leg stance in TC exercise. The increase in the duration of each one-leg stance and the plantar pressure distribution during the one-leg stance that are characteristics of TC exercise may improve the ability to balance on one leg by training the muscles in the simulated challenge posture and intensifying the feedback from the great toe.

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