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De Wei Mao, Youlian Hong and Jing Xian Li
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Characteristics of Foot Movement in Tai Chi Exercise

Background and Purpose. The concept of proper foot movement is always emphasized in practicing Tai Chi (TC). The purposes of this study were to describe the foot movement characteristics of TC and to compare duration of single- and double-limb support time during TC and during walking. Subjects. Sixteen experienced TC practitioners participated in the study. Methods. The participants’ performance of a whole set of 42-form TC movements was recorded with 2 cameras. A motion analysis system was used to identify the supporting and stepping characteristics of the foot during the practice. Results. Seven foot support patterns and 6 step directions were identified. The results revealed that, compared with normal walking, TC movement had more double-limb support and less single-limb support in terms of total duration. The duration of each support pattern was longer, and movement from one pattern to the next was slow. The duration of each step direction was short, and changes of direction were frequent. Discussion and Conclusion. Support patterns changed slowly, and, combined with various step directions, they were found to be better than those of walking in simulating the gait challenges that may be encountered in daily activities. [Mao DW, Hong Y, Li JX. Characteristics of foot movement in Tai Chi exercise. Phys Ther. 2006;86:215–222.]

Key Words: Balance control, Gait, Muscle strength, Step direction, Support pattern, Tai Chi.

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During normal locomotion, the foot cushions the musculoskeletal system during impact, supports the body during ground contact, transmits forces between the ground and the leg, adapts to uneven surfaces, keeps the body in balance, and serves as a system for sensory input. Numerous studies have demonstrated that some functional abilities such as walking speed and stride length, stepping in turning, lateral stepping, and stepping over obstacles are lower in older people compared with younger people. The poor performance of some functional abilities of elderly people has been linked to the problem of balance and falls. Some factors that induce falls and related injuries, such as decreased muscle strength (force-generating capacity of muscle) and flexibility and loss of proprioception of the lower extremities, have been investigated. To prevent falls in elderly people, exercise programs of resistance strength, balance control, and walking in different directions; home-based exercise programs; and Tai Chi (TC) exercise programs have been developed.

Tai Chi is a Chinese form of exercise that is derived from martial arts folk traditions. It entails extended and natural postures, slow and even motions, light and steady movements, and curved, flowing lines of performance. Several studies have shown the beneficial effects of TC exercise on balance control, muscle strength, and flexibility. According to the theory of TC, foot posture and movement are the foundation of the whole-body posture, and the concept of proper position and direction is always emphasized.

Studies on kinematics of TC have focused mainly on single movements. Little is known about the kinematics of the whole set of TC movements, especially on the foot movement characteristics. Although there are many different schools or styles of TC and each school or style has its own distinctive features, the basic principles are the same. The 42-form TC consists of 42 different movements. All of the basic and typical movements from various TC schools are combined in this form, which is used in national and international competition.

Walking is the basic form of ambulation in daily activities. Several studies have demonstrated the positive effects of walking training programs on postural stability, muscle strength, and cardiorespiratory responses in elderly people. Regular walking for elderly people has been recommended for increasing physical activity and decreasing the risk for falls. Thus, it is necessary to evaluate the unique foot characteristics of TC exercise as compared with normal walking. The purposes of this study were to describe the foot movement characteristics of TC and to compare duration of single- and double-limb support time during TC and during walking.

A description of these movements and a comparison of support times between walking and TC may provide insights for explaining the benefits of TC for people with various functional limitations.

Method

Subjects

Sixteen sex-matched, experienced TC practitioners (8 female and 8 male, age $[\bar{X} \pm SD] = 23.07 \pm 5.53$ years, body height $[\bar{X} \pm SD] = 166.0 \pm 7.6$ cm, body weight $[\bar{X} \pm SD] = 62.27 \pm 7.87$ kg, TC experience $[\bar{X} \pm SD] = 8.09 \pm 5.72$ years) with no previous diseases or injuries 1 year before the study were recruited. All subjects completed consent forms before testing.

Procedure

The 42-form TC was selected for this study. Two digital video cameras (JVC 9800*) with 50-Hz frequency were synchronized, with one camera focused on the lower extremities and the other camera focused on the whole-body movement. Small, lightweight reflective markers were attached to each subject to identify the ankles, toes, and heels of each foot. Before testing, the subjects were given ample time to warm up, and the performance of the whole set of 42-form TC movements was recorded for each subject.

* JVC Company of America, 1700 Valley Rd, Wayne, NJ 07470.
To clearly describe the foot movement and support characteristics, the foot support pattern was divided into 7 categories (Fig. 1), which were in accordance with the basic support forms of TC.14 These categories were: (1) full double-limb support, (2) single-limb left support, (3) single-limb right support, (4) left support with right toe touch, (5) left support with right heel touch, (6) right support with left toe touch, and (7) right support with left heel touch.

According to the description of the 5 stages of change of the step movement,14 the foot stepping direction was divided into 6 categories (Fig. 2). These categories were: (1) stepping forward—an anterior movement of one foot in relation to the support foot, (2) stepping backward—a posterior movement of one foot in relation to the support foot, (3) stepping sideways—a lateral movement of one foot in relation to the support foot, (4) up and down stepping—upward lifting of one foot above the knee height of the support leg, (5) stepping turning—pivotal rotation (medial or lateral) on the support foot with stepping action of other foot, and (6) stepping fixing or fixed step—both feet are fixed to the ground with no foot movement.

The APAS motion analysis system† was used to analyze the videotapes to determine each support pattern and step direction frame by frame. To establish high reliability, 3 principles were followed to determine each support pattern and step direction: (1) the 2 video views principle—2 captured video images were played in separate windows on the same screen, and each view was confirmed before determining the frames that recorded the beginning and end of each support pattern or step direction; (2) the whole-body principle—because TC movement is the coordination of all parts of the body, the motion of each body segment was considered; and (3) the continuous movement principle—the previous and next movements were considered when determining the present movement because the TC movement is even and continuous.

† Ariel Dynamics Inc, 6 Alicante St, Trabuco Canyon, CA 92679.

Figure 1.
Foot support patterns: (a) full double-limb support, (b) single-limb left support, (c) single-limb right support, (d) left support with right toe touch, (e) left support with right heel touch, (f) right support with left toe touch, and (g) right support with left heel touch.

Figure 2.
Categories of step direction: (a) stepping forward—an anterior movement of one foot in relation to the support foot, (b) stepping backward—a posterior movement of one foot in relation to the support foot, (c) stepping sideways—a lateral movement of one foot in relation to the support foot, (d) up and down stepping—upward lifting of one foot above the knee height of the support leg, (e) stepping turning—pivotal rotation (medial or lateral) on the support foot with stepping action of other foot, and (f) stepping fixing or fixed step—both feet are fixed to the ground with no foot movement.
In the practice of TC, various support patterns and step directions were combined and repeated. The durations and the repetitions of every specific pattern or step direction were recorded throughout the whole set of TC movements. For a given support pattern or step direction, the total duration was the sum of all durations of the pattern or direction. The duration of each support pattern and step direction was determined by dividing the sum of the total duration of the specific pattern or direction repetitions by the number of repetitions. For detecting the reliability, 2 researchers separately analyzed the videotaped performances of all the subjects.

**Data Analysis**

A one-way analysis of variance (ANOVA) was used to detect any differences between the male and female subjects on each of the dependent variables, including total duration, duration of each support pattern, and step direction. Because these variables are continuous measurements, intraclass correlation coefficients (ICC[3,k]) were calculated to determine the reliability of data obtained in the study. SPSS for Windows was used, and the significance level was set at .05.

**Results**

Based on the results obtained by the 2 researchers, statistical analysis showed that all of the ICCs were greater than .80 (Tab. 1), which indicated that the measurement reliability was high. After this process, the data obtained by the 2 researchers were averaged. For analysis, the total duration of every support pattern and step direction were normalized as percentages of the whole period of TC performance.

The support pattern distributions during the 42-form TC are shown in Table 2. The step direction distributions during the 42-form TC are shown in Table 3. One way ANOVA results demonstrated that there was no significant difference between male and female subjects in each of the dependent variables, including total duration, percentage of total duration, and duration of each support pattern or step direction. All of the parameters of the male and female subjects were pooled and averaged for further analysis.

Winter stated that, during normal walking, the duration for a complete gait cycle is about 1 second. In a complete cycle, the support patterns of both feet were symmetric, and there were 2 double-limb support and 2 single-limb support phases. The support time can be expressed as a percentage of the stride period or in seconds. The total duration of the 2 double-limb support phases was around 20% (0.20 second). The total duration of 2 single-limb support phases was around 80% (0.80 second). During the practice of TC, the total double-limb support duration was 64.26% (0.97 second), which was the sum of the full double-limb support duration of 33.63% (1.86 seconds), left support with other toe touch duration of 6.68% (0.55 second), left support with other heel touch duration of 7.61% (0.90 second), right support with other toe touch duration of 7.36% (0.59 second), and right support with other heel touch duration of 8.99% (0.95 second). The single-limb support durations for the left and right feet were similar at about 17.90% (1.94 seconds) and 17.83% (1.95 seconds), respectively. Figure 3 compares the total duration of double- and single-foot support as a percentage of the whole set of TC movements or the normal walking stride cycle. Figure 4 compares the duration of each double- and single-foot support (in seconds) during TC and normal walking.

**Discussion**

**Supporting Pattern**

Generally, walking as basic ambulation during daily activity is different from TC exercise. However, several studies have demonstrated that TC and walking are both moderate forms of exercise that are suitable for older people. Both types of exercise have beneficial effects on balance control, muscle strength, and cardiorespiratory responses in the elderly population.

Figure 3 demonstrates that the TC movement has longer double-limb support total duration (64.26% versus 20.00%) and shorter single-limb support total duration (17.85% versus 40.00%) than normal walking. The purposes of walking are to transport the body safely and efficiently across the ground using both legs and to provide both support and propulsion, whereas TC movement emphasizes stable, balanced, slow, and even motions. More double-limb support duration may be beneficial to maintain a balanced and even movement. In addition, other than the forward movement, foot movements during TC also have backward, sideways, turning, and fixing movements (Tab. 3). These movements produce the longer double-limb support duration, as shown in other studies demonstrating that...
during backward walking,25 sideways walking,26 and turning,3 the double-limb support duration was significantly longer than forward walking.

Some studies have demonstrated that TC exercise improves balance performance by increasing balance time27,28 and reducing the mean sway displacement of the center of pressure29,30 during single-limb support tests. This improved balance performance occurs because standing on one leg is a common posture in the practice of TC.30 However, the results obtained in our study showed that the normalized total single-limb support duration was 35.73%, which was much shorter than the support duration of 80% in normal walking (Fig. 3). In contrast, the durations of single-limb left (1.94 seconds) and right (1.95 seconds) support were the 2 largest values among the support patterns (Tab. 2). The durations of single-limb left and single-limb right support were much longer in TC (1.95 seconds) than in normal walking (0.40 second) (Fig. 4). These results revealed that the normalized total duration of single-limb support in TC was shortened, whereas the duration of each single-limb support was prolonged compared with normal walking. These results also supported the report of Wu et al,17 who found that there was a longer duration of single-limb stance time in his defined “Tai Chi gait” than in normal walking. In this connection, the longer time interval of each single-limb support may...
contribute to the improved single-limb support balance ability in TC exercise.

As discussed earlier, during TC exercise, the double support patterns included full double-limb support, left support with right toe touch, left support with right heel touch, right support with left toe touch, and right support with left heel touch. The durations of the support patterns were 1.86, 0.55, 0.90, 0.59, and 0.95 seconds, respectively. During normal walking, the duration of each double-limb support was 0.10 second. These data revealed that in addition to the longer single-limb support duration, the other support patterns have longer time intervals than in normal walking. The increased period in each support pattern reduced the speed of motion and slowed the changes from one pattern to another, thus prolonging the duration of contraction of the relative muscles, which may improve the strength and endurance of those muscles. In addition, the performance of TC relies on full double-limb weight bearing, full single-limb weight bearing, and single-limb weight bearing with other toe or heel semi-weight-bearing maneuvers. These patterns demand a high balance control capacity. The balance control of the center of gravity and the accurate adjustment of foot position during the practice of TC forces more muscles to be involved in the exercise, which may lead to increased muscle strength.

**Stepping Pattern**

Stepping backward is used in everyday activities such as approaching a sitting position in a chair. Some researchers have reported that backward walking has modified speed and stride length, increasing electromyography magnitude and patterns, and increased cardiorespiratory and metabolic responses when compared with forward walking. Thus, it has been suggested that backward walking should be considered to be a rehabilitation tool to improve daily functional abilities. Tai Chi exercise includes backward walking that may improve muscle strength and enhance the backward stepping ability that is needed in daily activities.

Lateral instability has induced a sizable proportion of falls to the side, which are most likely to result in hip fracture injuries. One of the strategies to compensate for the destabilization in the mediolateral direction is side-stepping. With increasing age, older adults consistently take more steps to recover equilibrium than younger adults take. Elderly people tend to use additional limb-movement reactions after the initial stepping reaction. That is, the new base of support established by the initial stepping reaction is insufficient to capture and arrest the motion of the center of mass. During TC exercise, the sideways movement with the coordination of trunk and upper limbs may match the demand of stepping sideways when perturbations occur.

Obstacles can be found indoors or outdoors, in flooring or sidewalk paving, at carpet edges, or in the form of electrical cords or door thresholds. It has been shown that almost 50% of falls in community-dwelling older adults occur during destabilizing activities such as stepping over an obstacle or negotiating a raised surface. Elderly people will be challenged by these destabilizing activities, which had a typical single-limb support pattern movement in the study by Lamoureux et al because these activities require considerable demands on the musculoskeletal system and thus pose a greater threat to stability. Chen et al reported that the foot clearance over an obstacle is approximately 3 times greater than in level gait. Older adults exhibited a significantly more conservative strategy when crossing obstacles, with slower crossing speed, shorter step length, and shorter obstacle–heel-strike distance. In contrast, the stepping up and down movement, in which one foot is supported with the other foot raised from the ground above knee level and then downward to the ground, is one of the movements in TC exercise. Practicing TC may help elderly people to manage challenging activities such as stepping over an obstacle and negotiating a raised surface because they have already simulated and practiced similar movements in TC exercise.

Turning is a powerful indicator of falling and is a characteristic that changes with age. Cumming and Klineberg examined the association between a history of falls and the risk for hip fracture in 412 older adults and identified the characteristics of falls that are related to hip fracture. They found that people who fell while performing a standing turn test were 7.9 times more likely than those who did not fall to have a subsequent fall resulting in a hip fracture. Thigpen et al studied movement characteristics during turning and found that elderly people took more steps and more time than young people to accomplish a turn. There was an almost total absence of a pivot type of turn in the elderly group. In the practice of TC, the turning maneuvers include one-foot support with other toe touching and internal or external pivoting, one-foot support with the other heel touching and internal or external pivoting, and even each foot touching with internal or external pivoting simultaneously. All kinds of pivoting maneuvers and many turning movements involved in TC are likely to improve the ability of turning.

Our results showed that the durations of stepping forward, backward, sideways, up and down, turning, and fixing were 2.10, 1.95, 2.08, 4.38, 0.97, and 1.77 seconds, respectively (Tab. 3). These results revealed that the duration of each stepping direction was just a few
seconds, which allows the directions of stepping to be adjusted frequently. The challenges of maintaining balance during daily life are often likely to demand changes in the base of support to enhance stability. Successful balance recovery by means of stepping requires accurate control of the foot movement as well as controlling the motion of the center of mass to arrest it within the boundaries of the new base of support established by the step. Thus, compensatory stepping in all directions is an important strategy for preserving stability. The TC movements in our study were combinations of stepping forward, backward, sideways, up and down, turning, and fixing that are similar to challenges to balance control that are encountered in daily activities. To prevent falls among elderly people, Campbell et al. developed a home-based exercise program that included walking backward and sideways, turning around, and stepping over an object. They found that the program improved physical function and was effective in reducing falls and injuries in elderly people.

Although the subjects in our study were experienced TC practitioners and the TC school is used for national and international competition, the standard deviations of the dependent variables were large in the support patterns (Tab. 2) and step directions (Tab. 3). This finding may suggest the adaptability of TC exercise. Few studies have demonstrated that there are substantial differences in the intensity and training effect induced by the variations of training in TC such as squat posture of the knees, duration of practice, and fitness level of subjects. The variety of support patterns and step directions that were revealed in the study may contribute to these differences. They may add new evidence to explain that the practice of TC is suitable, for example, either for individuals who are already functioning reasonably well but want to improve further or for people with rheumatoid arthritis.

Tai Chi is characterized by slow and even 3-dimensional motions and involves the coordination of all parts of the body. In our study, only a single camera was used to capture the TC activities, which may have introduced some error in recognizing the touchdown and takeoff of the foot. Moreover, only isolated foot movements were selected, with no consideration of trunk or upper-extremity movements, which provided limited information on the kinematics of TC movements.

Summary and Conclusions

Seven foot-support patterns and 6 step directions during TC exercise were determined. Compared with normal walking, TC movement has more double-limb support and less single-limb support total duration. The duration of each support pattern was longer, and there was a slow change from one pattern to the next pattern. The duration of each direction was shorter and frequently changed from one direction to another direction. Various support patterns changing slowly, combined with various step directions changing fully, may be better than walking at simulating the gait challenges that may be encountered during daily activities.

References


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