Ground contact characteristics of Tai Chi gait

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Abstract

Background: To date, no direct measurement has been done that quantitatively characterizes the foot–ground contact during Tai Chi Chuan movements. The goal of this study was to quantify the biomechanical characteristics of foot–ground contact during a Tai Chi gait (TCG), one of the basic but common Tai Chi Chuan movements.

Methods: The ground reaction force profiles, center of pressure (COP) and plantar pressure patterns under the stance foot of TCG were directly measured in a sample of 10 healthy young individuals.

Results: The medial force reached a peak value of 12 ± 2% body weight (BW) during early stance. The vertical force reached and maintained a peak value of 109 ± 2% BW during single stance, and shifted within a range of 10% and 70% BW during double stance phases. There was a uniformly small rate of loading in all three directions throughout stance. The peak plantar pressure was fairly constant throughout stance in the rear-foot region (maximum value of 0.27 ± 0.07 kPa/kg), but changed from 0 to 0.16 ± 0.04 kPa/kg in the fore-foot region. The peak pressure difference between the fore-foot and rear-foot regions was less than 0.06 ± 0.01 kPa/kg during single stance and the second double stance. The maximum plantar contact area during TCG was 60 ± 9% of the foot area. The foot COP displaced largely during the early and late part of the stance and maintained fairly stationary during single stance. The maximum COP displacement in the medial–lateral direction was 64 ± 8% of foot width.

Conclusions: TCG had a low impact force, a fairly evenly distributed body weight between the fore-foot and rear-foot regions, and a large medial–lateral displacement of the foot COP.

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1. Introduction

Tai Chi Chuan (TCC) is an ancient Chinese martial art. It has gained popularity in western countries in recent years for its recognized positive effects on health, balance, and fall prevention in the elderly [1,2]. Recently, researchers have begun sophisticated scientific measurements of TCC movements. These measurements include, for example, electrocardiography, blood pressure, exercise capacity, and electromyography of selected muscles during TCC movements [3–7]. The results from these measurements have provided both physiological and biomechanical evidences to help understand the mechanism of TCC’s positive effects [7,8].

One of the important biomechanical considerations of TCC movements is the pattern of foot–ground contact. While other parts of the body are free to move in space, the feet are constrained by the ground during stance. Thus, if there is any impact of the motion, it will occur at the foot–ground contact. In addition, the foot–ground contact provides a base of support to the moving body. The foot–ground contact force counteracts the gravitational force of the moving body in order to maintain balance and stability.

To date, no direct measurement has been done that quantitatively characterizes the foot–ground contact during TCC movements. Consequently, the purpose of this study was to quantify the biomechanical characteristics of foot-
ground contact during a TCC movement, the Tai Chi gait (TCG). TCG is a basic but most common leg motion in TCC movements [7]. It is a periodic motion, and has similar temporal patterns as normal gait. Thus, the isolation of this single leg motion from the entire TCC movements makes biomechanical quantification and comparison possible. In particular, in this study we examined the patterns of foot–ground contact force, plantar pressure distribution, and center of foot pressure movement during the stance phase of the Yang style TCG. In order to appreciate how TCG differs from other normal gaits, the foot–ground contact characteristics of TCG were compared to those of slow walking (SW).

2. Methods

2.1. Subjects

A total of 10 subjects (5 males, 5 females) were tested in this study. Their mean age was 27 ± 4 years. They were recruited from the students of the University of Vermont and from the local communities of the greater Burlington area, Vermont. At the time of recruitment, all subjects were physically active by participating in regular fitness exercises; and all subjects, except for one, did not know TCC. One subject learned the Yang style TCC 5 years ago and did practice only occasionally. All subjects were taught the Yang style TCG by a TCC master, and asked to practice the TCG 15 min daily. At the time of testing, all subjects were fluent in the Yang style TCG as determined by the TCC master, and had been practicing the TCG daily for at least the past 2 weeks. Before testing, each subject was asked to read and sign an Informed Consent Form that was approved by the University of Vermont Institutional Review Board.

2.2. Experimental protocol

Two biomechanical force plates (OR6-6-1000, Advanced Mechanical Technology Inc., Watertown, MA) and a biomechanical pressure plate (F-Mat, Tekscan Inc., Boston, MA) were used for measuring ground reaction force and plantar pressure characteristics during TCG and SW. The force plates and the pressure plate were placed within a 6 m walkway, separated by subject’s step length and step width. Prior to data collection, the force plates’ outputs were zeroed by adjusting a set of balance screws on the amplifier (MCA6, Advanced Mechanical Technology Inc.). The pressure plate was calibrated to subject’s body weight (i.e. having the subject stand quietly on the pressure plate) based on the manufacturer’s recommended calibration procedures [9].

Subjects were asked to practice their TCG on the walkway at their regular speed. The distance between the force plates and the pressure plate was adjusted and the starting position was determined so that subjects could land with the left foot first on the force plate, followed by the right foot on the pressure plate, and the consecutive left foot on the second force plate, during one stride of the complete gait. Once ready, subjects were asked to repeat the TCG over the force and pressure plates until five acceptable trials were collected. A trial was considered acceptable when the subject stepped on all of the plates correctly, as determined by the investigators who observed the subject’s performance. They were instructed verbally to perform naturally, not looking down on the walkway, and not worrying about stepping on the force and pressure plates.

In order to compare TCG with SW, subjects were also asked to walk at their self-determined, slow speed over the force and pressure plates, for at least five times. The location of the force and pressure plates was also adjusted so that they could be landed on with the corresponding foot during a complete gait cycle. All TCG and SW trials were done with bare feet. The signals from the force plates (i.e. ground reaction forces in the medial–lateral (ML), anterior–posterior (AP) and vertical directions) were low pass filtered at 10.5 Hz, and collected by a personal computer with a sampling frequency of 50 Hz for about 3 s for the walking trials, and 15 s for the TCG trials. The signal from the pressure plate was collected at 50 Hz.

2.3. Data analysis

The ground reaction force data was analyzed over the left foot stance phase, and the pressure plate data was analyzed over the right foot stance phase. The stance phase timing was determined based on the vertical ground reaction force profile. A detailed description of gait phase determination is provided elsewhere [7].

Following parameters were examined. For ground reaction force measurement, the maximum force and the maximum rate of loading (i.e. the first order time derivative, or slope) in each of the three directions were computed. For plantar pressure and contact area measurements, only the peak pressure and the maximum contact area profiles were used for analysis. For center of pressure, the maximum range of displacement in both AP and ML directions were computed. For the convenience of comparison, force and pressure data were normalized by subjects’ body weight (BW), and the contact area and center of pressure were normalized by subjects’ foot dimensions.

The mean and standard deviation of each variable, as well as the temporal features of both SW and TCG were calculated for each subject and compared using two-tailed t-test. They were considered statistically different when the P value was less than 0.05.

3. Results

Both TCG and SW were performed with consistent speeds among all subjects. The mean and standard deviation
Fig. 1. Ensemble average (all subjects) of normalized (a) ground reaction force and (b) rate of loading in ML, AP and vertical (U–D) directions, during TCG (solid line) and SW (dotted line) in one stance phase. Dash lines indicate one standard deviation from the mean of TCG. Three sub-phases within the stance phase of TCG are labeled: 1st double stance phase (DSI), single stance phase (SS), and 2nd double stance phase (DSII).
of TCG speed was 0.088 ± 0.05 m/s and SW speed was 0.84 ± 0.15 m/s, respectively.

3.1. Ground reaction force

The ground reaction force in the medial–lateral direction was mainly medial (see Fig. 1a). It was the largest during the first double stance (DSI) phase (with a peak value of 12 ± 2% BW), and oscillated several times throughout the stance. The vertical force reached and maintained a peak (109 ± 2% BW) during single stance (SS), and shifted between a large range of partial weight-bearing (from 10% to 70% BW) during the two double stance phases (DSI and SDII). The AP force also oscillated throughout the stance, with less than 11 ± 5% BW in each direction. Comparing to SW, TCG had significantly higher peak medial force (P = 0.01), but otherwise similar or significantly smaller peak AP and vertical forces. TCG also showed multiple loading–unloading patterns that were absent in the SW.

TCG also showed a uniformly small rate of loading in all three directions throughout the entire stance (less than 71 ± 16% BW/s in ML direction, 37 ± 18% BW/s in AP direction, and 191 ± 55% BW/s in vertical direction, see Fig. 1b). This was in direct contrast to the rate of loading during SW where there was significantly higher rate of loading (about 2–4 times) during DSI and DSII in all three directions (P < 0.00).

3.2. Plantar pressure

Peak plantar pressure was kept fairly constant throughout the stance in the rear-foot region (with the maximum peak pressure of 0.27 ± 0.07 kPa/kg), but changed largely (from 0 to 0.16 ± 0.04 kPa/kg) in the fore-foot region (see Fig. 2). Nevertheless, the peak pressure difference between the fore-foot and rear-foot regions was mainly observed in DSI (maximum value of 0.15 ± 0.04 kPa/kg), and was minimal throughout SS (0.06 ± 0.01 kPa/kg) and the majority of DSII (0.05 ± 0.01 kPa/kg). Comparing to SW, the maximum values of the peak plantar pressure in both fore-foot and rear-foot regions were statistically similar (P > 0.29). However, the pressure difference between fore-foot and rear-foot regions was significantly smaller (P < 0.00), especially during the single stance and the second double stance phases. In addition, during TCG, the peak pressure tended to occur mostly in the big toe, the 1st or 5th metatarsal head, and the heel. In contrast, the peak pressure occurred mostly under the 3rd metatarsal head during SW (see Fig. 3).

3.3. Plantar contact area

The maximum plantar contact area during TCG was 60 ± 9% of foot plantar area, which was statistically similar to that of SW (52 ± 4%). However, the contact area reached to
the peak value three times, once in each of the three substance phases during TCG, whereas it reached to the peak only once during SS in SW (see Fig. 4).

3.4. Foot center of pressure (COP)

The foot COP displaced over a large range under the foot during DSI and shortly before the end of the stance phase, and maintained fairly stationary during SS and the majority of DSII phases (see Fig. 5). Comparing to SW, TCG showed a significantly larger range of displacement in both ML (64 ± 8% in TCG versus 45 ± 8% in SW, P = 0.00) and AP (72 ± 7% in TCG versus 67 ± 5% in SW, P = 0.01) directions. Moreover, the foot COP in TCG was located consistently more towards the lateral side of the foot throughout the stance.

4. Discussions

This study was aimed at quantitatively characterizing the biomechanical features of foot–ground contact during TCG, one of the most basic and popular gaits in TCC movements. The isolation of the TCG from the rest of the TCC movements allows us to use the existing biomechanical measurement tools, and to quantitatively compare its biomechanical characteristics with other common gait movements. The results demonstrate that TCG had a low impact force to the foot, a fairly evenly distributed body weight between the fore-foot and rear-foot regions, and a large ML displacement of the foot COP.

The biomechanical characteristics of the foot–ground contact can be used to evaluate the control of the movement. The foot–ground contact characteristics of TCG as observed
in this study support that TCG is a movement that involves the precise control of body motion. First, TCG exhibits low impact foot–ground contact force during the initial foot contact period. Although, this can be partly due to the slow speed of TCG, gait speed is not the only factor determining the amount of impact. People with musculoskeletal problems such as activity-related tibiofemoral pain, for example, have a higher impact force than normal people walking at a similar speed [18]. We believe that the low impact as observed in the TCG is the result of the coordinated activations of the lower extremity muscles such as ankle dorsiflexors, hip flexor/knee extensors and hip abductors, all controlling the leg motions. In fact, it has been shown that these muscles are activated heavily during the stance phase of TCG, especially during the initial contact of the foot with the ground [7]. Without these muscles’ coordinated activations, the foot contact would have been sudden and with a large impact force. Second, during TCG the body weight is fairly evenly distributed between the fore-foot and rear-foot regions, and the foot COP is centered in the mid-foot region, especially during the single stance phase. This is by no means a coincidence. Earlier studies have shown that during quiet, upright stance, body weight is located more towards the heel region, resulting in more planter pressure in the rear-foot than in the fore-foot region [19,20]. Moreover, during single stance, the swing leg goes through a significant amount of hip adduction and flexion, and upper body goes through a significant amount of anterior displacement [7]. All of these tend to displace the body center of mass from the center of the stance foot. Therefore, maintaining foot COP in the mid-foot region and keeping the plantar pressure equally distributed between the fore and rear foot regions require a conscious and precise control of the neuromuscular system.

Quantifying the biomechanical characteristics of foot–ground contact during TCG could provide guidance towards clinical applications. For example, the level of impact force to the foot during foot-contact is one of the extrinsic factors to joint injuries [21]. It has been found in this study that TCG has significantly lower dynamic impact than SW. An exercise with low dynamic impact is particularly suitable to people with joint degenerative diseases who cannot participate in regular exercises. Elders and people with osteoarthritis are among the target groups of the TCC exercise. Studies have shown that TCC exercise by people with osteoarthritis does not exacerbate the disease [22,23].

In addition, it is found in this study that TCG is a full weight-bearing movement with a peak vertical force of about one times body weight. The total area of foot-ground contact and the peak plantar pressure are similar to those during SW. However, the peak pressure during TCG tends to occur often in the big toe and 1st and 5th metatarsal heads. These areas are considered high risk for ulceration in people with diabetes and peripheral neuropathy [12,24]. Therefore, one should be cautious when prescribing TCC exercise to these people. On the other hand, there are evidences that suggest an increased fore-foot/rear-foot pressure ratio (above 2) as an indicator for high-risk foot ulceration in people with diabetic neuropathy. In TCG, as well as in slow walking, the fore-foot/rear-foot pressure ratio is found less than one. This may suggest that TCG can be a safe weight bearing exercise. Nevertheless, the results in this study have provided quantitative information to assist healthcare providers make balanced decisions.

In this study, we also compared the foot-ground contact characteristics of TCG with those of slow walking. The purpose of the comparison was to quantitatively appreciate the difference between TCG and other normal gaits that we
perform on a daily basis. We have chosen slow walking for two considerations. First, it has been shown that the foot–ground contact characteristics depend on the speed of the activities [10,11]. Because the speed of TCG is extremely slow, we want to compare it to a normal gait that is relatively slow as well. In this study, the slow walking was performed at an average speed of 0.84 m/s. This is considered slow as compared to a normal walking speed of 1.3 m/s [11]. Second, although we want the speed of walking to be slow, we still want to preserve the naturalness of the gait. We realize that the speed of slow walking is still much faster than that of TCG. However, we do not want to lower the walking speed further because walking at a similar speed as TCG would have not been considered as a natural gait. Nevertheless, it is important to keep the comparison of TCG results in perspective. In particular, the similarities found between the TCG and SW in this study (such as peak planter pressure and contact area, and peak vertical force) may become significantly different between TCG and walking at faster speeds. In fact, the peak planter pressure results reported in this study are smaller to those reported by others, especially in the fore-foot region [12,13].

The characteristics of foot–ground contact also depend on the types of footwear [14–16]. In general, peak planter pressure is higher with barefoot contact as compared to in-shoe or cushioned surface contact [17]. Since in this study all subjects were barefooted during testing, we anticipate that the in-shoe TCG will have lower peak planter pressure than what have been reported in this study.

It should be pointed out that the results found in this study are based on a group of healthy young subjects. The biomechanical characteristics of their TCG may not be the same as other subject populations such as people with advanced age, or with neural/muscular/skeletal problems. Also, the biomechanical characteristics of TCG depend on the amount of practice, and the style. Further studies are needed to examine how each of these factors affects the TCG performances, and how a TCG can be modified to fit the needs of individual practitioners.

5. Conclusion

This study quantitatively documented the foot–ground contact biomechanics of a Yang-style TCG in a group of healthy young subjects. The results demonstrated that TCG had a low impact force to the foot, a fairly evenly distributed body weight between the fore-foot and rear-foot regions, and a large ML displacement of the foot COP.

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