

# Age-Related Differences in Tai Chi Gait Kinematics and Leg Muscle Electromyography: A Pilot Study

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**ABSTRACT.** Wu G. Age-related differences in Tai Chi gait kinematics and leg muscle electromyography: a pilot study. *Arch Phys Med Rehabil* 2008;89:351-7.

**Objective:** To compare the biomechanic features of Tai Chi gait by elders with those by young adults, and with those of normative gait.

**Design:** Cross-sectional study.

**Setting:** Laboratory-based testing.

**Participants:** Young (n=6; 3 women) and old (n=6; 5 women) Tai Chi practitioners.

**Intervention:** All subjects had practiced Tai Chi for at least 4 months.

**Main Outcome Measures:** Spatial, temporal, and leg muscle electromyography during Tai Chi gait and normative gait.

**Results:** The primary age-related differences in Tai Chi gait were during single stance, with elders having significantly shorter single-stance time (-50%), less lateral displacement (-30%), knee flexion (-42%), hip flexion (-39%), activation time in the tibialis anterior (-13%), soleus (-39%), and tensor fascia lata (TFL) (-21%), activation magnitude in the tibialis anterior (-39%), and coactivation time of the tibialis anterior and soleus (-47%). Compared with normative gait, elders during Tai Chi gait had significantly larger knee (139%) and hip (66%) flexions, longer duration (90%-170%) and higher magnitude (200%-400%) of the tibialis anterior, rectus femoris, and TFL muscle activities, and longer duration of coactivation of most leg muscle pairs (130%-380%).

**Conclusions:** The elders practice Tai Chi gait in higher posture than younger subjects. The Tai Chi gait poses significantly higher challenges to elder's balance and muscular system than does their normative gait.

**Key Words:** Elderly; Gait; Rehabilitation; Tai Chi.

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**A**DVANCING AGE IS associated with a remarkable number of changes in the physiologic systems, which often lead to increased frequency and severity of chronic diseases, increased risk of injuries due to falls, and eventual loss of independence. Each year, about 33% of people aged 65 years and over fall at least once a year<sup>1,2</sup>; accidental falls are the leading cause of injury-related deaths among elders<sup>3</sup> and are

the most common cause of injuries and hospital admissions for trauma among older adults.<sup>4</sup> The problem of falls in the elderly presents health and economic challenges to the nation because the number of adults age 65 and older is projected to reach 71 million, or roughly 20% of the U.S. population by 2030.<sup>5</sup>

Tai Chi Chuan (TCC) is becoming a popular exercise among elders for improving their general physical conditions. In particular, it has been shown that participating in long-term TCC exercise can increase muscle strength,<sup>6-8</sup> flexibility,<sup>9,10</sup> sensory organization in postural control,<sup>11,12</sup> and balance.<sup>7,13-15</sup> These changes are all important components for preventing falls in the elderly.<sup>16-24</sup>

Only limited studies have investigated the biomechanic characteristics of TCC movements. For example, Wu et al<sup>25,26</sup> quantitatively measured the spatial and temporal joint kinematics patterns, muscle activities in the lower extremity, and foot-floor contact characteristics during a TCC movement, the Tai Chi gait, in healthy young adults. Tai Chi gait is a series of continuous forward steps and strides, with distinct gait phases such as single stance, double stance, and swing. A popular TCC movement that involves the Tai Chi gait is Parting the Wild Horse's Mane. These studies revealed that Tai Chi gait is, compared with normative gait (ie, walking), a slower and crouched gait, involving larger and sustained lower-extremity motions in 3 dimensions, especially larger ankle dorsiflexion, knee flexion, and hip abduction during a long, sustained period of single stance.<sup>25</sup> Moreover, Tai Chi gait required the use of a different group of muscles than those involved in normative gait, and required a relatively longer duration of activation of these muscles. Chan et al<sup>27</sup> did a kinematic and electromyographic analysis of the push movement of TCC, and found high levels of activation in the lumbar erector spinae and the rectus femoris muscles, with both concentric and eccentric contractions in the rectus femoris and the medial head of gastrocnemius. Subjects maintained an upright posture and a low center of gravity while traveling slowly and steadily from one position to another. These unique biomechanic characteristics suggest that TCC movements are rather demanding, requiring a degree of leg muscle strength and postural control that is not otherwise needed during standing or walking.

We do not know if these characteristics are representative of the elderly population. Elders tend to walk more slowly, with a shorter step length, a shorter single-stance time, and a wider step width.<sup>28-30</sup> They generate less power in leg muscles, mostly in ankle plantarflexors and hip flexors.<sup>31,32</sup> These age-related changes in gait patterns are shown to be directly related to the decline in elder's joint range of motion (ROM), muscle strength, and postural stability.<sup>33,34</sup> Accordingly, we expect that the biomechanic characteristics of TCC movements will be different between young and the elderly, especially during the single-stance portion of the movements.

The purpose of this study was to compare the biomechanic features of Tai Chi gait as performed by healthy elders to those by young adults and to those of normative gait by the elders. It was hypothesized that elders during Tai Chi gait: (1) as compared with healthy young adults, would have shorter single-leg stance time, less knee and hip flexion, shorter duration and

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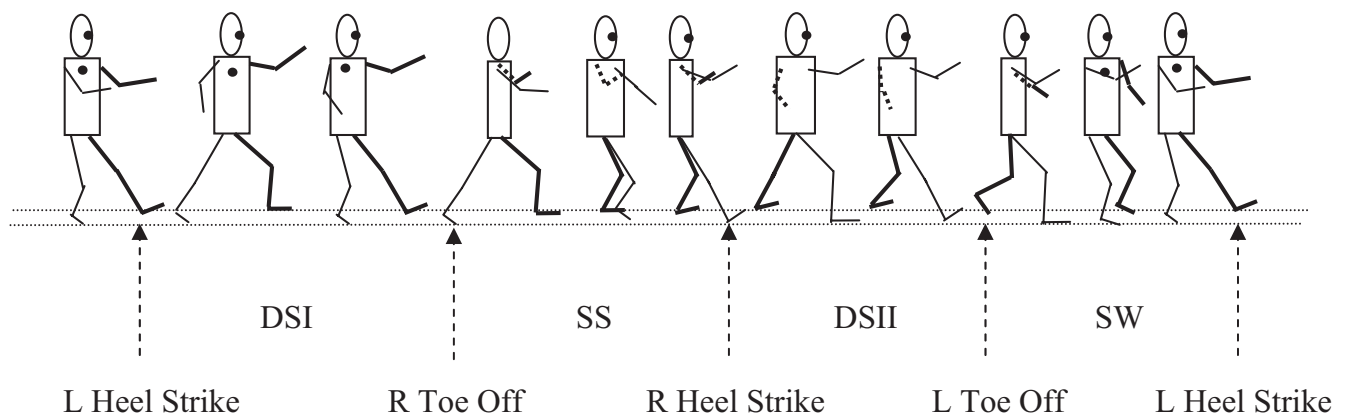


Fig 1. Illustration of a complete cycle of Parting Wild Horse's Mane. Abbreviations: DSI, double-stance I; DSII, double-stance II; L, left; R, right; SS, single stance; SW, swing.

lower magnitude of muscle activation, and shorter duration of muscle coactivation; and (2) as compared with normative gait, would have longer single-leg stance time, more knee and hip flexion, longer duration and higher magnitude of muscle activation, and longer duration of muscle coactivation.

## METHODS

### Participants

Six young adults (range, 21–45y) and 6 elderly adults (range, 61–85y) participated in the study. Subjects were recruited on a voluntary basis through fliers, elderly living communities, and TCC classes in the area. The inclusion criteria included that subjects had practiced Yang-style TCC for at least 3 times a week for 4 months before the study, and could complete the TCC with smooth transitions and with proper breathing patterns, an indication of essential fluency of TCC practice; had no presence of vestibular dysfunction, cardiovascular diseases, musculoskeletal disorders, lower-extremity fracture or sprain in the preceding 6 months, or current joint pain that prevented normative functioning; had normal, age-adjusted knee extensor strength<sup>35</sup> and ankle dorsiflexion ROM,<sup>19</sup> and were able to squat down to touch the floor and kick out each leg a minimum of 30° pain free. All subjects signed an informed consent form before testing that was approved by the institutional review board.

### Equipment

Isometric knee extensor strength was measured at 90° knee flexion with a hydraulic handheld dynamometer.<sup>a</sup> A motion analysis system<sup>b</sup> with three 50-Hz infra-red sensitive cameras was used to record the movement of reflective markers. The cameras were set up along the left side of an 8-m walkway, and were calibrated before testing for a 2m (height) by 2m (length) by 1m (depth) viewing volume with an overall root mean square (RMS) error of less than 5mm. Two biomechanical forceplates<sup>c</sup> were embedded in the walkway and placed so that the subject's left foot landed on the first plate at the beginning of a gait cycle and on the second plate at the end of the cycle. The ground reaction forces measured by the forceplate were low pass filtered at 10.5Hz and amplified with a gain of 2000 by 2 amplifiers provided by the manufacturer. The amplifiers were adjusted to offset the direct-current shift before testing. Six Ag/AgCl bipolar surface electromyography electrodes<sup>d</sup> were used to record electromyographic activities. Each electromyog-

raphy signal was band-pass filtered by a 2-stage amplifier<sup>b</sup> with a frequency range of 10 to 200Hz and integrated with a time constant of 5 seconds. The amplifier gain was selected such that the electromyographic signal from the maximum voluntary contraction of each muscle was not saturated. The recordings of the ground reaction force, electromyographic envelop, and reflective marker movement were synchronized and collected at 50Hz.

### Procedures

Each subject was asked to wear black spandex shorts. Anthropometric measurements were done including body height, weight, foot length and breadth, malleolus height and width, knee circumference, and anterior superior iliac spine (ASIS) breadth. A tracing of each subject's left foot was taken before testing and the locations of the medial and lateral malleoli, the locations of reflective markers on the foot, as well as the back of the heel and second toe were indicated on the tracing. The center of ankle, knee, and hip joints was calculated from these anthropometric measurements using estimation equations.<sup>36</sup>

We placed reflective markers on the left side of the subject's body: the fifth metatarsal head, heel, lateral malleolus, lateral femoral epicondyle, the greater trochanter, ASIS, shoulder, and the posterior extension of a shoulder harness. One additional marker was placed on the top right corner of each forceplate. Electromyography electrodes were placed on tibialis anterior, soleus, peroneus longus, tensor fascia lata (TFL), semitendinosus, and rectus femoris of the left leg.

Before testing, we asked each subject to practice the Parting the Wild Horse's Mane movement (fig 1) continuously for 5 minutes and was informed that the gait pattern in this movement was used for testing. A starting position was then identified so that the subject was able to consistently and naturally contact both forceplates with the left foot during the first cycle of the Tai Chi gait movement. Another starting position was also identified for the normative gait. Once ready, the subject was asked to stand at the starting position, and begin Tai Chi gait at a self-determined speed until being asked to stop (ie, at the end of the walkway). A minimum of 6 trials were repeated. In a similar manner, each subject was asked to walk at a self-determined slow speed, for a minimum of 6 repetitions. The slow speed was chosen for normative gait in order to reduce the speed difference between the 2 gaits. The subject was barefooted and was asked to keep his/her hands on the hips for both gaits to ensure the visibility of the reflective marker on

**Table 1: Subject Characteristics**

Characteristics	Young	Old	P
No. of subjects (women)	6 (3)	6 (5)	
Body height (cm)	177±10	158±10	.052
Body weight (kg)	70±16	69±11	.939
Knee extensor strength (Nm)	118±32	75±2	.039
Max ankle dorsiflexion (deg)	41±4	38±5	.296
Max hip extension (deg)	61±10	37±17	.080
Max hip abduction (deg)	59±14	50±10	.369

NOTE: Values are mean ± standard deviation (SD).

the greater trochanter by the cameras. A calibration trial was recorded before, during, and after the testing, respectively.

**Data Analysis**

Each gait cycle was divided into 4 phases: double-stance phase I, single-stance phase (single stance), double-stance phase II, and swing phase (see fig 1). The timing for these phases was determined based on the vertical ground reaction force profile.<sup>25</sup> The temporal variables included gait cycle time, and time of each phase of the gait cycle. The spatial variables included step length, lateral displacement of the hip, and angular movement of ankle (flexion and extension), knee (flexion and extension), and hip (flexion and extension, adduction and abduction) joints. The electromyographic variables included muscle activation time, muscle activation magnitude as determined by the RMS (the square root of the average power of the electromyographic signal for a given period of time) value of the electromyographic activity during each gait phase normalized by that of the corresponding muscle electromyographic activity during the calibration trial, and muscle coactivation time. All computations were similar to the ones in the previous study.<sup>25</sup>

A planned 2-tailed *t* test was used to compare the differences between the old and young groups, and a planned 2-tailed, paired *t* test was used to compare the differences between the Tai Chi gait and normative gait. A Bonferroni adjustment of a factor of 2 was used to control for the overall type I error at 5%. The difference was considered statistically different when the *P* value for each comparison was less than .025.

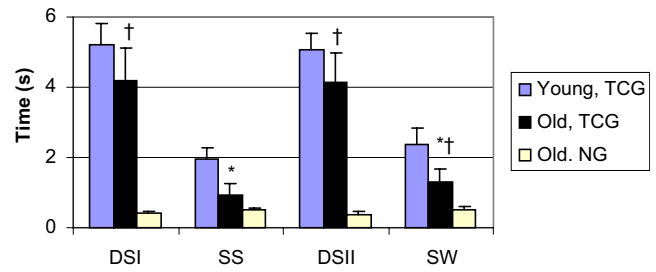
**RESULTS**

**Subject Profiles**

The age range was from 61 to 84 (mean, 71.5±8.3) years for the elderly and 21 to 35 (mean, 28.2±5.6) years for the young subjects. The mean TCC practice duration was 9.7±12.9 months for the elderly, and 13±5.6 months for the young subjects (*P*=.288). The elderly subjects, as compared with young subjects, were significantly shorter in body height, and had significantly weaker knee extensor strength (table 1). There were no significant group differences in body weight, and joint ROMs in the lower extremity.

**Temporal Variables**

There were significant group differences in Tai Chi gait in cycle time, stance time, single-stance time, and swing time (*P*<.016) (fig 2). The elders shortened the gait cycle time by shortening the single-stance and swing time by about 50% each. There were no significant group differences in intersubject variation for the cycle time, single-stance time, and swing time (table 2). Comparing 2 gaits in elders, the duration of double-stance phase I, double-stance phase II, and swing phase



**Fig 2. Mean time in different phases of gait cycle. The means and standard deviations (SDs) of the duration in double-stance phase I, single stance, double-stance phase II, and swing phase of Tai Chi gait (TCG) in both young and elders and of normative gait (NG) in elders. \*Significant difference between young and old in Tai Chi gait; †significant difference between Tai Chi gait and normative gait in elders.**

of Tai Chi gait was significantly longer (by 10 times for the double-stance phase I and double-stance phase II, and 1.5 times for swing phase, *P*<.007) than normative gait.

**Spatial Variables**

The stride length of Tai Chi gait by elders (.92±.07m) did not differ significantly from that of the young (1.03±.08m, *P*=.152) or from that of normative gait by elders (.92±.08m, *P*=.959). The lateral displacement of the greater trochanter of elders during Tai Chi gait (.37±.07m) was significantly smaller than that of the young (.53±.03m, *P*=.013), but significantly larger than normative gait (.02±.01m, *P*=.002), suggesting that elders had narrower step width than the young in Tai Chi gait, but wider step width in Tai Chi gait than in normative gait.

The ankle, knee, and hip joint motions during the single-stance phase of Tai Chi gait differed significantly between the 2 groups (fig 3A). The elders had significantly more ankle dorsiflexion (by 21%, *P*=.004) and less knee and hip flexion (by 42% and 39%, respectively; *P*<.001) than the young, indicating that elders assumed a higher posture than the young. Comparing these joint motions with normative gait of the elders, their knee and hip flexions during Tai Chi gait were significantly larger (by 139% and 66%, respectively, *P*<.001), indicating that they assumed a lower posture in Tai Chi gait than in normative gait.

The ROM of the ankle and hip joints during the swing phase of Tai Chi gait also differed significantly between the 2 groups (fig 3B). The elders had significantly less ROM in ankle

**Table 2: Intersubject Variability of Spatial and Temporal Variables During Tai Chi Gait**

Characteristics	Young	Old	P
Cycle time (s)	0.73±0.44	0.77±0.29	.847
Single-stance time (s)	0.15±0.06	0.24±0.23	.399
Swing time (s)	0.23±0.11	0.19±0.09	.569
Step length (cm)	5.6±1.6	4.6±0.9	.984
Hip lateral displacement (cm)	1.1±0.3	1.5±1.1	.449
Ankle dorsiflexion (single stance) (deg)	2.6±1.0	3.5±1.6	.160
Knee flexion (single stance) (deg)	2.0±0.5	2.7±1.7	.309
Hip flexion (single stance) (deg)	2.3±1.0	3.3±2.2	.594

NOTE: Values are mean ± SD.

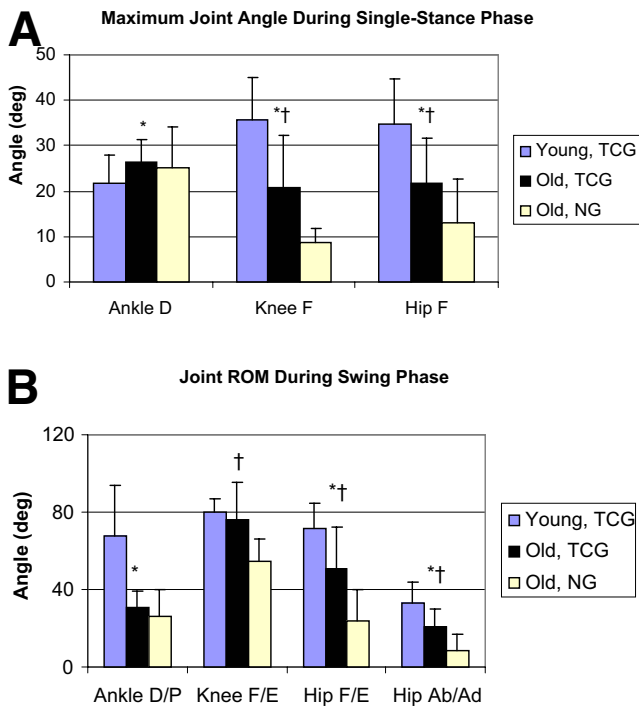


Fig 3. The means and SDs of (A) maximum joint motion during single-stance phase and (B) joint ROM during swing phase, of Tai Chi gait and normative gait, in the young and old groups. Abbreviations: Ab/Ad, abduction and adduction; D/P, dorsiflexion and plantarflexion; F/E, flexion and extension. \*Significant difference between young and old in Tai Chi gait; †significant difference between Tai Chi gait and normative gait in elders.

dorsiflexion and plantarflexion, hip flexion and extension and abduction and adduction than the young (by 55%, 29%, and 38%, respectively,  $P < .001$ ). Comparing the Tai Chi gait and normative gait by elders, the range of knee and hip motions were significantly larger (by 353%, 110%, and 139%, respectively,  $P < .001$ ) during Tai Chi gait.

There were no significant group differences ( $P > .309$ ) in intersubject variability in all spatial variables of Tai Chi gait (see table 2).

**Electromyographic Variables During Single Stance**

**Muscle activation time.** The activation time of the tibialis anterior, soleus, and TFL muscles was significantly shorter (by 13%, 39%, and 21%, respectively,  $P < .025$ ) in elders than in young adults during Tai Chi gait (fig 4A). Comparing the 2 gaits in elders, there were significant differences in the activation time of all muscles but the semitendinosus ( $P = .510$ ), with the tibialis anterior, peroneus longus, rectus femoris, and TFL muscles all longer (by 99%, 36%, 143%, and 106%, respectively,  $P < .002$ ) and the soleus muscle shorter (by 36%,  $P < .001$ ).

**Muscle activation magnitude.** The RMS value of the tibialis anterior muscle electromyographic activity during Tai Chi gait was significantly smaller (by 39%,  $P = .001$ ) in elders than in young adults (fig 4B). Comparing gait differences in elders, the RMS values of the tibialis anterior, rectus femoris, and TFL muscle electromyographic activity during Tai Chi gait were significantly higher (by 200%, 403% and 252%, respectively,  $P < .002$ ).

**Muscle coactivation time.** The coactivation time of the tibialis anterior and soleus muscles during Tai Chi gait was significantly shorter (by 47%,  $P = .010$ ) in elders than in the young (fig 4C). However, the coactivation time of the tibialis anterior and soleus muscles in elders did not differ significantly between Tai Chi gait and normative gait ( $P = .675$ ), but the coactivation time of all other muscle pairs during Tai Chi gait

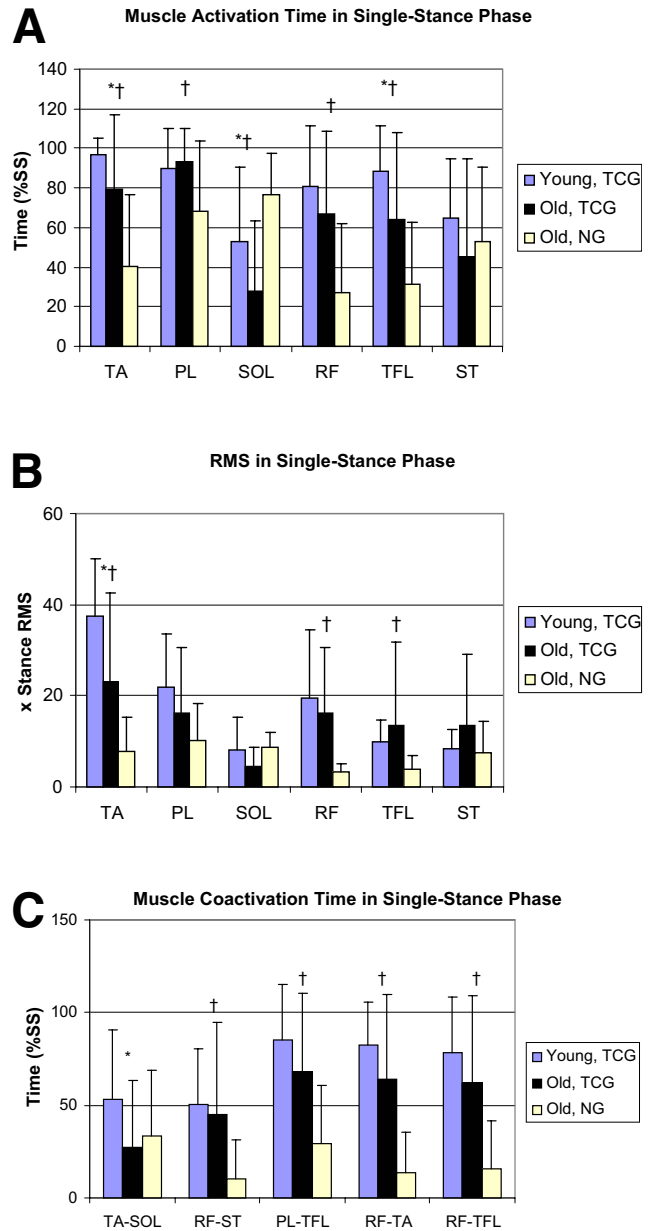


Fig 4. The means and SDs of (A) activation time of 6 muscles, (B) RMS values of 6 muscles, and (C) coactivation time of 5 muscle pairs, during single-stance phase of Tai Chi gait and normative gait, in the young and old groups. The activation time and coactivation time are normalized by the single-stance time, and the RMS value of each muscle electromyographic activity is normalized by the corresponding RMS value during quiet stance. Abbreviations: PL, peroneus longus; RF, rectus femoris; SOL, soleus; ST, semitendinosus; femoris TA, tibialis anterior. \*Significant difference between young and old in Tai Chi gait; †significant difference between Tai Chi gait and normative gait in elders.

was significantly longer than that during normative gait (by 130%–380%, respectively;  $P < .002$ ).

## DISCUSSION

One of the main purposes of this study was to compare the biomechanic characteristics of a TCC movement, Tai Chi gait, in elderly and young adults. For the first time, it has shown that there are age-related differences in the biomechanic characteristics of the Tai Chi gait movement. The primary differences are during the single-stance phase. In particular, elders have shorter single-leg stance time, less lateral displacement of greater trochanter, less knee and hip flexion, shorter activation duration of the tibialis anterior, soleus, and TFL muscles, lower activation magnitude of the tibialis anterior muscle, and less coactivation of the tibialis anterior and soleus muscles, during the single-stance phase of the Tai Chi gait. These findings partially support our first original hypothesis.

The shortened single-leg stance time in elders during Tai Chi gait is supported by literature. Single-leg stance is a challenging balance task due to the reduced base of support compared with double-leg stance. Studies have shown that elders have difficulty controlling trunk sway while standing on 1 leg or walking over a narrow base.<sup>37</sup> As a result, elders have a significantly reduced single-leg stance time compared with healthy young adults,<sup>30</sup> and elders with a history of falls have even less single-leg stance time than those without a history of falls.<sup>38</sup> The single-leg stance during Tai Chi gait is more challenging than static 1-leg stance, single stance of normal walking, or tandem walking, in that the swing leg during Tai Chi gait has a significantly larger range of hip and knee flexion and hip abduction than normative gait (see fig 3B), introducing more disturbance to the 1-leg standing balance. Thus, shortening the single-leg stance time seems to be a practical solution in order to maintain functional balance.

The altered activation patterns of leg muscles in elders during Tai Chi gait is perhaps the result of their altered kinematics strategy. For example, the significantly smaller knee and hip flexions but larger ankle dorsiflexion in elders allow the whole body center of gravity to fall anterior to the ankle joint, resulting in a gravity assisted ankle dorsiflexion and placing less demand on dorsiflexors (ie, the tibialis anterior) and coactivation of dorsiflexion and plantarflexor pairs (ie, the tibialis anterior and soleus). Similarly, the significantly narrower lateral displacement of the greater trochanter in elders reduces the need of the hip abductor (ie, TFL) activity. For elders, these altered muscle activation patterns are important because of their reduced muscle strength with aging, especially their dorsiflexors and hip abductors.<sup>39-41</sup>

The smaller range of knee and hip motion during single-stance and swing phases of Tai Chi gait in elders is probably not related to joint flexibility. In this study, the active joint ROMs in the lower extremity did not differ significantly between the young and old groups (see table 1), and are larger than the maximum joint motion during Tai Chi gait (see fig 3). It is not clear, however, whether these group differences are related to the experience with TCC practice. Although both groups had been practicing TCC on a regular basis for a much longer period than the suggested time for mastering the Tai Chi gait (about a week of practice, 20min/d),<sup>25</sup> the mean practice time of the elderly was shorter than the young. Future studies should control for the practice duration of all subjects.

The age-related spatial and temporal differences in Tai Chi gait may have direct implications on the effectiveness of general TCC practice on balance. Hain et al<sup>42</sup> compared the outcome effects of a same TCC protocol on people with different ages (eg, people in age range, 20–60, 61–75,  $\geq 76$ y).

They found that the same TCC protocol benefited the youngest subject group the most, and the oldest group the least. This age-related difference in TCC effect may well be contributed by the age-related differences in the spatial and temporal patterns of their TCC practice as shown in this study. In particular, the shortened single-leg stance time, the reduced lateral displacement of the greater trochanter in single stance, and/or the reduced swing leg ROM in elders may reduce the challenge to their upright balance, and thus reduce the effect on balance training. Future studies are needed to confirm this causal effect.

Despite the less rigorous movement of the elderly subjects during the single-stance phase of Tai Chi gait, the elders do exhibit significant differences between their Tai Chi gait and normative gait. In particular, the single-stance time is twice as long, knee flexion is twice as large, and the tibialis anterior, rectus femoris, and TFL muscles are active at least twice as long and as high. These differences support our second original hypothesis, and are qualitatively consistent with previous findings in young TCC practitioners.<sup>25</sup> The differences in muscle activation patterns are primarily attributed to the deeper knee flexion, slower speed, and the gentleness and precise control of body movement during Tai Chi gait. These differences have several important practical implications. First, it has been shown that the strength of the tibialis anterior, rectus femoris, and TFL muscles declines significantly with age, which is a significant risk factor for falls and fall related injuries in elders.<sup>17,39-41,43</sup> Thus, TCC practice may provide the benefits of improving functional strength of these muscles, improving balance and reducing the risks for falls in elders. Second, TCC practice by elders may help improve their walking patterns. As people age, their walking patterns change, leading to less efficiency and more instability.<sup>28-32</sup> With long-term TCC practice, they will be able to walk with a larger knee flexion to lower-body center of gravity for better balance and to reduce impact to the upper body. Third, as compared with walking, TCC could be challenging for elders, especially during the single-stance phase and for those who have weak leg muscle strength, poor balance, and/or other musculoskeletal problems. It might be wise to adjust the speed and knee bent angle during TCC practice for elderly beginners and gradually improve the performance over time.

## Study Limitations

Tai Chi gait as tested in this study is only 1 portion of the complete TCC practice. It does not include other movements in TCC such as trunk rotation, turn and kick, push down, and stand. Thus, the benefit of TCC practice on balance and strength may be larger than what is inferred by the study of Tai Chi gait. Moreover, this study tested only a small number of subjects, and had uneven numbers of female subjects between the 2 age groups. The variations in subject's physical condition and sex could contribute to the group differences in TCC kinematics and muscle action patterns. The effects of these variations should be investigated in future studies. A power analysis indicated that a sample size of 7 per group is needed to detect group and gait differences in single-stance time, 18 per group to detect group and gait differences in knee and hip joint kinematics, and 310 per group to detect group and gait differences in major muscle activation patterns, all with at least 80% power.

## CONCLUSIONS

This study quantitatively characterized and compared the biomechanic features of the Tai Chi gait by healthy elders with those by young adults, and to those of normative gait by elders.

The results showed primary age-related differences in the biomechanic characteristics of the Tai Chi gait during the single-stance phase, with elders practicing Tai Chi gait in higher posture than younger subjects and less activation of leg muscles. However, as compared with normative gait, the Tai Chi gait poses significantly higher challenges to elder's balance and muscular system. Thus, TCC would be a better exercise in improving leg muscle strength and balance and reducing the risks for falls in elders.

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#### Suppliers

- a. Fabrication Enterprises Inc, PO Box 1500, White Plains, NY 10602.
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