Speed effect of selected Tai Chi Chuan movement on leg muscle activity in young and old practitioners

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ABSTRACT

Background: Tai Chi Chuan is becoming a popular exercise for improving balance and preventing falls in the elderly. To date, there is no quantitative study investigating the effect of Tai Chi Chuan movement speed on leg muscle function. This study investigated the effect of Tai Chi Chuan exercise performed at different speed on leg muscle activity characteristics in both young and old Tai Chi Chuan practitioners.

Methods: Surface electromyography of six leg muscles and kinematics of lower extremity joints were measured in young and old subjects during Tai Chi Chuan practice at fast, normal, and slow speed, respectively. The magnitude and duration of activation, and durations of isometric, concentric and eccentric actions of each muscle were compared among three speeds and between two groups.

Findings: The activation duration of all six leg muscles was significantly longer at slower speed than at faster speed (P < 0.039). The durations of isometric, concentric and eccentric actions were either longer at the slower speed or did not change with speed for all six leg muscles. The action of knee extensor was primarily isometric at slower speed (P = 0.004), and increased significantly to concentric and eccentric at faster speed (P < 0.031). The activation magnitude of posterior leg muscles increased with speed (P < 0.009). The old subjects had significantly shorter activation duration and lower activation magnitude in several leg muscles than the young, but similar speed effect as the young.

Interpretation: The activation duration and function of leg muscles, especially the knee extensor muscle, are significantly affected by the speed of the selected Tai Chi Chuan movement. Practicing Tai Chi Chuan at different speed may alter the role of muscular function in movement control.

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1. Introduction

Tai Chi Chuan (TCC) is an ancient Chinese martial art and has become a popular exercise in recent years among people young and old. Many studies have documented its positive effect on improving muscle strength and function (Wu et al., 2002b; Song et al., 2003; Lan et al., 2000), postural control and balance (Hong et al., 2000; Tsang and Hui-Chan, 2004; Tsang et al., 2004), and on reducing the risk of falls (Li et al., 2004, 2005; Wolf et al., 2000; Tsang and Hui-Chan, 2004; Tsang et al., 2004), and to be an equivalent of aerobic exercise of moderate intensity (Zhuo et al., 1996, 2001) in the elderly population.

TCC is consisted of a series of slow body movements. Its progression speed is about 10 times slower than normal walking (Wu et al., 2004). Nevertheless, these slow movements are shown to be an equivalent of aerobic exercise of moderate intensity (Zhuo et al., 1984; Li et al., 2001; Chao et al., 2002; Lan et al., 2001), and stimulate significantly higher amount of muscle activity (i.e., duration and magnitude) in the lower extremity as compared to normal walking (Wu et al., 2004; Chan et al., 2003).

It has been generally believed that the slower the TCC movements are carried out, the more difficult they become, and thus the better the exercise effects. However, to date, there is no quantitative study investigating the effect of TCC movement speed on leg muscle functions. Would the duration and intensity of muscle activation change with speed? Would muscle functions (i.e., as a mover, stabilizer, or a controller) change with speed? And, if yes, would these changes be similar in people of different ages?

The purpose of this study was to examine the effect of TCC movement speed on muscle activity characteristics in both young and old TCC practitioners. In particular, we compared the muscle activity characteristics during one TCC movement, the “Part wild horse’s mane”, performed at three different speeds. This TCC movement involves a cyclic motion of both legs progressing forward while the body rocks back and forth during double stance and the arms alternately swing to each side of the body (Fig. 1). It was hypothesized that when the selected TCC movement was done at a slower speed, major leg muscles would be activated significantly longer and with a higher magnitude for both young and old adults. In addition, the durations of isometric, concentric, and eccentric actions of leg muscles would be increased proportionally at slower speed.

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2. Methods

2.1. Subjects

Healthy young and old human volunteers were recruited for the study through flyers at local TCC clubs or classes. The inclusion criteria included having been practicing Yang style TCC on a regular basis for at least four months before the study; and having no presence of vestibular dysfunction, cardiovascular diseases, musculoskeletal disorders, lower extremity fracture or sprain in the presence of vestibular dysfunction, or apparent weak knee extensor strength and limited ankle dorsiflexion range of motion.

A total of 12 subjects (six young and six old) were tested. Their anthropometric data is shown in Table 1. The mean of self-reported dorsiflexion range of motion.

\[ \text{Dorsiflexion range of motion (degree):} \]

\[ \begin{array}{lcc}
\text{Young} & \text{Old} & P \\
28 (SD 6) & 72 (SD 8) & \\
39 (SD 3) & 51 (SD 1) & \\
174 (SD 8) & 156 (SD 10) & 0.007 \\
70 (SD 14) & 65 (SD 11) & 0.483 \\
118 (SD 32) & 75 (SD 2) & 0.038 \\
41 (SD 4) & 38 (SD 5) & 0.296 \\
\end{array} \]

2.2. Equipment

Two biomechanical force plates (Advanced Mechanical Technology Inc., Watertown, MA, USA) were used to measure foot-floor contact events of the left foot during a complete movement cycle. They were placed in an 8-m walkway about one stride length apart. The force output was low pass filtered at 10.5 Hz and amplified with a gain of 2000 by two amplifiers provided by the manufacturer. A three-camera based Elite Motion Analysis System (Elite, Bioengineering Technology and Systems, Milano, Italy) was used to record the movement of multiple reflective markers. The cameras were positioned along one side of the walkway, and were calibrated over the force plates’ area with an overall error of <5 mm. Six silver/silver chloride bipolar surface electromyography (EMG) electrodes (Myotronics-Noromed, Inc., Tukwila, WA, USA) were used to record EMG activities of leg muscles. Each EMG signal was band-pass filtered by a two-stage amplifier with a frequency range of 10–200 Hz, rectified and integrated with a time constant of 5 s. The amplifier gain was selected such that the EMG signal from the maximum voluntary contraction of each muscle was not saturated. All signals were synchronized and collected at 50 Hz.

2.3. Procedures

The kinematics and surface EMGs were measured on the left leg only because the “Part wild horse’s mane” movement is left–right symmetrical through one complete cycle (see Fig. 1). Six muscles were selected for testing because of their primary roles for the ankle, knee and hip joint motion in the sagittal and frontal planes during the “Part wild horse’s man” movement. They were tibialis anterior (TA), soleus (SO), peroneus longus (PL), tensor fascia lata (TFL), semitendinosus (SD), and rectus femoris (RF). Reflective markers were placed on the left side of each subject’s body at the fifth metatarsal head, heel, lateral malleolus, lateral femoral epicondyle, the greater trochanter, anterior superior iliac spine, shoulder, and the posterior extension of a shoulder harness (Wu et al., 2004).

Subjects were first asked to warm up by practicing the “Part wild horse’s mane” movement for at least 5 min. The distances between the two force plates and a starting position were adjusted so that subjects were able to contact both force plates consecutively with the left foot during the first cycle of the selected TCC movement. Once ready, subjects were asked to stand at the starting position and perform one complete cycle of the selected TCC movement at a self-determined normal speed for six times. Then, subjects were asked to perform the selected TCC movement again at a slower and a faster speed, respectively, six trials each. In addition, subjects were asked to stand quietly for three seconds once before, and once after each bout of six TCC trials. The kinematics and EMGs were recorded during the TCC trials and stance trials. All subjects were barefooted.

2.4. Data analysis

A complete cycle of the “Part wild horse’s mane” is shown in Fig. 1. The movement had a stance phase and a swing phase for left foot-floor contact which were marked by consecutive left heel strike and left toe off events (see Fig. 1). The cycle time was defined as the duration from the two consecutive left heel strikes, and was determined from the vertical ground reaction force profile of the force plates. Stride length was defined as the anterior–posterior distance between the left heel at first heel strike and the left heel at the second heel strike (Fig. 1). Postural height was defined as the vertical distance of the left greater trochanter to the floor, normalized by the mean vertical distance during quiet stance trials. Both stride length and postural height were computed based on the reflective marker positions.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Young (n = 6)</th>
<th>Old (n = 6)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (year)</td>
<td>28 (SD 6)</td>
<td>72 (SD 8)</td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>3f, 3 m</td>
<td>5f, 1 m</td>
<td></td>
</tr>
<tr>
<td>Body height (cm)</td>
<td>174 (SD 8)</td>
<td>156 (SD 10)</td>
<td>0.007</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>70 (SD 14)</td>
<td>65 (SD 11)</td>
<td>0.483</td>
</tr>
<tr>
<td>Knee extensor strength (Nm)</td>
<td>118 (SD 32)</td>
<td>75 (SD 2)</td>
<td>0.038</td>
</tr>
<tr>
<td>Ankle active range of motion (degree)</td>
<td>41 (SD 4)</td>
<td>38 (SD 5)</td>
<td>0.296</td>
</tr>
</tbody>
</table>

Fig. 1. Illustration of a complete cycle of “Part wild horse’s mane”.
The angular movements of the ankle joint complex (dorsiflexion/plantarflexion and inversion/eversion), knee joint (flexion/extension) and hip joint (flexion/extension and adduction/abduction) were computed based on the reflective marker positions using the same protocol described elsewhere (Wu et al., 2004). Briefly, the markers on each body segment and bony landmarks were used to form a set of joint coordinate system (JCS) for the ankle, knee and hip joints, respectively (Wu et al., 2002a; Grood and Suntay, 1983). The JCS had three axes: a mediolateral–lateral axis, an anterior–posterior axis, and a floating axis. Flexion/extension of the knee and hip (or plantar/dorsiflexion of the ankle) was the motion of its two adjacent body segments about the mediolateral–lateral axis of the JCS, and adduction/abduction of the knee and hip (or inversion/eversion of the ankle) was the motion about the floating axis of the JCS.

The activation duration and magnitude of each muscle were determined based on the EMG profile. A muscle was considered being activated, or “ON”, when its EMG amplitude exceeded a predetermined threshold (i.e., the mean value plus eight times standard deviation of the EMG amplitude during the quiet stance trials). The “ON” status was first determined automatically by a computer program, and then confirmed manually by the operator. The magnitude of the muscle activation was represented by the root-mean-square (RMS, the square root of the average power of the EMG signal for a given period of time) value of the EMG signal, normalized by the averaged RMS value of the corresponding muscle EMG during the two quite stance trials immediately before and after the set of TCC trials.

The durations of concentric, eccentric, and isometric actions of each muscle were computed by combining its “ON” status and its length change status (i.e., lengthened, shortened, or no change) (Wu et al., 2004). The length change status of one joint muscles (i.e., TA, SO, PL and TFL) was determined by the direction of the movement of the corresponding joint. For example, when the ankle joint was dorsiflexing, the TA was shortened, and SO was lengthened. One the other hand, the length change status of two joint muscles (i.e., RF and SD) was determined by a weighted sum of the changes in the knee and hip joint angles (i.e., the velocity of knee and hip joint movement), as proposed by Visser et al. (1990). A joint movement was considered no change when its velocity was less than its maximum velocity during all quite stance trials.

Two-way repeated measures Analysis of Variance was used for statistical analysis, with subject treated as random, age (young and old) as the between subject variable and speed (fast, normal, and slow) as the within subject variable, and cycle time, stride length, postural height, duration and magnitude of muscle activation, and durations of isometric, concentric and eccentric actions as the dependent variables. Post-hoc analysis was conducted if significant age and speed interaction or significant speed effect was found. A P value of 0.05 or less was used for statistical significance.

3. Results

3.1. Temporal and spatial variables

The results showed significant speed effect ($P < 0.001$) and significant speed $\times$ age interaction ($P = 0.020$) in whole cycle time (see Fig. 2). The cycle time decreased with an increase in speed in both groups. Although the young group showed longer cycle time at slow and normal speed than the old group, no significant age effect was found ($P = 0.091$).

There was no significant speed effect and speed $\times$ age interaction ($P > 0.199$) but significant age effect ($P < 0.011$) in stride length and the lowest postural height during stance. The old group had significantly shorter stride length (0.92 ± 0.12 m) than the young (0.99 ± 0.07 m), and higher postural height (95.1 ± 2.3% stance height) than the young (89.9 ± 2.2% stance height).

3.2. Duration of muscle activation

There was significant speed effect in the absolute duration of muscle activation (ON time) of all muscles ($P < 0.039$) (see Fig. 3), with a shorter activation time at a faster speed. There was also significant age effect in four muscles (TA, RF, PL and SO) ($P < 0.050$), with a shorter duration in the old group than the young group. In addition, significant speed $\times$ age interaction was found in TA and RF muscles ($P < 0.010$).

During the selected TCC movement, each of the six muscles had all three types of actions (i.e., isometric, concentric and eccentric). Significant speed effect was found in isometric action duration in RF, TFL and SD ($P < 0.017$), concentric action duration in TA and TFL ($P < 0.008$), and eccentric action duration in TA, TFL and SO ($P < 0.018$) (see Fig. 4). In general, the faster the speed, the shorter the action duration. Comparing the two age groups, the old group had shorter durations than the young, with significant age effect in isometric action duration in RF and SD ($P < 0.050$), and concentric action duration in TA ($P < 0.050$). In addition, significant speed $\times$ age interaction was found in isometric action duration in RF and TFL ($P < 0.031$).

When normalized by the ON time of each muscle, significant speed effect was found in isometric action duration in RF and SD ($P < 0.027$), with a decrease in duration at a faster speed. Significant speed effect was also found in concentric and eccentric action durations in RF ($P < 0.031$). However, these durations increased with the speed (see Fig. 5). There was no significant speed $\times$ age interaction in all normalized muscle action durations, but significant age effect in isometric duration of SD ($P = 0.01$) with the old group shorter than the young.

3.3. Magnitude of muscle activation

There was no significant speed effect in four muscles (TA, PL, RF and TFL, $P > 0.170$). For the two posterior muscles (SO and SD), there was significant speed $\times$ age interaction and significant speed effect ($P < 0.032$). The young group showed significantly higher magnitude at a faster speed, and the old group showed less or lower magnitude than the young at a faster speed (see Fig. 6). There was also significant age effect in TA and PL ($P < 0.05$) with the old group showing significantly lower magnitude than the young group.
4. Discussions

The main objective of this study is to examine whether and how the speed of the selected TCC movement, "Part wild horse’s mane", affects leg muscle activities. For the first time, we have quantitatively demonstrated that the speed of TCC movement affects primarily the activation duration and type of action of these leg muscles. In general, all six leg muscles are activated significantly longer at slower speed than at faster speed, and the durations of isometric, concentric and eccentric actions are also longer at slower speed. The action of RF and SD muscles is primarily isometric at slower speed, and the action of RF increases significantly to concentric and eccentric at faster speed. Speed does not seem to affect significantly the activation magnitude in four of the six leg muscles, except for the two posterior leg muscles (i.e., SO and SD) whose magnitude increases with speed.

The magnitude of muscle activation is believed to be associated with the step length (Nilsson et al., 1985). It has been shown that

![Fig. 3](image1.png) Fig. 3. The mean and standard deviation of absolute activation durations of six muscles during stance phase at slow, normal and fast speed in young and old groups, respectively. Symbol * indicates significant speed effect, ^ significant age effect, and + significant speed × age interaction.

![Fig. 4](image2.png) Fig. 4. The mean and standard deviation of absolute activation durations of isometric (ISO), concentric (CON) and eccentric (ECC) actions of six muscles during stance phase at slow, normal and fast speed in both young and old groups. Symbol * indicates significant speed effect, ^ significant age effect, and + significant speed × age interaction.
the magnitude of leg muscle activity increases with the step length during walking and running (Nilsson et al., 1985; Yang and Winter, 1985). Although no data is available to directly support this relationship during TCC movements, our previous study comparing the spatial kinematics and muscle EMG patterns between the young and old subjects seems to suggest the similar association between step length and muscle EMG magnitude (Wu, 2008). Thus, in this study, we purposely controlled the step and stride length while varying the speed of the selected TCC movement. As a result, the stride length was not significantly different across the three speeds in both age groups. Therefore, the speed effect we observed in the EMG magnitude, especially in the posterior leg muscles, is not affected by stride length.

Similarly, the magnitude of muscle activation can also be associated with the postural height, which is one of the major determinants of TCC practice intensity. In this study, we have found that the old subjects have significantly higher postural height than the young subjects at all three speeds, suggesting that the old sub-

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**Fig. 5.** The mean and standard deviation of normalized activation durations of isometric (ISO), concentric (CON) and eccentric (ECC) actions of six muscles during stance phase at slow, normal and fast speed in both young and old groups. Symbol * indicates significant speed effect, and ^ significant age effect.

**Fig. 6.** The mean and standard deviation of normalized RMS value of muscle EMGs during the whole movement cycle at slow, normal and fast speed in the young and old groups. Symbol * indicates significant speed effect, ^ significant age effect, and + significant speed × age interaction.
jects' TCC practice is less rigorous. This may partially explain why the old subjects have lower EMG magnitude than the young subjects, especially in TA, and PL muscles. However, we have found no significant speed effect in postural height in both groups. Thus, we believe that the speed effect we observed in the EMG magnitude, especially in two posterior leg muscles (i.e., SO and SD), is not affected by postural height or TCC movement intensity.

The increase in the activation magnitude of the two posterior leg muscles at faster speed may be related to the increased demand in accelerating and decelerating limbs during the transitions between stance and swing (Yang and Winter, 1985). When moving at a faster speed, the transition time becomes shorter. By increasing the level of activation of the posterior muscles, they could generate sufficient amount of power to either push the stance leg off the ground or to decelerate the leg before landing. This strategy is consistent with the one found during walking and running (Ivanenko et al., 2006; Prilutsky and Gregor, 2001; Winter and Yack, 1987). It is also consistent with our findings that the SD muscle has significantly decreased isometric action duration at faster speed, and increased concentric and eccentric action durations with speed, especially in the young subjects, thus functioning more as a mover or decelerator, rather than a stabilizer.

One of the hallmarks of TCC exercise is that its movements are carried out slowly. Very often, the TCC practice emphasizes on slowing down the movement speed, which is rather difficult for beginners. Our findings suggest that at a slower speed, the leg muscles are activated longer and have more isometric activation than the concentric and eccentric activation, especially for the RF and SD muscles. It is perhaps the prolonged and precise control of muscle activation, not the magnitude of muscle activation, that makes the slow TCC movement more difficult than the faster movement.

The findings of the significantly longer duration of isometric action of the RF muscle at slower speed may be one of the keys to understanding the mechanism of TCC practice for improving balance and postural control. Knee extensors play a major role in maintaining upright balance, and in postural adjustment in the event of a fall. In a study aimed at identifying risk factors for falling among noninstitutionalized elderly persons, Robbins et al. have reported that knee extensors weakness is one of the primary factors strongly associated with falling (Robbins et al., 1989). In another study examining the isometric contractions of knee extensors in young and older people with and without a history of falls, Carville et al. have found that the isometric contraction of the elderly fallers is less steady than both the young and elderly non-fallers (Carville et al., 2007). They suggest that this decreased steadiness could be a cause of falls in older people. Thus, the prolonged isometric action of the knee extensors during slower TCC practice may improve their steadiness in force production and, in turn, contribute to the improvement of balance and prevention of falls. Consequently, slower TCC practice may be more effective in improving muscular control and postural balance than the faster TCC practice.

Our findings also suggest that the postural height during TCC movement does have an impact on the duration and magnitude of leg muscle activation, as evidenced by the differences between the young and old groups. However, practicing TCC at slower speed is still better than at faster speed in terms of muscular control even at a higher postural height. Thus, it is perhaps more important to emphasize on the speed rather than the postural height of the TCC movement for the older people.

The relationship between muscle activity and TCC speed may be affected by the experience with TCC. In this study, the older subjects have an average of 10 ± 13 months of practice experience, whereas the young subjects have an average of 13 ± 6 months of practice experience. It is suggested that an average of 12 months of practice is needed to master the TCC (Farrell et al., 1999). Thus, for beginners to do the TCC movement at a different speed, it is likely that their movement is not the ideal form. The results in this study are only based on one TCC movement, “Part wild horse’s mane”, and should not be generalized to the entire TCC sequence. Future studies that investigate the speed effect on muscle activities should expand to other TCC movements. Nevertheless, the leg motion in this study is used in approximately 64% of the movements in a simplified TCC form, and more than 55% in a complete Yang style TCC form (Shen and Gu, 1998). It is one of the most popular movements in TCC.

5. Conclusion

This study compared the muscle activity characteristics during the “Part wild horse’s mane” movement at slow, normal and fast speed by healthy young and old TCC practitioners. The results demonstrate significant speed effect in activation duration of leg muscles. The slower the TCC movement is, the longer the muscles are activated. The RF and SD muscle actions are primarily isometric at slower speed, functionally behaving as a stabilizer. In fast TCC action becomes more concentric and eccentric, functioning as an accelerator or decelerator. Thus, practicing TCC at different speed may alter the role of muscular function in movement control.

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