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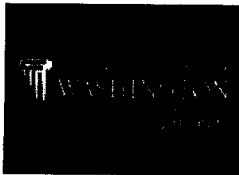
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# Neural mechanisms underlying balance improvement with short term Tai Chi training

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**ABSTRACT. Background and aims:** Though previous research has shown that Tai Chi reduces falls risk in older adults, no studies have examined underlying neural mechanisms responsible for balance improvement. We aimed to determine the efficacy of Tai Chi training in improving neuromuscular response characteristics underlying balance control in balance-impaired older adults. **Methods:** Twenty-two balance-impaired older adults were randomly divided into Tai Chi (TC) or control groups. Nineteen subjects (age 68-92, BERG 44 or less) completed the study. TC training included repetitive exercises using TC motor and biomechanical strategies, techniques, and postural elements. Control training included axial mobility exercises, balance/awareness education and stress reduction. Groups trained 1.5 hours/day, 5 days/week for 3 weeks. After post-testing the control group received TC training. Subjects walked across a force plate triggered to move forward 15 cm at 40 cm/sec at heel strike. Tibialis anterior (TA) and medial gastrocnemius (GA) responses during balance recovery were measured with electromyograms (EMGs). Four clinical measures of balance were also recorded. **Results:** TC subjects, but not controls, significantly reduced both TA response time from  $148.92 \pm 45.11$  ms to  $98.67 \pm 17.22$  ms ( $p \leq 0.004$ ) and occurrence of co-contraction of antagonist muscles ( $p \leq 0.003$ ) of the perturbed leg. Clinical balance measures also significantly improved after TC. **Conclusions:** TC enhanced neuromuscular responses controlling the ankle joint of the perturbed leg. Fast, accurate neuromuscular activation is crucial for efficacious response to slips or trips.

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## INTRODUCTION

One of the first reports investigating the effect of Tai Chi training on motor function in older adults was performed by Wolf et al. (1). Subjects practiced either static balance training (on a computerized platform), dynamic

balance training (Tai Chi) or participated in wellness discussions, with training sessions 1-2 times per week for 15 weeks. Wolf et al. found the risk ratio for falls was reduced to 0.63 in the Tai Chi group (significantly less than controls) but was not reduced in the static balance group compared to the wellness discussion group. Though this study is of interest in showing a reduced risk for falls in older adults as a result of Tai Chi training, it does not examine the factors contributing to the reduced risk.

Wolfson et al. (2) found that practicing Tai Chi for one hour a week for 6 months maintained significant strength and balance gains made during a previous balance and strength training program (three hours/week for 3 months). Balance was measured using stance tests that included sensory organization abilities, size of functional base of support, and single leg stance time. Researchers did not examine what neural mechanisms were influenced by Tai Chi training.

Yan (3) compared three types of training in nursing home residents. One group performed a twenty-four posture Tai Chi form, a second group walked, and a third group jogged. Training was 45 minutes, 3 times a week for 8 weeks. Only the Tai Chi trained group balanced significantly longer on a stabilometer platform after the training. Further research is needed to explain what mechanisms contributed to this improvement, and if more dynamic types of balance such as reactive balance control during gait would also show improvement.

A major factor contributing to falls is the inability to return a perturbed center of body mass to a stable base of support. Fifty percent of falls in elderly populations are thought to be due to unexpected and sudden motion of the base of support while ambulating, 35% are thought to be due to an external disturbance to the person's center of mass (COM), and 10% are attributed to dizziness, seizure, or ischemic attacks (4). This suggests that interventions, assessments and test measures using sudden motion of the base of support during walking can be used to study changes in balance control. This also implies that

**Key words:** Aging, dynamic balance, EMG, posture, Tai Chi.

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therapeutic interventions should include balance skill training that practices controlling a variety of spatial and temporal changes in the COM and base of support during a dynamic movement such as gait.

Previous research in our lab by Tang and Woollacott (5) examined neuromuscular mechanisms underlying age-related declines in reactive balance by perturbing young or healthy older subjects with a forward platform movement while they walked across a force plate. Postural responses were recorded using electromyograms (EMGs) placed on the tibialis anterior (TA) and medial gastrocnemius (GA). A simulated slip, similar to slipping on ice, was created by triggering the platform to slide 10 cm forward at 40 cm/s at heel strike. The study hypothesized older adults would use a less effective reactive balance strategy than young adults when experiencing an unexpected forward slip occurring at heel strike during walking. Results indicated that when compared to young adults, postural muscle responses of older adults were characterized by: 1) longer contraction onset time, 2) longer muscle burst durations and 3) increased co-activation of agonist and antagonist muscles.

We are taking Tai Chi research further by using a testing paradigm similar to Tang and Woollacott (5) in order to determine the effects of Tai Chi training on neuromuscular response characteristics underlying balance performance in balance-impaired older adults. Training effects due to Tai Chi will be compared to a similar intensity training using axial mobility exercises and balance education. We hypothesize that neural mechanisms contributing to improved reactive and proactive balance after Tai Chi training will include: 1) a shortening of time to postural muscle contraction onset in response to a perturbation, 2) improved muscle response organization and 3) reduced co-contraction of antagonist muscles during postural adjustments. Additionally, we hypothesize Tai Chi training will improve measures using Functional Reach, Timed Up and Go, One leg stance time, and Tandem stance time.

The short-term goal of our research is to increase the understanding of the contributions of neural mechanisms underlying balance improvement with Tai Chi training in balance impaired older adults. The long-term goals are to apply our research findings to the development of innovative, enjoyable, and efficacious clinical methods for treating balance impairments in balance-impaired populations both in community and workplace settings as balance enhancement or maintenance programs.

Our study differs from other Tai Chi studies in five ways. To date, Tai Chi interventions have not included balance-impaired older adults that have surgical interventions to their back, hips and knees. Since it is likely that any intervention for balance impaired older populations would include individuals with such surgeries, we did not exclude

these subjects. Second, previous Tai Chi studies have relied heavily on standing balance measures (1-3, 6, 7), whereas our study tests neuromuscular responses during a large/fast perturbation while walking. Third, Tai Chi research has not looked at differences in balance responses in the same subjects after two types of training (control and Tai Chi). Our control group received Tai Chi balance training after control training. This allowed us to examine differences in neuromuscular responses before and after two types of training in the same subjects. Fourth, previous Tai Chi research (1-3, 6, 7) focused on practicing Tai Chi postural sequences, whereas our intervention focused on Tai Chi principles (motor and biomechanical techniques and postural elements) used to control dynamic balance. These underlying elements (similar to an alphabet) were then gradually incorporated into a single Tai Chi form posture after they were initially taught separately. A total of 12 Tai Chi postures were used. Fifth, prior studies have not examined a short-term (3 weeks) intensified training that can fit within clinical settings.

## METHODS

### Clinical/behavioral measures

#### Clinical procedures

The clinical/behavioral outcome measures [Functional Reach (FR) (8), Timed Up and Go (TUG) (9), single right leg stance, single left leg stance, tandem stance right leg behind, and tandem stance left leg behind] were chosen because they represent commonly used clinical tests that assess the efficacy of balance skills in older adults (10), and they could be quantified. Tai Chi and control trained groups participated in identical test sessions before and after their training periods. Outcome measures assessed before each type of training established a pretest for post-training comparison.

Subjects were tested barefoot or in stocking feet. Each measurement task was demonstrated by the examiner until participants felt they clearly understood the task. Data were recorded from the first trial the subject was able to perform because our study focused on initial balance responses used to recover from a fall. The maximum time recorded for single and tandem stance tests was 30 seconds (2). Subjects whose score was at the maximum of 30 seconds were scored with the value of 30 seconds. If a subject scored 30 seconds at pre and post-training, their difference score was 0. Single stance time was tested on the right and left leg separately. Tandem stance was tested once with the right leg in front and once with the left leg in front. Using only 1 trial for TUG and FR measurements departs from normal testing procedures. However, this was done in order to have comparable responses on clinical and laboratory tests.

*Timed Up and Go (TUG).* Subjects stood up from a chair, walked 3 meters, turned around, returned and sat down. Subjects were directed to walk at a comfortable

speed as if they were walking outside. Performance was timed in seconds with a stopwatch. The test is related to functional capacity measured by the Barthel Index (11).

**Functional Reach (FR).** Subjects stood with feet shoulder-width apart and raised their right arm to 90 degrees in front. The distance they were able to lean forward without moving their feet was recorded in inches. FR examines the limits of stability in the forward direction (12) and is related to the range of motion in the axial spinal column. It is sensitive to change after exercise (13).

**Single Stance Time.** Single leg stance is considered one of the most challenging tests of stability because the whole body center of mass must be balanced on an extremely narrow base of support. Due to the challenging nature of this task, it has become the most frequently used measure of balance in studies involving balance-impaired older adults (14). Subjects were tested with eyes open. Subjects were instructed to stand on one leg and raise the other leg above the ground. The number of seconds the subject could maintain balance without touching the ground with the elevated foot or grabbing a support was recorded by a stop watch. The maximum time recorded was 30 seconds (2, 15).

**Tandem Stance Time.** Tandem stance is a bipedal variation of single stance. It requires standing unsupported with one foot placed so that the heel of the forward foot is in front of the toe of the back foot and both feet form a straight line. (2). The maximum time recorded was 30 seconds.

### Participants and recruitment

Screening was a two-stage process. First a phone interview was conducted to ascertain the ability of subjects to qualify for and participate in the testing and training required by the study. If they passed the phone interview, subjects were invited to the Motor Control lab for clinical and platform testing. Participation criteria included 1) age of 65 or older, 2) diagnosed as balance-impaired by their doctor or physical therapist, 3) Berg balance score of 45 or less (16), 4) no diagnosed central nervous system disorders and 5) able to stand without support. All subjects were cognitively able to follow instructions. Subjects with arthritis, back, knee, or hip surgery were not excluded from the study because these subjects were considered to represent the real world population that a balance intervention program would need to address. Subjects lived independently in the community and were able to drive or ride the bus to training and test sites. An "Informed Consent" form approved by the Committee for the Protection of Human Subjects/Institutional Review Board of the University of Oregon was signed by each participant. Work with human subjects conformed to the standards set by the Declaration of Helsinki.

Twenty-two balance-impaired older adults were randomly divided into Tai Chi or control groups. Nineteen

subjects age 68 to 92 years (mean 77.55) completed the study. The Tai Chi group consisted of 10 females and one male (n=11) and the control group consisted of seven females and one male (n=8). The control group initially had three additional female subjects. Two dropped out because they wanted to receive only Tai Chi training, and one was dropped because she declined to be tested on the moving platform. One of the controls (ID #14) did not complete the crossover training because of an out of state family emergency. Control and Tai Chi groups (Table 1) were similar in age ( $p=0.96$ ), height ( $p=0.63$ ), mass ( $p=0.30$ ), and impairment (arthritis,  $p=0.15$ , spinal surgery  $p=0.41$ , knee surgery  $p=0.75$ , hip replacement  $p=0.17$ , Berg  $p=0.96$ , Timed Up and Go (TUG)  $p=0.79$ , Functional Reach (FR)  $p=0.57$ ). Subjects' Berg balance scores ranged from 44 to 24. The Berg balance test was highly specific (96%) in identifying non-fallers from fallers, in that persons scoring 45 or above have a high probability of not falling. The Berg balance test was less sensitive (53%) to directly identify people who fall, in part due to those subjects with the lowest scores minimizing their fall risk by the use of assistive devices. However, overall results supported the use of 45 as a generalized cut-off score (16). Functional Reach scores ranged from 13 to 4.5 inches (0.330 to 0.114 m). Only 4 of 19 subjects were able to reach beyond 10 inches (0.254 m) at baseline and were within norms for their age and sex (8). None of the subjects' baseline TUG scores (18.47-10.04 sec) were within range for independent balance (i.e. <10 seconds), and all were within range for independent balance transfers (<20 seconds) (9).

### Intervention protocol

Participants received training for 1.5 hours/day, 5 days/week for 3 weeks (total 21 hrs) in local community centers. The original schedule was based on 15 training days, but the last day for the first group was July 4. Therefore, all training was shortened by one day (1.5 hrs) so groups would receive the same amount of training time. All groups received a similar amount of exercise time and discussion time. Participants were not trained on any outcome measure to prevent a specificity of training confound. Pretesting for each group took place during the week before training. Post-testing took place the week after training. Thus, the average time between trials was 4 weeks.

### Tai Chi training

Our training techniques do not differ from traditional Tai Chi training, but do differ from previous reports of interventions. Traditional methods first practice well coordinated sequencing of changes (flow) within a standing posture. Studying the form means learning to coordinate several Tai Chi principles (center of mass control, segmental positioning, muscle force control, flowing oscil-

Table 1 - Demographics of the groups.

	Gender	Age	Ht (cm)	Mass (Kg)	Berg	TUG (sec)	FR (in)
<b>Tai Chi</b>							
ID # 1	f	75.0	165.0	69.5	42.0	13.79	8.0
2	f	68.0	164.0	75.2	30.0	10.04	9.5
3	f	75.0	162.0	94.0	24.0	13.03	10.0
4	f	92.0	169.0	61.5	41.0	15.66	13.0
5	f	81.0	156.0	66.0	41.0	12.55	10.0
6	f	82.0	167.0	71.0	38.0	14.69	6.0
7	f	76.0	164.0	70.5	41.0	11.30	9.0
8	m	71.0	165.0	66.0	42.0	11.70	11.0
9	f	86.0	149.5	61.0	33.0	18.31	6.0
10	f	73.0	156.0	71.5	40.0	10.09	9.0
11	f	75.0	162.0	63.5	42.0	12.58	8.0
Mean		77.6	161.8	70.0	37.6	13.07	9.05
SD		7.0	5.7	9.1	6.02	2.47	2.05
<b>Control</b>							
ID # 12	f	68.0	170.00	75.5	40.0	12.27	9.00
13	f	80.0	160.00	80.0	36.0	12.80	6.00
14	f	82.0	163.00	58.0	41.0	10.06	6.25
15	f	81.0	159.00	69.5	44.0	12.62	10.50
16	f	85.0	164.00	69.0	28.0	18.47	4.50
17	m	75.0	179.00	98.0	44.0	12.05	6.50
18	f	73.0	149.00	67.0	39.0	13.00	12.00
19	f	76.0	164.00	88.5	28.0	15.85	12.00
Mean		77.5	163.5	75.7	37.5	13.39	8.34
SD		5.5	8.70	12.8	6.41	2.59	2.92

Tai Chi (Group 1) and Control (Group 2a and 2b) were similar in age ( $p=0.96$ ), height ( $p=0.63$ ), mass ( $p=0.30$ ), and impairment (arthritis  $p=0.15$ , surgery to spine  $p=0.41$ , knee  $p=0.75$ , or hip  $p=0.17$ ), Berg ( $p=0.96$ ), TUG ( $p=0.79$ ), FR ( $p=0.57$ ). TUG: Timed Up and Go; FR: Functional Reach.

lation and dynamic balance) during changes in the configuration of the base of support. Standing exercises first practice controlling each principle. Then exercises gradually combine two principles and so on, so that a growing number of Tai Chi principles are incorporated within a single exercise/posture. Later a full Tai Chi posture is practiced while standing. Then walking postures are added. Each posture and gesture is carefully practiced individually so the students can seek to correct their mistakes and gain the benefit of the practice. Lastly, students would learn how to link each of the postures into a sequence (17).

Simplified Tai Chi exercises and repetition of single Tai Chi postures were performed with flexed joints in a slow, smooth, continuous rhythmical flow while attending to the following: 1) accuracy of multi-joint trajectories, 2) whole body geometry, 3) a vertical position of the head and trunk during weight transfer and single limb support, 4) continuous support of the center of mass while practicing multiple configurations of the base of support, 5) accurate positioning of the legs and feet, and 6) bilateral movements along eight directions.

Each postural exercise was first demonstrated by Dr. Gatts (Dr. Gatts was trained in Tai Chi full time for 9 years with a Chinese master and has taught Tai Chi for 22 years). Demonstration was followed by a detailed verbal explanation that described how the exercise benefits the motor control and biomechanical elements involved in balancing, and how the Tai Chi movements can be used to increase awareness of fall onset. How to incorporate the exercises into recovery strategies to prevent future falls was demonstrated and discussed.

Examples of the Tai Chi program: Twelve Classical Tai Chi postures were used. Each posture was taught on one side, and later practiced as a mirror image on the opposite side and repeated on both sides for 10-15 cycles. We used the following 12 postures: Commencement, White Stork Cools its Wing, Brush Knee, Play the Guitar/Play the Harp, Repulse the Monkey, Heel Kick, Toe Kick, Golden Cockerel, Fair Lady Works the Shuttles, Part the Wild Horses' Mane, Cloud Hands, Cross Hands. A chapter listing the health benefits of each posture may be found in Tai Chi Chuan: The 27 Forms (18).

### *Control group training*

Control group balance training incorporated elements theoretically similar to Tai Chi training. Control training included the following components: balance education, awareness education, stress reduction, deep breathing, and axial mobility exercise. Balance education included information and discussion about environmental and home safety and the interaction of factors contributing to falls (14, 19, 20). Awareness education included information on age-related changes in sensory, neuromuscular, biomechanical and cognitive systems and how these changes contribute to decreased balance control, including the ability to attend to multiple factors while balancing or walking. Discussion of techniques and strategies to increase sensory awareness of fall onset, factors contributing to falls or near falls, useful recovery strategies, and what could be done to prevent falls in the future were also covered (14, 15, 21, 22). Exercise, deep breathing, stress reduction, and tension control components used the Axial Mobility exercise program (23) and the Guide to fitness after fifty (24). The Axial Mobility exercises were chosen because they were designed to improve postural alignment, increase range of motion, coordinate relaxed movement as opposed to effort, relax tight muscles using deep breathing, use muscle groups with appropriate mechanical advantage, and enhance participation of appropriate synergistic muscles used in activities of daily living. The control group received Tai Chi training after post-control training testing.

Examples of Axial Mobility Program exercises include: forward and backward weight shifts, practiced while using the pelvis to initiate and control the weight shifts, lateral trunk flexion, relaxed trunk and lower extremity rotation, isolated lower trunk rotation, isolated upper trunk rotation, lateral pelvic tilt in standing, coordinated trunk and upper extremity movement in an unsupported sitting position, segmental motion of the spine and pelvis on all fours (cat and camel poses, isolated flexion and extension of the lumbar region, forward and backward rocking in the sagittal and diagonal plane) (23).

### **Lab tests**

#### *Lab procedures*

Tai Chi and control groups participated in identical test sessions before and after training periods. Subjects were also tested barefoot or in stocking feet for the lab measures. Previous research has shown that adaptations in balance responses to platform perturbations can occur by the third trial (21). In order to reduce the likelihood of repeated exposure influencing the automatic response measures and confounding the results due to conditioned motor learning, we had the subject perform only two perturbed normal walking trials. We analyzed muscle responses from the first perturbation trial. Berger et al. (25) have shown that EMG responses are unaltered by pre-

warning or random onset of the perturbation. Therefore, this frail subject population was told that the plate would move quickly forward 15 cm at right heel strike. Instructions were given to walk at self-selected speed from a designated starting point determined during walking practice (without perturbation) in order to have the right heel fully contact the center of the force plate. Subjects practiced the walk until they could consistently step onto the center of the forceplate.

### *Perturbation apparatus*

The simulated slip was given while subjects walked across a custom built force platform consisting of two separate metal platforms (1.84 m long x 0.51 m wide x 0.35 m high) incorporated into the center of a 10 m long x 1.10 m wide x 0.35 m high wooden walkway. A moveable force plate (0.61 m long x 0.17 m wide) was placed in the center of each platform. A 15 cm forward translation of the right plate at 40 cm/sec was triggered by a right heel strike while the left plate did not move. This velocity was chosen because it matched reported horizontal heel velocities on slippery surfaces during realistic slips (26). Platform movements were triggered by a PC via a D-A converter. Analog data (EMG and force platform data) were collected with a data acquisition system (AMLAB, Australia).

Each forceplate contained four strain gauges that measured vertical ( $F_z$ ), horizontal mediolateral ( $F_y$ ) and antero-posterior ( $F_x$ ) ground reaction forces. A feedback circuit used a 40 Newton  $F_z$  force signal to trigger a right plate forward translation at the subject's right heel strike. This setup prevented a false trigger of the plate, but did result in a 20-40 ms delay between the heel strike and the onset of the plate movement due to the mechanical delay in the circuit. All data were therefore analyzed from the time of the onset of actual plate movement. An overhead suspension cable was attached to a body harness worn by the subject to ensure their safety.

### *Electromyographic (EMG) data*

Neuromuscular responses during perturbed walking were recorded by EMG surface electrodes MA-300 from Motion Lab Systems, Inc (Baton Rouge, LA). EMGs were placed on the right tibialis anterior (TA) and right medial gastrocnemius (GA). The area of placement of the electrode was first cleaned with alcohol. A small amount of hypoallergenic conducting gel was then placed on the skin and rubbed off prior to application of the EMG. The EMG was secured to the muscle with pre-wrap bandages. This process insured good contact with the muscle. The ground was placed on the ulna head of the wrist. The electrode output went to a preamp/power supply that attached to a vest worn by the subject. Common-Mode Rejection Ratio (CMRR) was  $>100$  dB at 40 HZ. The EMG signal output level was  $\pm 5$  Volts Full Scale. All

raw analog EMG signals were on-line preamplified (gain 4000) and analog filtered (20-2000 HZ) and then converted into digital signals sampled at 1200 HZ for 6 seconds duration per trial. The built-in low pass analog filter was set at 600 HZ.

Further data processing took place using custom written programs in MATLAB (The MathWorks, Mass). Prior to data analysis EMG signals were full-wave rectified and low pass filtered using a fourth order dual-pass Butterworth filter. Cutoff frequency was 50 HZ. The plate onset time for each trial was determined as the time the plate registered 3 standard deviations (SD) above its baseline stationary position. Baseline muscle activity was calculated for each muscle for each trial by averaging its summed activity for 500 ms before plate onset. EMG activity was calculated and graphed for 50 ms before plate onset to 1800 ms after plate onset. Comparison of EMG activity in each muscle for the first perturbed trial was made to investigate pre and post-training differences in: 1) onset latency, 2) muscle burst duration, 3) co-contraction of the agonist/antagonist, 4) reversed activation (GA onset preceded TA onset), and 5) percent duration (to account for differences in walking speed).

Muscle onset latency was defined as the time between plate onset and the time at which muscle activity increased 2 SD above baseline activity. Muscle duration was defined as the time between muscle onset and offset, with offset defined as the time at which muscle activity fell below 2 SD for longer than 30 ms. Co-contraction was defined as the time the TA and GA were simultaneously active longer than 10 ms during burst duration. Reversed activation was defined as a trial during which GA onset preceded TA onset. Percent duration was defined as the percent of time a muscle was active while the right foot remained on the plate.

### Statistical analysis

#### Study design

The study design is a pretest post-test design with a treatment group and control group which then receives the treatment. This experimental design was chosen in order to examine pretest and post-training changes in clinical/behavioral measures and perturbation balance responses, 1) in different subjects given Tai Chi or control training, 2) in the same subjects given two types of training (control and Tai Chi), 3) to see if the two Tai Chi trained groups would show similar trends in their performance measures, and 4) to find out in which measures those trends would be most apparent.

#### Clinical data analysis

PROC MIXED from SAS statistical software was used to run a linear model which accounts for the inclusion of a within-subjects factor (control and treatment) and the unequal group sizes. To determine if the Tai Chi or control

interventions resulted in significant changes from pretest to post-test, a one way analysis of covariance (ANCOVA) evaluated each measure individually. The categorical variable "group" was the main effect of interest (containing 3 levels: Tai Chi only= group 1, control= group 2a, Tai Chi after control training= group 2b). The dependent variable was the observed differences from pretest to post-test from each subject for all measures. The model used pretest scores as the covariate to control for subject differences at pretest. The post-test control group training scores functioned as the pre Tai Chi training pretest for group 2b.

A key assumption allowing us to use ANCOVA was that pretest baseline values were distributed equally across groups (Group 1 vs Group 2a). A repeated measures approach assumes that the expected differences between pretest and post-test scores of individuals within each group will be the same and in the same direction (treatment effect). That is, the differences do not depend on the pretest value. The ANCOVA approach allows for the possibility that the observed differences may depend upon the pretest value. If the differences do not depend on the pretest value, this is exactly the same as a repeated measures ANOVA. If the covariate (pretest value) is significant, then the post-test value depends upon the pretest value, and the ANCOVA becomes a more powerful test. ANCOVA increases statistical power by accounting for pretreatment group differences and reduces Type II error rate. (27).

A global *F* test for each measure was first examined to see whether the population means, adjusted by the pretest value, differed significantly across groups. If this *F* test was significant for a measure, follow-up tests using differences in least squares means were done using 3 pairwise comparisons to determine which differences among the three groups were non-zero. Significance levels were set at 0.05.

#### Lab data analysis

SAS statistical software was used to run a *t*-test with PROC MEANS to examine each measure one at a time. The results were then compared with non-parametric tests from PROC UNIVARIATE. The dependent variables were 1) EMG contraction onset time for tibialis anterior (TA) (agonist) muscle, used to regain forward walking momentum after the slip, and the gastrocnemius (GA) (antagonist) muscle, 2) occurrence of co-contraction of agonist and antagonist muscles (determined by 10 msec or more overlap of the muscle bursts), 3) efficiency of muscle response organization (determined by number of trials the TA (agonist) was activated prior to the GA (antagonist). Since we used only the first trial, this measure also indicated the number of subjects in each group showing reversed muscle response.

We hypothesized that after Tai Chi training TA onset would be faster and co-contraction and reversed activation (GA onset before TA onset) would decrease. Since our hy-

Table 2 - Main effects of training on clinical/behavioral measures\*.

Measure	TC			Control					
	Group 1			Group 2a			Group 2b (TC)		
	Mean	SE	p	Mean	SE	p	Mean	SE	p
Timed Up & Go (sec)	3.53	0.49	0.0001	0.08	0.57	0.8949	3.02	0.62	0.0001
Functional Reach (in)	3.31	0.63	0.0001	2.90	0.77	0.0011	4.22	0.93	0.0002
Stand on Right leg (sec)	13.06	3.25	0.0007	0.19	3.65	0.9583	9.65	4.00	0.0260
Stand on Left leg (sec)	12.58	2.41	0.0001	0.30	2.63	0.9101	4.11	2.83	0.1644
Tandem Stance R Leg Behind (sec)	12.79	3.00	0.0004	0.004	3.44	0.9991	8.20	3.85	0.0452
Tandem Stance L Leg Behind (sec)	12.81	3.00	0.0003	2.27	3.42	0.5133	9.84	3.85	0.0182

\*Least square means from ANCOVA model with main effects for group. Mean and standard error are based on the pre-post difference scores; p-value for main effect  $\leq 0.05$ . SE: standard error.

potheses were directional it was appropriate to use one-tailed tests for significance ( $\alpha=0.05$ ). Pretest EMG data for ID# 11 was lost due to equipment error, thus, EMG analysis for Group 1 used  $n=10$ . Tai Chi and control groups did not differ significantly from each other before training on TA onset ( $p=0.340$ ), TA duration ( $p=0.094$ , GA onset ( $p=0.420$ ), GA duration ( $p=0.237$ ), co-contraction ( $p=0.132$ ), and reversed activation ( $p=0.212$ ).

The dependent variable EMG onset was measured on a continuous scale collected before and after each type of training. Our Repeated Measures Factorial Design included one within-subjects factor (training effect as measured by testing times) and one between-subjects factor (training group: Tai Chi vs Control training). The within-subjects effect of training (pairwise comparisons of testing time: pre-post control, pre-post Tai Chi) on the dependent variables, and the between-subjects effect training group (Tai Chi, control training) were investigated.

Response organization and occurrence of co-contraction were discrete random variables measured with two outcomes: correct (agonist contracts before antagonist muscle, 10 msec or less overlap of the TA and GA muscle bursts) / incorrect (antagonist contracts before agonist, 11 msec or more overlap of the TA and GA muscle bursts). The design for this analysis was a Repeated Measures Factorial Design including one within-subjects factor (3 training test periods) and one between-subjects factor (training group). Taking into account the correlated structure of the response collected across test periods for each subject, logistic regression coefficients were computed to estimate the odds of a correct response in each group and then to compare the odds ratio of the treatment group with the control group. PROC GENMOD of SAS was used for estimating a repeated measures model with categorical data, as it allowed choosing an appropriate covariance structure. We chose to run an Exact Pearson Chi-Square Test designed for tables with small cell

counts to examine the effect of time and an Exact Logistic Regression Test for the effect of training.

Muscle activity was normalized for possible differences in walking velocity at pre-test and post training. We used the formula: TA or GA duration / msec foot remains on the plate = % of time is muscle active. For example: TA is active for 100 ms / foot on plate for 300 ms = 33%. This means that the TA muscle is active for 33% of the time that the foot is on the plate (shown as % duration Table 3).

## RESULTS

### Clinical/behavioral results

Table 2 shows the main effects of training on each of the outcome measures. Means and standard error are shown in seconds (except Functional Reach shown as inches) using the difference scores. Group 1 is the Tai Chi only group, Group 2 is the control/crossover group (Group 2a= control training, Group 2b= Tai Chi training). Tai chi trained groups showed significant improvement on most balance measures: FR ( $p\leq 0.0001$  and  $0.0002$ ), TUG ( $p\leq 0.0001$  and  $0.0001$ ), right leg stance ( $p\leq 0.0007$  and  $0.0260$ ), left leg stance ( $p\leq 0.0001$  and  $0.1644$ ), tandem right leg behind ( $p\leq 0.0004$  and  $0.0452$ ), tandem left leg behind ( $p\leq 0.0003$  and  $0.0182$ ). The control group showed significant improvement on one measure, Functional Reach ( $p\leq 0.0011$ ) but no improvement on TUG ( $p\leq 0.8949$ ), right leg stance ( $p\leq 0.9583$ ), left leg stance ( $p\leq 0.9101$ ), tandem right ( $p\leq 0.9991$ ), and tandem left ( $p\leq 0.5133$ ).

Both Tai Chi (3.31 in, 0.084 m) and control (2.90 in, 0.074 m) training increased Functional Reach distance. However, after Tai Chi, the distance control subjects were able to lean was significantly increased (4.22 in, 0.107 m). Time taken to complete the TUG was reduced for Tai Chi (group 1= 3.53 sec) compared to hardly any change for the controls (group 2a=0.08 sec). After the controls completed the Tai Chi training,

Table 3 - Main effects of training on TA and GA measures\*.

Measure	TC			Control					
	Group 1		p≤	Group 2a		p≤	Group 2b (TC)		
	Mean	SD		Mean	SD		Mean	SD	p≤
TA onset 1 (ms)	148.92	45.11		136.42	73.21		104.98	25.58	
TA onset 2 (ms)	98.67	17.22	0.004*	104.15	23.8	0.138	87.62	10.19	0.028*
TA duration 1 (ms)	158.95	105.60		223.27	92.61		158.33	82.15	
TA duration 2 (ms)	161.50	63.70	0.473	165.52	78.73	0.099	144.76	65.45	0.400
% TA duration 1†	15	12		20.00	9.00		18.00	8.00	
% TA duration 2†	17	7	0.298	19.00	8.00	0.426	17.00	9.00	0.451
GA onset 1 (ms)	349.49	168.90		328.75	242.99		238.81	87.52	
GA onset 2 (ms)	316.93	66.43	0.310	242.81	81.81	0.173	380.95	119.74	0.025*
GA duration 1 (ms)	246.97	120.50		325.88	278.74		242.86	253.2	
GA duration 2 (ms)	88.93	68.55	0.002*	223.23	240.9	0.060	166.90	126.19	0.250
% GA duration 1†	22	14%		27	22		27	25	
% GA duration 2†	10	8%	0.012*	25	24	0.340	21	17	0.300
% Subjects Reversed 1†	33			50			14.30		
% Subjects Reversed 2†	0		0.105	12.5		0.128	0		0.500
Co-contraction 1 (ms)	60.33	80.15		119.90	123.58		60.81	113.52	
Co-contraction 2 (ms)	0.50	1.58		58.63	105.28		0.00	0.00	
% Subj. Co-contraction 1†	50			63			43		
% Subj. Co-contraction 2†	0		0.016*	50		0.192	0		0.096

\*Paired-sample *t*-tests, one-tailed,  $p \leq 0.05$ . 1 designates pretest and 2 designates post test. TA= tibialis anterior, GA= gastrocnemius. †: a) % TA or GA duration indicates normalized muscle activity as a percent of time the muscle is active while the foot remains on the plate to account for possible differences in walking velocity; b) % of Subjects with Reversed activation and % Subjects with Co-contraction used an odds ratio to compare odds of the event occurring at time1: time2.

their TUG score decreased (group 2b=3.02 sec). Other behavioral measures show a similar training effect. Single right leg stance time increased after Tai Chi (group 1=13.06 sec) compared to controls (group 2a=0.19 sec). After Tai Chi controls were able to balance longer (group 2b=9.65). Single left leg stance time increased most in Tai Chi group 1 (12.58 sec). The controls showed little improvement (0.30 sec), although after Tai Chi they increased their stance time (4.11 sec). Cutoff time was 30 seconds. Tandem stance right leg behind time increased after Tai Chi (group 1=12.79 sec), showed hardly any difference after control training (group 2a=0.0004 sec), then increased after the controls received Tai Chi (group 2b=8.20 sec). Tandem stance left leg behind increased after Tai Chi (group 1=12.81 sec), control (group 2a=2.27 sec), and further improved after Tai Chi (group 2b=9.84 sec). Cutoff time was 30 seconds. Subjects testing at the maximum cutoff of 30 seconds were scored with the value of 30 seconds. If a subject scored 30 seconds at pre and post training, their difference score was 0.

*Neuromuscular results*

Table 3 shows the main effects of training on each of the neuromuscular measures. Muscle onset, duration, and co-contraction means and standard deviations are

shown in milliseconds. The number 1 designates pretest and 2 designates post-training for each measure.

Both Tai Chi trained groups significantly reduced their TA onset times (group 1 by 50.25 ms,  $p \leq 0.004$ ; group 2b by 17.36 ms,  $p \leq 0.028$ ). Although the control group 2a reduced TA onset by 32.27 ms it was not significant ( $p \leq 0.138$ ); see Figure 1A. TA muscle burst duration showed no significant change after training in any of the groups (group 1  $p \leq 0.473$ , group 2a  $p \leq 0.099$ , group 2b  $p \leq 0.400$ ). GA onset did not change significantly in group 1 ( $p \leq 0.310$ ) or group 2a ( $p \leq 0.173$ ), but did change significantly in group 2b ( $p \leq 0.025$ ). This was primarily due to two subjects who took 282 ms and 295 ms longer to activate their GA after Tai Chi training. GA muscle burst duration decreased significantly in group 1 (158.04 ms,  $p \leq 0.002$ ). Control group 2a approached significant reduction (102.65 ms,  $p \leq 0.060$ ), and after Tai Chi training (group 2b) they further reduced their GA duration by 75.96 ms, though this was not significant ( $p \leq 0.250$ ). Adding these two times together we have a total reduction in the crossover group's GA burst duration of 178.61 ms. The lack of significance in group 2b may be due to a threshold in the amount of reduction possible relative to the task.

Percent of group showing reversed activation also represents the percent of subjects or trials in each

group showing reversed activation, since we analyzed only one trial for each subject. Both Tai Chi and control training improved muscle organization shown by activating the TA before the GA. This sequencing is a functionally appropriate response used to reposition the lagging center of mass over the advancing right stance leg that has been moved quickly forward by the accel-

eration of the platform. The effect of time showed that group 1 reduced the number of reversals from 33 to 0%, group 2a from 50 to 12.5%, and group 2b from 14.3 to 0% (Fig. 1B), although none were significant (group 1  $p \leq 0.105$ , 2a  $p \leq 0.128$ , 2b  $p \leq 0.500$ ). The effect of training showed that odds of occurrence of reversed activation after training was almost equal in both groups: 6.23 times less after Tai Chi ( $p \leq 0.103$ ) and 6.16 times less after control ( $p \leq 0.282$ ). This implies that both exercise programs were very similar in decreasing the occurrence of reversed activation.

The effect of time on co-contraction during postural adjustments was reduced in group 1 from 50 to 0%, group 2a from 63 to 50%, and group 2b from 43 to 0% (Fig. 1C). Only group 1 showed significance (group 1  $p \leq 0.016$ , 2a  $p \leq 0.192$ , 2b  $p \leq 0.096$ ). The effect of training showed that the odds of occurrence of co-contraction was 18 times less after Tai Chi compared to 1.6 times less after control training (Tai Chi 18:1,  $p \leq 0.003$ , control 1.6:1,  $p \leq 0.10$ ). Thus, Tai Chi was highly effective in reducing the co-activation of TA and GA muscles during a large/fast perturbation while walking in these balance-impaired older subjects. Since co-activation reflects increased expenditure of energy used to regain balance and slows down restoration of joint/segment angular trajectories used to maintain the gait cycle (5), balance responses would likely be faster and cause less tripping if this response were eliminated.

Figure 2A-B shows raw EMG data from a single subject in group 1 relative to platform onset which is indicated by a vertical line. Figure 2A illustrates several muscular activation problems at pretest in an 86 year old subject who had fallen 3 times and could not get up. The GA is activated before the TA muscle, indicating a reversed activation which tends to pull the center of mass further backward. Also, both muscles are co-activated for the entire period the plate is moving. This caused a disruption in the gait cycle causing the subject to drop the left swing leg to the ground to prevent a backward fall. Post Tai Chi training (Fig. 2B) shows improved muscle activation characteristics associated with a smooth recovery (no drop of the swing leg to the ground). The TA is activated before the GA and there is no coactivation. Muscle bursts are clearly defined and maintain the on/off coordination of a healthy gait cycle.

Percent duration measure indicates the percent of time a muscle was active from heelstrike to toeoff. We used this measure to indicate possible changes in walking velocity. No significant differences were found for % TA duration (group 1  $p \leq 0.298$ , group 2a  $p \leq 0.426$ , group 2b  $p \leq 0.451$ ). Percent GA duration was not significantly different in the crossover group (group 2a  $p \leq 0.340$ , group 2b  $p \leq 0.300$ ). Group 1 percent GA duration was significantly ( $p \leq 0.012$ ) reduced after Tai Chi. This change was probably linked to the significant reduction in the length

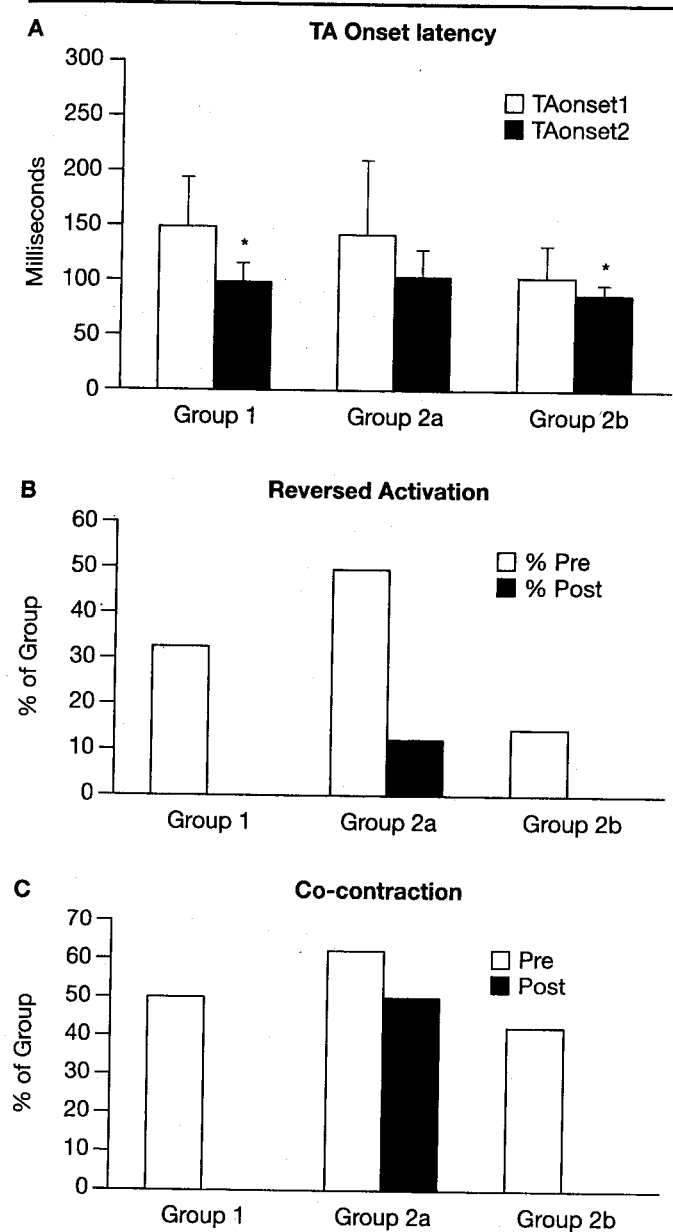


Fig. 1 - Group 1 received Tai Chi (TC) only. The control group first received control training (2a). After post-control training testing they then received TC (2b). A) Tibialis anterior onset latency is shown for each group. Onset 1 indicates before the intervention and onset 2 is after the intervention. B and C) Pre is before the intervention and post is after the intervention. Groups 1 and 2b do not have a post bar because they eliminated reversed activation (i.e. GA onset before TA) and co-contraction.

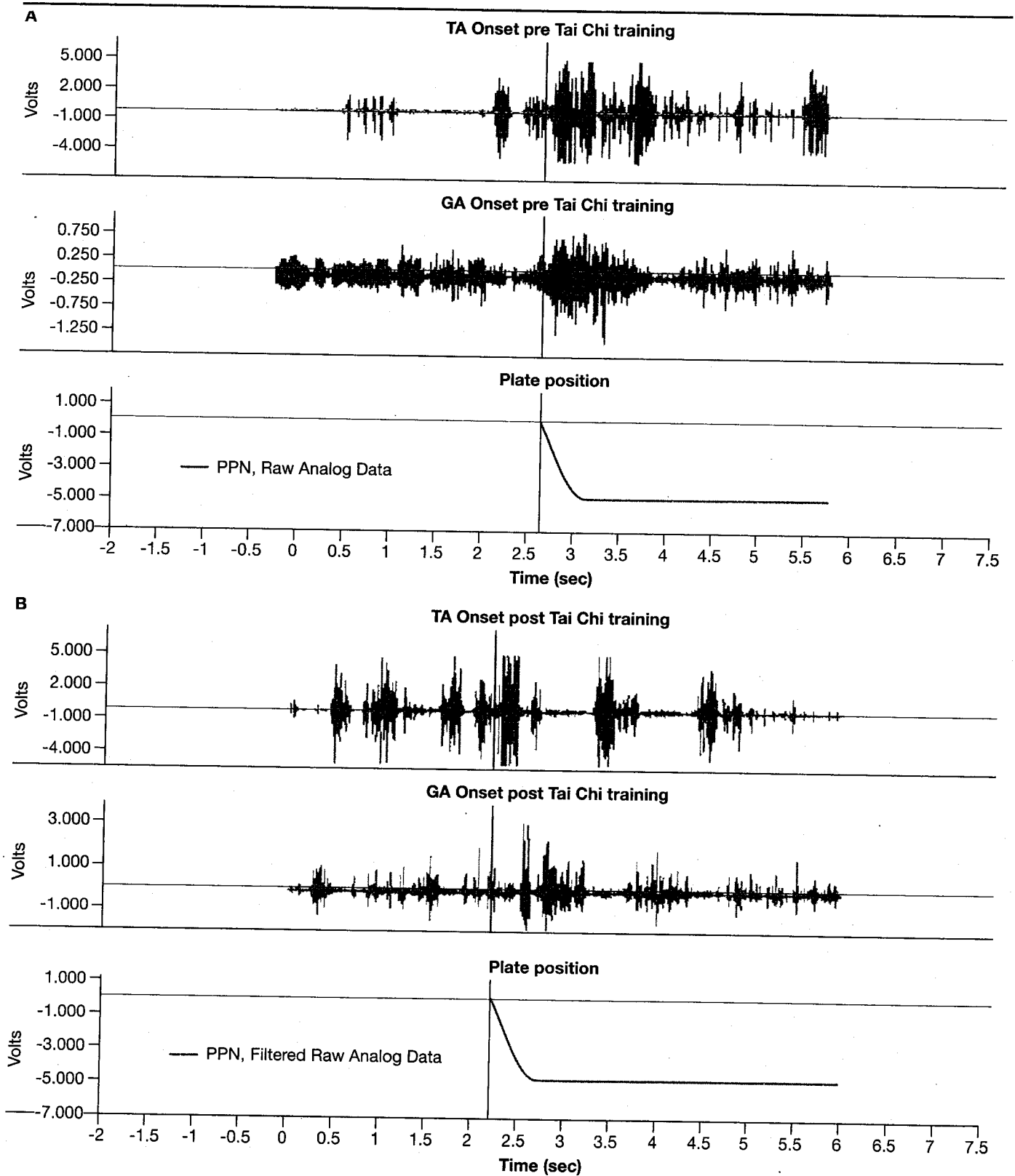


Fig. 2 - Raw EMG data from a single subject in Group 1. Plate onset is indicated by the vertical line. A) Muscular activation problems are shown by the GA onset occurring before the TA onset and both muscles are co-contracting the entire time the plate is moving. This caused the subject to drop the swing leg to the ground to prevent a fall. B) After Tai Chi (TC) training muscle characteristics improve. TA onset occurs before the GA and co-contraction is eliminated. Muscles bursts are clearly defined and maintain the on/off coordination of a healthy gait cycle.

of GA muscle burst ( $p \leq 0.002$ ) and a robust decrease in the likelihood of a co-contraction (18:1).

## DISCUSSION

Previous research that has investigated the effect of Tai Chi training on balance has found that after training there is a lengthening of time to the first fall, maintenance of balance improvements acquired by other balance training, and improvement on standing measures of balance (1-3). However, these studies did not examine what mechanisms contributed to this improvement, and if reactive balance control during gait (dynamic balance) would also improve. Prior research in our lab found that older adults showed difficulty maintaining an upright posture and normal gait cycle during recovery from a slip due to delayed distal muscle activation and high rates of co-contraction (5). These responses resulted in a decreased ability to maintain the momentum of forward progression while modulating their posture to retain balance control. In the current study we investigated the neural mechanisms that contribute to improved balance after Tai Chi training, examining differences in neuromuscular mechanisms controlling the ankle joint of the perturbed leg during large/fast forward movement of the base of support during walking. We also used four clinical/behavioral measures of balance efficacy in order to see if similar trends existed between clinical and laboratory measures of balance improvement.

Single leg stance time, tandem stance time, Functional Reach (FR) and the Timed Up and Go (TUG) tests are clinical measures used to test balance during reaching forward, standing up, sitting down, standing on one leg, tandem stance, and walking. These tests have been shown to correlate with functional mobility (28, 10). Our results demonstrated significant improvements on all clinical/behavioral measures in Tai Chi group 1 and significant improvements on five of the six measures in the crossover Tai Chi group 2b. Control group 2a changed significantly only on the FR measure, and after Tai Chi they made further significant improvement in the distance they could reach.

Our EMG results showed that neuromuscular mechanisms underlying balance control exhibited a similar trend to that of the clinical measures. After Tai Chi training TA onset time and co-contraction were both significantly reduced. This supported our original hypothesis. None of the groups significantly reduced TA duration. Control trained groups showed no significant change in TA onset time and little change in co-contraction rates. Both Tai Chi and control training were very similar in their ability to reduce the occurrence of reversed activation.

Previous research on muscle response onsets in healthy and balance impaired older adults show similar differences in latency (balance impaired vs healthy) to the improve-

ments (pre vs post training) we found in our own study (29). The only difference was that the improvements in the balance-impaired subjects in our study were larger. Thus, older adults who have functional balance problems have slower onset latencies and functionally well-balanced older adults show latencies within our range from pre to post-training.

Results indicate that Tai Chi training enhanced reactive postural responses, and developed more efficacious use of neural mechanisms controlling the ankle joint of the perturbed leg. These responses may represent a polysynaptic spinal or brainstem reflex loop crucial for controlling balance responses to slips or trips because they have been shown to be activated within 70-90 ms of perturbation onset in healthy young adults. This is faster than vestibular or visually mediated responses, and these responses can be modified by training and experience (5, 25, 30). Berger et al. (25) suggested that the early part of the stumbling EMG responses in leg muscles represent complex reactions generated in a spinal pathway by group II and III afferents and controlled by supraspinal centers.

Fast, accurate, and flexible neuromuscular activation is crucial for efficacious responses to the quickly changing dynamics involved in slips or trips. The TA must contract as soon as possible in response to a forward slip of the advancing foot so as to pull the lagging center of mass over the stance foot. If a reversed activation happens the GA will cause further backward falling of the COM. This requires the contralateral swing leg to drop to the ground to prevent a fall. This interrupts the gait cycle, and often requires a second step by the interrupted swing leg to fully recover balance and proceed with a forward progression. Elimination of reversed activation and faster muscle onset of the TA makes it possible to smoothly continue the gait cycle without tripping or falling backward.

Tai Chi was highly effective in reducing the co-activation of TA and GA muscles during a large/fast perturbation while walking in these balance impaired older subjects. Since co-activation reflects increased expenditure of energy used to regain balance and slows down restoration of joint/segment angular trajectories used to maintain the gait cycle (5), balance responses would likely be faster and cause less tripping if this response were eliminated.

The orderly recruitment of muscles, here the tibialis anterior (TA) activated before the gastrocnemius (GA), serves to pull the body's center of mass forward over the stance leg. This compensates for the backward displacement of the center of mass caused by the acceleration of the platform moving forward. Co-activation of the TA and GA contributes to stiffening of the ankle joint which delays postural adjustments and continuation of the gait cycle. Elimination of co-contraction allows the involved muscles and joints to remain flexible. This allows the muscles to quickly make segmental adjustments that restore the disrupted ankle joint trajectory, recapture the body's center

of mass over the stance leg, restore forward momentum and maintain the gait cycle.

In our study, lab and clinical/behavioral measures show a similar trend; Tai Chi training improved balance significantly more than did control training. This suggests that Tai Chi training translated into functional balance efficacy. Co-contraction and reversed activation were eliminated and TA onset time was reduced by up to 50 ms.

How might the changes present in the Tai Chi intervention have contributed to the study's findings? We theorize that the program's unique aspects contributed to our results, but this remains to be tested further. Although traditional Tai Chi includes educational components related to balance control, relating movements being performed to fall prevention strategies is a significant departure from most Tai Chi interventions reported in clinical journals previously. We consider this as an important component for balance intervention programs because it illustrates how to use the training strategies to prevent a fall. It also helps students value the usefulness of the Tai Chi exercises and postural repetitions to allow them to become technically more able to perform these strategies. One of the differences between this study and previous studies (1, 31) that may have led to strong effects of training is that we focused on the underlying balance principles involved in each form trained rather than on linking a series of different postures. In addition, this training was more intense than most others, with sessions occurring 5 times per week for 1.5 hours/day.

#### *Limitations of the study*

A possible limitation of adding the crossover Group 2b to our testing procedure could be that it allowed "conditioned motor learning" to occur at time 3 if times between tests were relatively short. However, pretesting for each group took place during the week before training. Post-testing took place the week after training. The average time between trials was 4 weeks. Each perturbation took 500 ms and each clinical measure was performed only once. Since subjects were given only two normal walking perturbations at each testing period, it would mean that subjects were conditioned for a total of 1 second, separated by 4 weeks before the next trial. Therefore we feel confident that little conditioning took place.

In addition, one might consider the limited number of muscles (ankle agonist and antagonists of the perturbed leg) monitored pre vs post-training to be a limitation of the study. Bilateral onset latencies in the ankle, knee and trunk were not measured in our study because previous research (5) showed that older adults had equivalent slowing of responses in both the ipsilateral and contralateral leg to the perturbation as compared to young adults. The muscles that we chose as representative of the 10 muscles that Tang and Woollacott used were tibialis anterior (the first to be activated) and its antagonist, because the slowing of

the TA was representative of the other agonist muscles of the ipsi- and contra-lateral legs and the gastrocnemius responses were representative of the antagonist co-contraction that we tended to observe at other joints as well as the ankle joint. This characterization of responses at the ankle joint allowed us to analyze fewer variables, yet gather the key information about improvements in muscle response characteristics associated with the dynamic balance training of Tai Chi.

#### CONCLUSIONS

Our results support the use of alternative and complementary forms of medicine such as Tai Chi for the improvement of balance in older adults. We found a transfer of Tai Chi treatment effect on all clinical/behavioral measures of balance and increased efficacy of neuromuscular response characteristics underlying dynamic balance control, contributing to the transfer effect. Data from our study can be used to guide clinicians interested in "evidence-based practice," so that the mechanisms by which Tai Chi improves reactive balance can be more clearly understood. This evidence should also support the acceptance of Tai Chi training as an option for reimbursable therapy. An increased acceptance of its validity by the medical community should also increase the referrals for Tai Chi training in this population and thus increase the percentage of people who can independently manage balance problems.

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