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How Tai Chi improves balance: Biomechanics of recovery to a walking slip in impaired seniors

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Abstract

Background and aims: This study examined the effect of Tai Chi (TC) training on biomechanical responses to large, fast walking perturbations in balance-impaired seniors.
Methods: Twenty-two seniors (age 68–92, BERG 44 or less) with surgical interventions to knees, hips, and back were randomly divided into control or TC groups. Groups trained 1.5 h/day, 5 days/week for 3 weeks. Controls received TC training after post-control testing. Subjects walked across a force plate triggered to move forward 15 cm at 40 cm/s at right heel strike (RHS). Kinematics, center of pressure (COP) and center of mass (COM) responses were measured.
Results: TC but not control training significantly reduced tripping ($p \leq 0.005$), medial cross-step distance ($p \leq 0.038$), and increased use of swing leg heel strike ($p \leq 0.001$). COM anterior–posterior (A/P) path significantly increased after TC ($p \leq 0.017$) but not control training. TC training showed a trend toward increased COM-COP A/P angular separation at RHS ($p < 0.067$).
Conclusions: Tai Chi training significantly enhanced balance responses by more efficacious use of mechanisms controlling stepping strategies of the swing leg. COM A/P path significantly increased after TC implying improved ability to tolerate unsteadiness. COM-COP A/P separation angle at RHS increased suggesting a longer step and increased mechanical loading at the hip.

Keywords: Tai Chi; Falls; Human locomotion; Dynamic balance recovery; Aging; Gait; Balance; Posture

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1. Introduction

Although several studies show the effectiveness of Tai Chi (TC) on balance control [1–3] (addendum 1), no studies have, to date, examined effects of TC on biomechanical responses to large, fast walking perturbations in impaired seniors. Given that balance recovery during walking involves the ability to make rapid, coordinated, and accurate adjustments of body posture to prevent falling, and that the inability to recover from a slip or trip during walking accounts for the majority of falls in balance-impaired seniors [4], it would be most informative to examine the effect of TC training on recovery mechanisms during a slip while walking.

Previous research in our lab used a moveable platform to cause a slip similar to slipping on ice while walking [5]. Kinematics indicated that older adults used less effective recovery strategies. They had higher incidences of slipping and contralateral foot strike (causing a trip; addendum 2), greater trunk hyperextension, and larger arm elevations than did younger subjects. Winter [6] also recorded kinematic patterns of normal gait in healthy elders in order to pinpoint changes influencing balance recovery. He found elders used more flat-footed landings, less push off, and shorter steps compared to young adults when recovering balance on a normal surface.

Balance control during perturbed gait is complex and involves more than the selection of a recovery strategy (here defined as adaptive positioning of body segments such as arms and swing leg). It also involves control of displacement and

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velocity of the center of mass (COM). Control of the COM is a key variable for balance control because the body mechanically behaves as if all its mass is concentrated at this point [7]. The most hazardous phase for a slip during level walking is the period shortly after heel-strike of the swing leg. This is the time during which body weight is being transferred forward toward the leading foot and the COM is behind the center of pressure (COP). If the COM is not brought quickly over the leg receiving the weight transfer, the result will be a backward fall [5]. It is this backward fall of the COM that may require an early foot strike of the contralateral swing leg to prevent collapse of the COM due to gravity (addendum 2).

Gatts and Woollacott [8] previously reported that after TC training, balance-impaired elders (with surgical interventions to spine, knees, hips, arthritis) showed significantly improved neuromuscular control of ankle muscles during perturbed walking, with responses up to 50 ms faster than before training, reduced co-contraction of agonist and antagonist muscles and better muscle response organization. Significant improvements on four clinical measures of functional balance were also found (Timed Up and Go, Functional Reach, One leg stance time, Tandem stance time). Our present study investigates the effects of training on other key factors contributing to dynamic balance recovery. We examined whole body kinematics, COM, and COP changes pre- and post-training during a large, fast walking perturbation. We used these data to: (1) define biomechanical mechanisms and recovery strategies commonly used by this at risk group before balance training, and (2) determine in what manner these mechanisms and strategies were affected by TC or control training (addendum 3).

We hypothesized balance would improve after TC as shown by a decreased number of trips, improved control of step width (indicated by decreased medial cross-step distance), improved foot position indicated by increased use of heel-strike to continue gait (versus flat or toe-step) which allows a smooth forward progression, increased separation of sagittal COM-COP at slip foot heel-strike and toe off (indicating increased mechanical load on the support limb and increased ability to tolerate unsteadiness), more vertical angle of the trunk at slip foot heel-strike, and reduced elevation of arms during recovery. Since TC teaches flexible movement of the upper body (containing 2/3 of the body mass [9]) while maintaining a stable base of support, we hypothesized COP path would decrease and the COM path would increase, since stability limits within which the person could safely move would increase and movement under the stance foot would decrease due to the TC training.

2. Methods

2.1. Participants

Subjects were recruited from the local community. Inclusion criteria included: (1) age of 65 or older, (2) designated by their doctor or physical therapist as balance deficient, (3) no diagnosed central nervous system disorder and (4) able to stand without support and follow verbal instructions. People with arthritis, back, knee, or hip surgery were not excluded because they represent the real world population that balance interventions would need to address. 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 standards set by the Declaration of Helsinki.

Twenty-two seniors were randomly divided into TC or control groups. Nineteen subjects completed the study (demographics: age 68–92 years, mean 77.5 years; control group: $n = 8$, seven females, one male; TC group: $n = 11$, 10 females, 1 male). Initially the control group had three additional females who were dropped either because they wanted only TC training or did not want to be tested on the platform. Subject #14 completed control training but did not complete crossover TC training because of a family emergency.

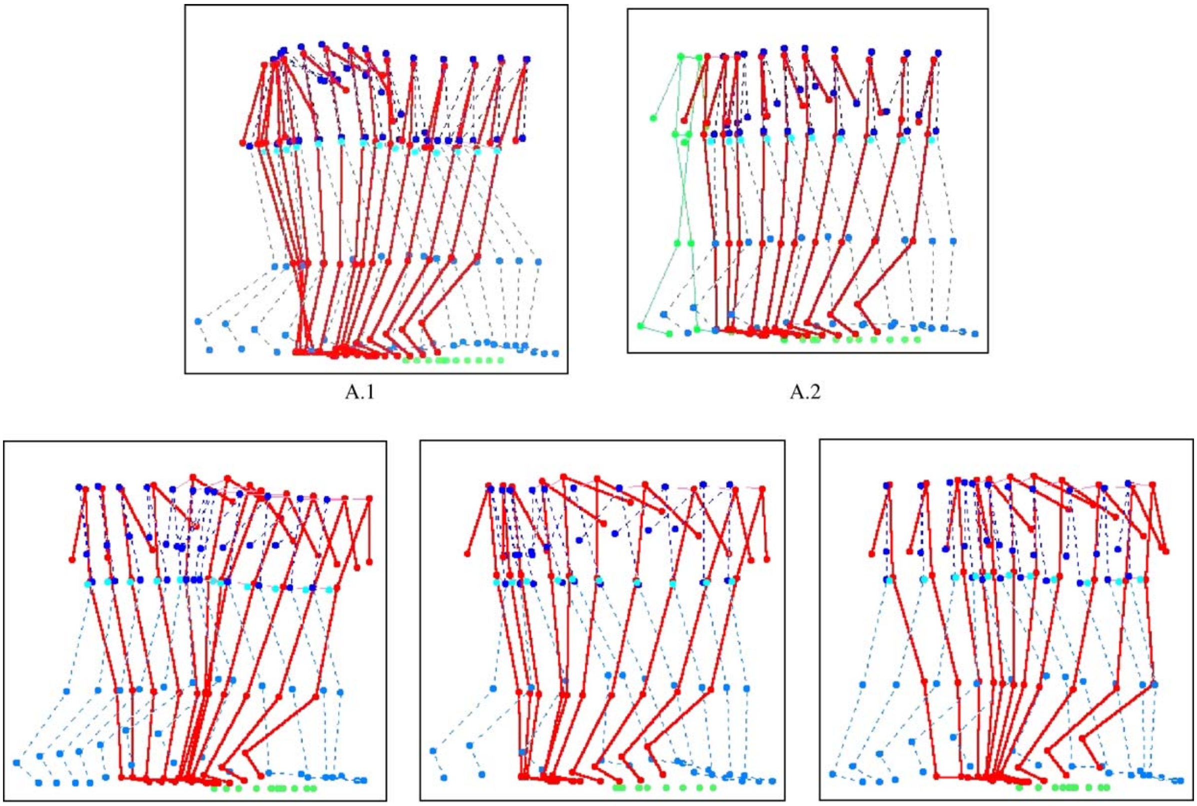
2.2. Intervention protocol

All groups received training 1.5 h/day, 5 days/week for 3 weeks in local community centers. Control training included balance education [10,11], awareness education [11–14], Axial Mobility exercises [15], and stretching [16]. TC training included twelve Yang style postures: Commencement, White-Stork, Brush-Knee, Play-Guitar, Repulse-Monkey, Heel-Kick, Toe-Kick, Golden-Cockerel, Works-Shuttles, Part-Horses’-Mane, Cloud-Hands, and Cross-Hands. A chapter listing the health benefits of each posture may be found in Tai Chi Chuan: The 27 Forms [17] (addendum 4).

2.3. Lab testing protocol

Subjects walked barefoot at normal walking speed down a 10 m walkway containing a custom built platform (Institute of Neuroscience Technical Service Group, University of Oregon). A 15 cm forward translation of the right plate at 40 cm/s was triggered by right heel-strike (RHS) (addendum, Fig. 1). This velocity matched horizontal heel velocities on slippery surfaces during realistic slips reported by Strandberg and Lanshammar [18]. The left plate did not move. An overhead suspension cable was attached to a body harness worn by subjects to ensure safety. Collection time was 6 s. We analyzed data from the first trial because this is similar to a real life slip. A second trial was collected as backup. Berger et al. [19] showed electromyographic responses were unaltered by pre-warning or random onset of a perturbation; therefore this frail subject population was told the plate would move quickly forward 15 cm at right heel-strike (addendum 5).

Custom written programs in MATLAB (The MathWorks, Mass) were used for data processing. Time of plate



A.1 A.2

B.1 B.2 B.3

Fig. 1. Stick figures illustrating whole body kinematics at baseline and after training in one subject from Group 1 and one subject from crossover Group 2. (A.1) Subject from Group 1 tripped at pretest indicated by trunk falling back, and then forward, (A.2) but did not trip post Tai Chi (indicated by more vertical trunk and segmental control throughout the movement). (B.1) A subject from Group 2 tripped at pretest, and (B.2) after control training, but (B.3) did not trip after Tai Chi training. Note the difference in recovery response after Tai Chi and after Control training at post-test, and the similarity after Tai Chi.

movement onset was determined as the point at which it moved three standard deviations (S.D.) above baseline position. Unloaded platform trials were taken at each test session and used to create a file that was subtracted from loaded platform trials to eliminate movement artifacts. Data were low-pass filtered at 15 Hz using a fourth order dual pass Butterworth filter [20] (addendum 6).

Kinematic data were collected using six cameras (3D Motion Analysis System, version 6.1 PEAK Performance Technologies, Englewood, CO). Twelve reflective markers were placed bilaterally over the 2nd metatarsal, lateral malleolus, lateral epicondyle of femur, greater trochanter of femur, acromion process of the scapula, and lateral epicondyle of the humerus of each subject. Data were sampled at 120 Hz. Marker position was used to reconstruct movement of 12 body links: six for upper extremities (one connecting hips, one connecting shoulders, one for each trunk side, one for each arm) and six for lower extremities (two feet, two shanks, two thighs). One reflective marker was placed on the right plate to register plate movement and act as a reference for transformation of local COP coordinates to global kinematic coordinates. Position data were low-pass filtered with a cut off frequency of 6 Hz using a fourth order dual pass Butterworth filter and data conditioner optimizing programs built into the PEAK system [20]. A nine-segment model (right and left foot, shank, thigh, arm, and head-neck-trunk) was used to reconstruct whole body COM as a virtual point within the spatial model of the PEAK system. Segment mass, center of segment mass, and anthropometric reference data were adapted from Dempster [21] (addendum 7). COP was sampled at 1200 Hz (addendum 8).

2.4. *Statistical analysis*

2.4.1. *Study design*

The experimental design was a pretest posttest design with a treatment group (Group 1) and a control group (Group 2a) which later received the treatment (Group 2b). We chose this design in order to: (a) examine recovery strategies balance-impaired seniors use to recover from walking perturbations before training, (b) examine the same measures after subjects were given TC or control training, (c) examine changes in the same subjects given two types of training (control and TC), (d) determine if the two TC trained groups show similar trends in performance measures at post-test, and (e) determine where change in performance would be most prominent.

2.4.2. Data analysis

Parameters selected were recovery strategies used to prevent falling and to regain forward walking momentum (i.e. trip or not, swing leg heel-strike versus toe or flat-foot, swing leg cross-step (medial position difference of left ankle marker at final left toe-off and left foot strike used to step off the plate)), right shoulder angle (range), right trunk angle (at right heel strike (RHS)), whole body COM (anterior–posterior, medial–lateral and vertical velocity range, position, path length), COP (anterior–posterior and medial–lateral maximum velocity, position, path length), and COM-COP separation angle (at RHS, right toe-off (RTO)). Trip occurrence was defined as early termination of swing leg and subsequent touchdown. A swing leg heel-strike versus toe or flat foot strike was defined by the left swing leg foot position used to step off the plate. A swing leg cross-step occurred if a subject placed the left swing leg foot medially when stepping off the plate compared to their previous toe-off position and was calculated using ankle marker data.

SAS® statistical software was used to run a paired sample *t*-test to examine pretest to posttest change in each group for each measure one at a time. Results were then compared with non-parametric tests. Alpha was set at 0.05. A trend toward significant differences was defined as *p*-values between 0.055 and 0.07. Other measures that were discrete random variables (trip, swing leg heel-strike) were measured with two outcomes: yes (event occurred)/no (event did not occur). The between-subjects factor for Group 1 (TC treatment) became a within-factor for the control Group 2a, because Group 2a later received the TC treatment (designated Group 2b). Logistic regression coefficients were computed to estimate odds of a 'yes' response at each time and compared to form an odds ratio of time 2 versus time 1. Odds ratios were computed for an effect over time for the treatment group. With 0 counts in certain combinations of treatment and time, we used Firth's bias reduction that computes logistic regression coefficients in the presence of separation of the data [22,23]. Separation of data primarily occurs in small samples with highly predictive risk factors. Pretest lab data for subject 11 was lost due to equipment error; thus, analysis for Group 1 used $n = 10$.

3. Results

Subjects' functional balance was examined using three clinical tests (Berg Balance Scale, Functional Reach (FR), and Timed Up and Go (TUG)). Control and TC 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,

Table 1
Demographics of the groups

	Gender	Age	Height (cm)	Mass (kg)	Berg	TUG (s)	FR (in.)
Tai Chi							
ID number 1	F	75	165	69.5	42	13.79	8
ID number 2	F	68	164	75.2	30	10.04	9.5
ID number 3	F	75	162	94	24	13.03	10
ID number 4	F	92	169	61.5	41	15.66	13
ID number 5	F	81	156	66	41	12.55	10
ID number 6	F	82	167	71	38	14.69	6
ID number 7	F	76	164	70.5	41	11.3	9
ID number 8	M	71	165	66	42	11.7	11
ID number 9	F	86	149.5	61	33	18.31	6
ID number 10	F	73	156	71.5	40	10.09	9
ID number 11	F	75	162	63.5	42	12.58	8
Mean		77.6	161.8	70	37.6	13.07	9.05
S.D.		7	5.7	9.1	6.02	2.47	2.05
Control							
ID number 12	F	68	170	75.5	40	12.27	9
ID number 13	F	80	160	80	36	12.8	6
ID number 14	F	82	163	58	41	10.06	6.25
ID number 15	F	81	159	69.5	44	12.62	10.5
ID number 16	F	85	164	69	28	18.47	4.5
ID number 17	M	75	179	98	44	12.05	6.5
ID number 18	F	73	149	67	39	13	12
ID number 19	F	76	164	88.5	28	15.85	12
Mean		77.5	163.5	75.7	37.5	13.39	8.34
S.D.		5.5	8.7	12.8	6.41	2.59	2.92

TC (Group 1) and control (Groups 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.

Table 2
Effects of training on recovery strategies[a], shoulder and trunk angles[b]

Measure	TC (Group 1)			Control					
				Group 2a			Group 2b (TC)		
	Number	Odds ratio	$p\leq$	Number	Odds ratio	$p\leq$	Number	Odds ratio	$p\leq$
Trip pre	9 of 10			7 of 8			3 of 7		
Trip post	2 of 10	0.028	0.003[a]	3 of 8	0.086	0.070	0 of 7	0.086	0.070
Heel strike pre	0 of 10			2 of 8			2 of 7		
Heel strike post	7 of 10	45	0.001[a]	2 of 8	1	0.715	6 of 7	15	0.051[a]

Measure	TC (Group 1)			Control					
				Group 2a			Group 2b (TC)		
	Mean	S.D.	$p\leq$	Mean	S.D.	$p\leq$	Mean	S.D.	$p\leq$
Cross-step pre	0.0375	0.0076		0.0676	0.0736		0.0540	0.0453	
Cross-step post	0.0176	0.0179	0.034[b]	0.0633	0.0359	0.458	0.0235	0.0242	0.268
R shoulder angle									
Range RHS-RTO pre	20.6	13.2		21.9	21		15.3	18	
Range RHS-RTO post	15.0	15.1	0.071	14.5	16	0.071	17.7	14	0.339
R trunk angle									
At RHS pre	6.5	4.5		5.8	2.9		5.2	1.5	
At RHS post	4.9	2.8	0.091	4.7	2.0	0.218	4.5	4.0	0.290

Cross-step in meters.

[a] Odds ratio for each recovery strategy (trip, heel strike), $p\leq 0.05$. An odds ratio of 1 indicates no change.

[b] Paired-sample *t*-tests, one-tailed, $p\leq 0.05$.

$p=0.17$; Berg $p=0.96$; TUG $p=0.79$; FR $p=0.57$). Subjects' Berg balance scores ranged from 44 to 24. A score of 45 or less was considered 96% specific to separate non-fallers from fallers [24]. Functional Reach scores ranged from 13 to 4.5 in.; only 4 of 19 subjects were able to reach farther than 10 in. and were within norms for their age and sex at pre-training. None of the TUG scores (18.47–10.04 s) were within independent balance function range (<10 s), and all were within range for independent balance transfers (<20 s) [25]. We have previously reported significant improvements on these measures after TC [8], while controls improved significantly only on FR.

Table 2 shows training effects on recovery strategy (slip, heel-strike, cross-step), shoulder and trunk angles. Group 1 received only TC training. Group 2 (the control/crossover) received control training first, then after testing received TC training (Group 2a = control training, Group 2b = TC training). Groups 1 and 2a did not differ significantly at pretest on number of trips ($p\leq 0.878$), heel-strikes ($p\leq 0.171$), medial cross-step distance ($p\leq 0.206$), range of right shoulder angle RHS to RTO ($p\leq 0.876$), and right trunk angle at RHS ($p\leq 0.710$).

Fig. 1 shows stick figures that illustrate whole body kinematics at pre- and post-training in one subject from Group 1 and one subject from crossover Groups 2a and 2b. Group 1 subject slipped backward at pretest, extended the arm upward to help regain balance, and then fell forward as they attempted to continue the gait cycle. Subject did not trip during recovery post TC (indicated by more vertical trunk throughout), used much less arm elevation, and smoothly continued the gait cycle. Group 2 subject tripped during recovery both at pretest and after control training (note the backward and forward fall of the body in reaction to the trip). Note post TC the control subject shows similar kinematics to post TC subject in Group 1(addendum 9).

Fig. 2A shows that 9/10 subjects in Group 1, 7/8 in Group 2a, and 3/7 subjects in Group 2b tripped at pretest. After training, 2/10 subjects in Group 1 ($p\leq 0.003$), 3/8 in Group 2a ($p\leq 0.070$), and 0/7 in Group 2b ($p\leq 0.070$) tripped. Fig. 2B shows 1/10 subjects in Group 1, 2/8 in Group 2a and 2/7 subjects in Group 2b used a swing leg heel-strike (versus a toe or flat foot strike) to step off the plate at pretest. After TC, groups significantly increased use of a heel-strike to continue the gait cycle. Post-test, 7/10 subjects in Group 1, 2/8 in Group 2a, and 6/7 in Group 2b used a heel-strike. The odds ratio that subjects would use a heel-strike was significantly greater after TC training (Group 1 = 45, $p\leq 0.001$; Group 2b = 15, $p\leq 0.051$) but showed no difference after control training (Group 2a = 1, $p\leq 0.715$). Table 2 and Fig. 2C show that medial cross-step distance was reduced by over 50% after TC and was significantly less for Group 1 ($p\leq 0.034$). Groups 1 and 2b were combined to examine effects of TC training. After TC, slips significantly decreased (odds ratio = 0.071, $p\leq 0.005$), use of heel-strike significantly increased (odds ratio = 18.6, $p\leq 0.001$), and cross-step distance was significantly reduced ($p\leq 0.038$).

Table 3A shows training effects on whole body COM velocity (m/s) and path length (m) during right heel-strike (RHS) to right toe-off (RTO). TC and control groups did not differ significantly from each other before training on range of COM A/P velocity ($p\leq 0.829$), range of COM M/L

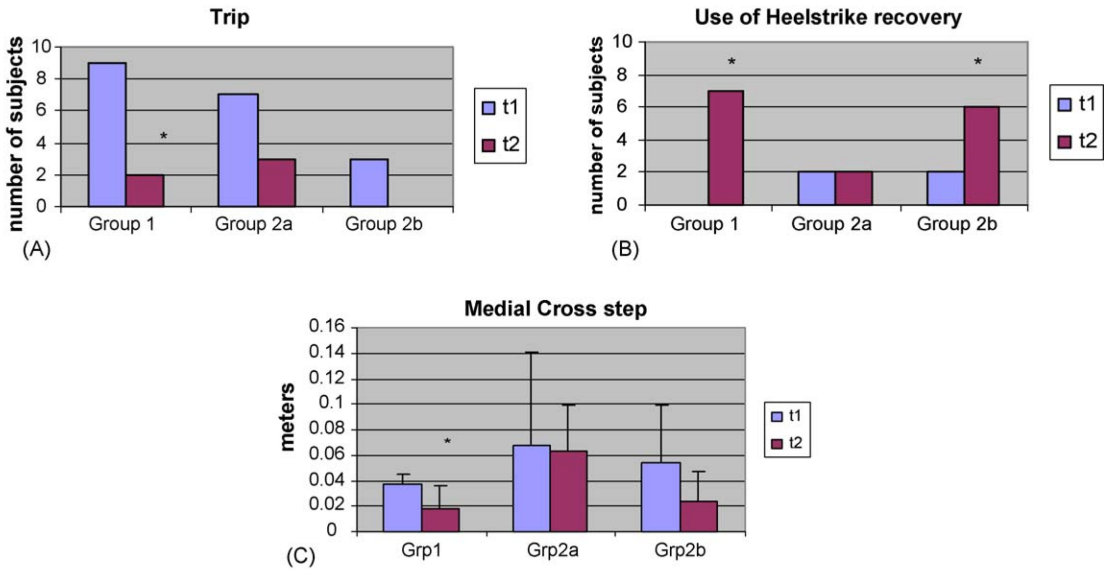


Fig. 2. Graphs showing pre and post training group data for: (A) number of subjects in each group that tripped; (B) number of subjects using a heel strike; (C) distance (m) of medial cross-step (difference in left ankle marker position at toe off and touchdown). t1: pre-test; t2: post-test.

Table 3A
Effects of training on COM[a]

Measure	TC (Group 1)			Control					
	Mean	S.D.	$p\le$	Group 2a			Group 2b (TC)		
				Mean	S.D.	$p\le$	Mean	S.D.	$p\le$
Velocity (range)									
COM A/P pre	0.278	0.105		0.270	0.090		0.133	0.043	
COM A/P post	0.194	0.090	0.065	0.161	0.040	.010[a]	0.110	0.024	0.103
COM M/L pre	0.196	0.077		0.229	0.111		0.179	0.043	
COM M/L post	0.154	0.078	0.127	0.185	0.044	0.188	0.204	0.038	0.176
COM vertical pre	0.062	0.040		0.114	0.030		0.103	0.047	
COM vertical post	0.088	0.055	0.130	0.097	0.047	0.214	0.088	0.043	0.196
Path distance									
COM A/P pre	0.490	0.160		0.647	0.087		0.616	0.067	
COM A/P post	0.594	0.123	0.028[a]	0.627	0.070	0.211	0.651	0.066	0.211
COM M/L pre	0.098	0.054		0.131	0.073		0.076	0.014	
COM M/L post	0.086	0.019	0.285	0.077	0.013	0.054[a]	0.098	0.013	0.003[a]
COM vertical pre	0.045	0.023		0.079	0.042		0.051	0.009	
COM vertical post	0.043	0.016	0.429	0.052	0.009	0.056	0.050	0.013	0.429

Training effects	TC (Groups 1 and 2b)			Control		
	Mean	S.D.	$p\le$	Mean	S.D.	$p\le$
Velocity (range)						
COM A/P pre	0.218	0.111		0.270	0.090	
COM A/P post	0.159	0.084	0.036[a]	0.161	0.040	0.010[a]
COM M/L pre	0.190	0.060		0.229	0.111	
COM M/L post	0.170	0.070	0.280	0.185	0.044	0.188
COM vertical pre	0.080	0.050		0.114	0.030	
COM vertical post	0.088	0.050	0.274	0.097	0.047	0.214
Path distance						
COM A/P pre	0.542	0.142		0.647	0.087	
COM A/P post	0.617	0.105	0.017[a]	0.627	0.070	0.211
COM M/L pre	0.089	0.043		0.131	0.073	
COM M/L post	0.091	0.017	0.438	0.077	0.013	0.054[a]
COM vertical pre	0.047	0.019		0.079	0.042	
COM vertical post	0.046	0.015	0.406	0.052	0.009	0.056

All measures are from right heel strike (RHS) to right toe off (RTO); A/P: anterior–posterior; M/L: medial–lateral.

[a] Paired-sample *t*-tests, one-tailed, $p \le 0.05$. Velocity shown in m/s, path shown in meters.

Table 3B
Effects of training on COP[a]

Measure	TC (Group 1)			Control					
	Mean	S.D.	$p\leq$	Group 2a			Group 2b (TC)		
				Mean	S.D.	$p\leq$	Mean	S.D.	$p\leq$
Max vel COP A/P pre	0.551	0.205		0.456	0.273		0.611	0.045	
Max vel COP A/P post	0.528	0.237	0.408	0.619	0.048	0.069	0.503	0.274	0.172
Max vel COP M/L pre	0.146	0.183		0.134	0.143		0.133	0.039	
Max vel COP M/L post	0.131	0.057	0.403	0.120	0.042	0.399	0.086	0.042	0.067
COP A/P path pre	0.069	0.033		0.057	0.036		0.085	0.024	
COP A/P path post	0.067	0.036	0.441	0.084	0.022	0.066	0.070	0.041	0.244
COP M/L path pre	0.012	0.007		0.011	0.010		0.014	0.005	
COP M/L path post	0.014	0.007	0.296	0.014	0.005	0.228	0.011	0.007	0.091

Training effects	TC (group 1 & 2b)			Control		
	Mean	S.D.	$p\leq$	Mean	S.D.	$p\leq$
Max vel COP A/P pre	0.576	0.159		0.456	0.273	
Max vel COP A/P post	0.518	0.245	0.209	0.619	0.048	0.069
Max vel COP M/L pre	0.132	0.141		0.134	0.143	
Max vel COP M/L post	0.113	0.055	0.288	0.120	0.042	0.399
COP A/P path pre	0.076	0.030		0.057	0.036	
COP A/P path post	0.068	0.037	0.259	0.084	0.022	0.066
COP M/L path pre	0.013	0.006		0.011	0.010	
COP M/L path post	0.012	0.007	0.447	0.014	0.005	0.228

All data from last 250 ms of right leg single stance preceding left foot strike.

[a] Paired-sample *t*-tests, one-tailed, $p \leq 0.05$. Velocity shown in m/s, path shown in meters.

velocity ($p \leq 0.491$), COM A/P path sway length ($p \leq 0.085$), COM M/L path sway length ($p \leq 0.877$). COM A/P velocity range reduced significantly in control Group 2a ($p \leq 0.010$) as a result of training. When the two TC groups were combined to examine training effects, a significant reduction in range of COM A/P velocity was also found for TC ($p \leq 0.036$). COM A/P path length increased in both TC groups (Group 1 significantly, $p \leq 0.028$), while controls reduced their path. Combining the TC groups, a significant increase was found ($p \leq 0.017$). COM M/L total path length did not show a training related trend. To account for possible pre- and post-test differences in walking speed

Table 3C
Effects of training on COM-COP separation angle[a]

Measure	TC (Group 1)			Control					
	Mean (°)	S.D. (°)	$p\leq$	Group 2a			Group 2b (TC)		
				Mean (°)	S.D. (°)	$p\leq$	Mean (°)	S.D. (°)	$p\leq$
RHS A/P pre	8.65	3.43		11.25	2.08		10.91	2.29	
RHS A/P post	10.08	2.70	0.122	11.00	2.14	0.329	12.19	3.12	0.204
RTO A/P pre	10.37	7.44		13.81	5.70		12.97	3.02	
RTO A/P post	11.49	6.80	0.337	13.38	3.02	0.419	13.60	3.02	0.385
RHS M/L pre	7.10	2.59		6.04	5.50		6.83	2.29	
RHS M/L post	7.10	2.53	0.481	6.90	2.13	0.302	8.01	1.33	0.042[a]
RTO M/L pre	7.14	2.05		7.56	3.10		6.41	2.51	
RTO M/L post	6.13	3.37	0.238	5.93	2.71	0.193	7.39	1.98	0.209

Training effects	TC (Groups 1 and 2b)			Control		
	Mean (°)	S.D. (°)	$p\leq$	Mean (°)	S.D. (°)	$p\leq$
RHS A/P pre	9.58	3.15		11.25	2.08	
RHS A/P post	10.95	2.98	0.067	11.00	2.14	0.329
RTO A/P pre	11.44	6.03		13.81	5.70	
RTO A/P post	12.36	5.53	0.297	13.38	3.02	0.419
RHS M/L pre	6.99	2.40		6.04	5.50	
RHS M/L post	7.45	2.12	0.240	6.90	2.13	0.302
RTO M/L pre	6.84	2.21		7.56	3.10	
RTO M/L post	6.65	2.88	0.419	5.93	2.71	0.193

RHS: right heel strike; RTO: right toe off; A/P: anterior–posterior; M/L: medial–lateral. COM-COP separation angle is measured relative to vertical.

[a] Paired-sample *t*-tests, one-tailed, $p \leq 0.05$.

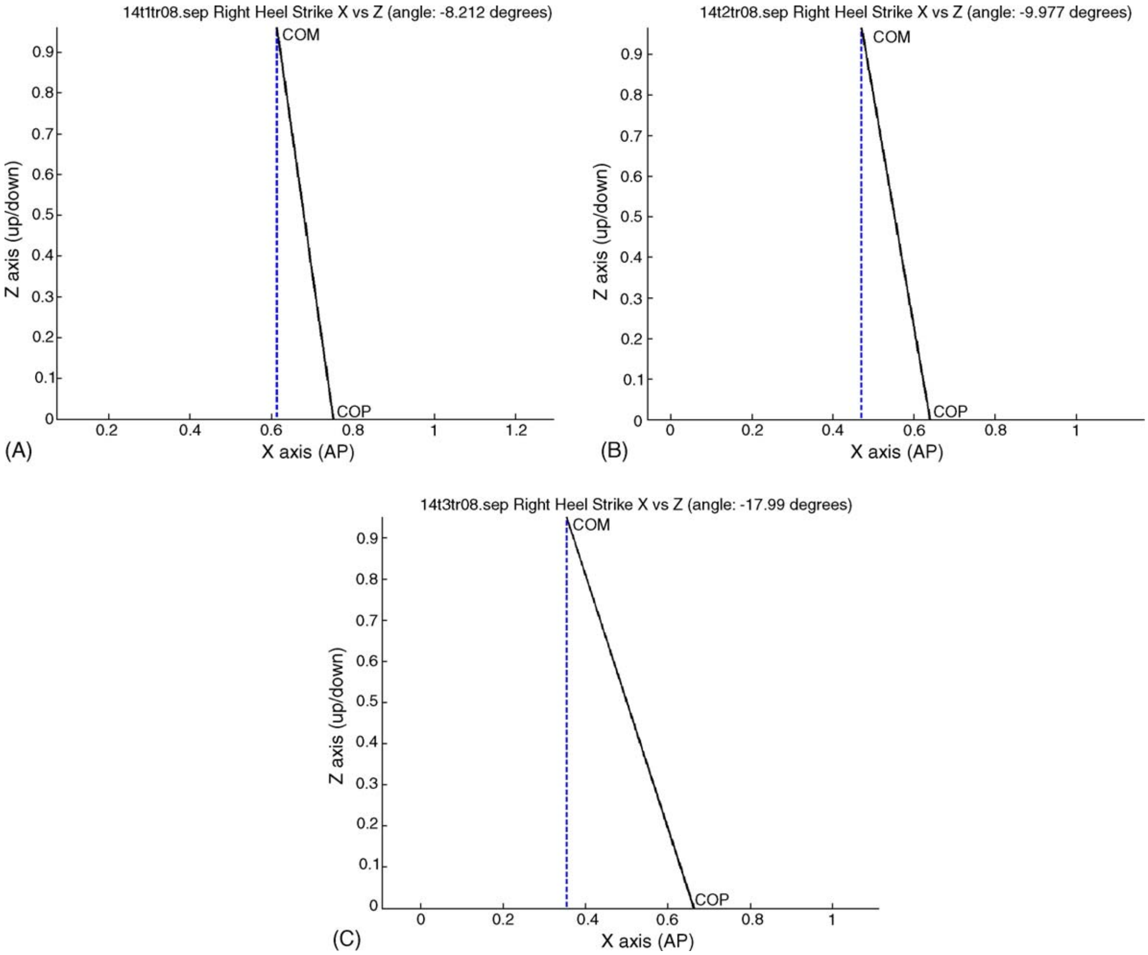


Fig. 3. Increases in sagittal plane COM-COP separation angle at RHS. The dotted line indicates projection of the center of gravity (COG), which is the vertical projection of the COM to the ground. The solid line connects the COM to the COP. (A) Subject in crossover Group 2 at baseline has 8.21° of separation. (B) Same subject after control training has 9.98° separation. (C) Same subject after Tai Chi training has a large increase in the COM-COP separation angle (17.99°), indicating a less cautious gait and longer step length.

we looked at COM A/P velocity at plate onset. A significant difference was not found (Group 1 $p \leq 0.081$, Group 2a $p \leq 0.061$, Group 2b $p \leq 0.329$).

Table 3B shows COP results. Because most subjects tripped at baseline, COP data from the last 250 ms during which all subjects were in right single leg stance were used for this table. TC and control groups did not differ significantly at baseline on COP A/P maximum velocity ($p \leq 0.213$), COP M/L maximum velocity ($p \leq 0.437$), COP A/P total path ($p \leq 0.235$), COP M/L total path ($p \leq 0.412$). Although none of the COP measures changed significantly, a training trend (p-values between 0.055 and 0.07) was found. Controls increased maximum COP A/P velocity (control $p \leq 0.069$), and total path (control $p \leq 0.066$).

Table 3C shows COM-COP separation angle at RHS and RTO. COM-COP separation angle was measured in the A/P and M/L plane relative to vertical. Groups did not differ significantly at baseline on A/P separation at RHS ($p \leq 0.066$) or RTO ($p \leq 0.283$) or M/L separation at RHS ($p \leq 0.627$) or RTO ($p \leq 0.746$). COM-COP A/P separation angle at RHS, although not significant, also showed a training related trend. The angle increased after TC (RHS $p \leq 0.067$). Fig. 3 illustrates the A/P separation angle at RHS in a subject from the crossover group.

4. Discussion

Our hypothesis that TC would reduce tripping and improve gait cycle kinematics was supported. TC significantly reduced tripping (addendum 10), significantly increased use of heel-strike and significantly reduced medial cross-step distance of the swing leg during gait recovery. Improved control of mechanisms underlying the stepping strategy is important because only by safe placement of the swing foot is a fall averted at each step of the gait cycle [9] and older adults with a history of falling use a flatter foot at heel-strike and show decreased dorsiflexion ability [26,27]. Pre-TC subjects used larger medial placement of the swing leg to step off the plate. This foot placement narrows the step width and moves the swing foot closer to the COM, rather than the COM moving towards the future position of the swing foot as occurs in normal gait progression.

Subjects tended to fall forward as they stepped off the plate before TC training. Perhaps medial placement of the swing leg allowed quicker braking of the forward fall of the COM. However, medial foot placement is not optimal for fall recovery nor for the ability to continue the gait cycle because it narrows the base of support, may cross the legs, and could compromise the ability to maintain equilibrium or respond to subsequent imbalance [28], and during level walking the most hazardous slip phase is after step contact as body weight is being transferred [29] (addendum 11).

Our hypothesis that whole body COM path would increase after TC was supported in the A/P plane. TC training significantly increased COM A/P path. This increase was possibly due to increased A/P flexibility in the right hip joint and longer step length as suggested by the trend toward a larger COM-COP A/P separation angle at RHS. Since the control group decreased their COM A/P path at post-test and TC Group 1 significantly increased their distance at post-test, the increased path was not due to previous experience on the plate. Additionally, after controls received TC, they also increased their path. Thus, we conclude the increase is a result of TC training.

A training trend was found for COM-COP A/P separation angle at RHS. This angle increased after TC. Hahn and Chou [30] pointed out that the greater the distance between COM and COP, the greater the torque about the stance hip would be, due to a greater imbalancing force of a longer moment arm for the body weight. Since cautious gait uses small steps, and has been linked to falling [29], the increased angle at RHS implies a less cautious gait and increased confidence in one's ability to avert a fall. Additionally, Chang and Krebs [31] suggested the COM-COP relationship provided information about dynamic balance control because the magnitude of the separation described the ability to tolerate unsteadiness and was a valid tool for discriminating unsteady seniors from healthy seniors. Our lack of significance may be due to the small number of subjects and/or a longer intervention may be needed for some subjects with joint surgery.

Repeating the study using larger groups and replication by other researchers would allow stronger conclusions about TC's influence on the CNS's ability to control dynamic relationships and interactions between the base of support, the center of mass, and the pattern of coordination between the two lower extremities during a walking balance challenge, and to examine the extent to which individuals are able to improve balance responses despite existing impairments (addendum 12).

5. Conclusion

Successful balance recovery from a slip while continuing the gait cycle requires rapid and accurate repositioning of the swing leg foot trajectory and end position while simultaneously controlling the motion of a moving COM so as to bring it over the new base of support within the boundaries of the advancing foot [32]. In this study we report significant changes in two key balance control mechanisms after TC. Impaired seniors significantly increased their ability to: (1) control stepping strategy (swing leg and foot trajectory and end position) used to recover a normal gait cycle and, (2) increase COM A/P motion during RHS-RTO. Additionally, TC groups showed a trend toward increased COM-COP A/P separation at RHS implying improved ability to tolerate unsteadiness, support increased mechanical loading at the hip, and suggesting they have greater confidence in their ability to recover balance when stepping onto a moving surface.

It is important to point out that, although Wu [33] suggests there may be a required threshold of 40 or more TC sessions to be effective, Wolf et al. [2] showed a significant reduction in fall risk with 30 training sessions. In our study we were able to see significant changes with only 14 sessions using our TC balance therapy program and an intensified training schedule. Thus, it may be that some of our variables that approached significance would have become significant with the addition of a few more training sessions, especially considering the variety of impairments in our subjects. Although some may suggest that the study length is a limitation, we feel our study length presents new and important information about a short, intensified TC balance therapy that can be applied in clinical balance rehabilitation programs analogous to the way constrained-use therapy has been applied to stroke rehabilitation.

Currently there is strong emphasis on clinical practice being ‘‘evidence-based.’’ Our results support use of intensive TC training as an option for reimbursable therapy. Because this training can be performed in groups, and as it offers social support for training adherence, use of this training would be expected to increase the percentage of people who can independently manage balance problems.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2006.03.011.

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