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Tai Chi and vestibular rehabilitation effects on gaze and whole-body stability

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Abstract. Tai Chi (TC) is a comparatively new intervention for peripheral vestibular hypofunction, which is often treated with vestibular rehabilitation (VR). We compared gaze stability (GZS), whole-body stability (WBS) and footfall stability (FFS) during locomotion among 26 people with vestibulopathy (VSP), randomized into two treatment arms (13 TC and 13 VR). Each intervention program was offered for 10 weeks. GZS improved more for VR than for TC, but WBS (and FFS) improved more for TC than for VR. There was a significant relationship between changes in GZS and WBS for the VR subjects ($r = 0.60$, $p = 0.01$), but not for TC subjects. There was a significant relationship between changes in WBS and FFS for both VR ($r = 0.65$, $p < 0.01$) and TC ($r = 0.58$, $p = 0.02$) groups; the relationship disappeared in the VR but not the TC group when controlling for GZS. These findings suggest that VR and TC both benefit patients with VSP but via differing mechanisms. Moreover, these data are the first to test the assumption that improving gaze control among patients with VSP perforce improves postural stability: it does not. We conclude that GZS is most improved in those who receive VR, but that TC improves WBS and FFS without improving GZS, suggesting patients with VSP can rely on non-gaze related mechanisms to improve postural control.

Keywords: Vestibulopathy, gaze stability, whole body stability, Tai Chi, vestibular rehabilitation

1. Introduction

Vestibulopathy (VSP) is caused by damage to the peripheral vestibular system, often resulting in profound balance impairment [4]. Inability to maintain visual stability is one effect of VSP, from diminished or absent function of the vestibular-ocular reflex (VOR). Decreased whole body dynamic postural control contributes to functional limitation in people with VSP [1, 23,24,29], and is thought to be a direct consequence of reduced VOR and vestibulo-spinal reflex (VSR) function [16]. Vestibular rehabilitation (VR) is an exercise program intended to reduce VSP balance impairment [19,41] by promoting adaptation to or compensation for VOR and VSR loss, via gaze stability and balance retraining. Although several studies have demonstrated improved static and dynamic stability following VR [18,21,28], whether these improvements are related to improved gaze stability has not been investigated.

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Tai Chi (TC) is among a growing number of alternative therapies for treating a variety of human impairments, including posture and balance disorders [17,50, 51,53,55]. TC integrates a detailed regimen of physical movement and breathing techniques, intermixed with cognitive enhancement of visualization and focused internal awareness [52,59]. Although recent evidence suggests that improvements in overall body control with TC may offer an alternative or complimentary approach to treating balance impairment (see Wayne et al. [46] for a review), and that TC may improve biomechanical characteristics of gait (Wu et al. [56], Tsang et al. [44]), there are no studies that have directly compared whole-body and gaze stability outcomes between VR and TC treatments for patients with VSP. One objective of this study was to determine the relative benefits of VR and TC on whole-body stability and gaze stability, during a dynamic locomotor task, repeated stepping, in older patients with VSP.

The fundamental differences in the rehabilitative approaches of VR and TC may also provide a novel approach to better understanding the mechanisms of improved whole-body stability during locomotion in people with VSP, and how reliant these improvements are on gaze stability. Based on the principle that VR improves dynamic whole-body control through a combination of balance retraining and gaze stabilization exercises [18,21,29,41,42], and given that TC can also benefit people with balance impairment [48,49] an obvious question arises as to how TC might benefit people with VSP, since TC does not directly involve gaze training exercises. Indeed, TC incorporates techniques to relax the body and mind, including an emphasis on a soft, non-focused gaze [47]. The second objective of this study was to explore what mechanisms might be responsible for improved whole-body stability during locomotor activity in patients with VSP, who either undergo VR or TC training. TC might improve whole-body stability by non-gaze related mechanisms, such as improved lower-extremity motor control. One such metric might be footfall (stepping) stability. We chose three key stability measures: gaze, whole body, and footfall stability to investigate the effects of TC and VR interventions among persons with vestibulopathy.

Our two objectives led to the following hypotheses: Due to the differences inherent in the two rehabilitative approaches, 1) patients undergoing VR treatment will have greater improvements in gaze-stability than patients undergoing TC treatment; and 2) patients undergoing TC treatment will have greater improvements in whole-body stability and footfall stability than patients undergoing VR treatment. Furthermore, we expect that different mechanisms will be responsible for improvements in whole-body stability, whereby 3) patients undergoing VR treatment will demonstrate a direct correlation between changes in whole-body and footfall stability that will be explained by gaze stability changes; and 4) patients undergoing TC treatment will have a direct correlation between changes in whole-body and footfall stability that will not be explained by gaze stability changes.

2. Methods

2.1. Subjects

Fifty-three patients with vestibular hypofunction and balance impairment were randomized into either a group vestibular rehabilitation (VR) intervention, or a group Tai Chi (TC) exercise intervention. Thirty-three of the patients had unilateral vestibular hypofunction (15 from acoustic neuroma), and 20 had bilateral vestibular hypofunction. All patients had gait and balance problems secondary to vestibulopathy. Diagnoses were obtained as previously described [28]. The average time post-onset of vestibulopathy for the study sample was 2.94 years (± 2.73 years). All subjects were community dwelling and reported varying degrees of limitations in locomotor ability and had experienced at least one course of VR since the time of onset of their vestibular symptoms. Inclusion criteria required that each subject did not have VR less than 6 months prior to study enrollment and had never participated in a TC program. Of the 53 patients enrolled, 15 dropped out or were excluded prior to completing the intervention, primarily due to unrelated health issues. An additional 12 subjects did not perform the stepping trials for both visits, thus our final sample included 26 subjects. All subjects provided written informed consent according to institutional guidelines on human research.

2.2. Interventions

The VR and TC group treatment interventions were conducted in six (3 VR and 3 TC groups) small cohorts with an average of 8 subjects per group. Each intervention program was 10 weeks in duration, meeting once weekly for approximately 70 minutes in the same exercise room, but on separate weekdays, for the two different treatments. The instructors were blinded to the measurements taken before and after the interventions, and to the exercises provided to the other treatment program, and each treatment program was lead by the same instructor for the three treatment cohorts. One or two assistants were present for all sessions to insure participants' safety. At each session ample time was available to: 1) review material introduced in prior sessions; 2) introduce new material; 3) ask questions and share personal experiences or concerns regarding the practices; and 4) cool down and rest.

Tai Chi Intervention: The TC intervention incorporated three objectives outlined in a balance-related TC program developed by Wolf and colleagues [49,51]. First, all training emphasized movements that were easily comprehensible. Second, the sequence of exercises introduced reflected a progression that increasingly challenges postural stability, with a shift in weight bearing from bilateral to unilateral support. Third, the program emphasized increasing the magnitude of trunk and arm rotation while diminishing the base of support. The five specific TC movements employed in this study – 'raising the power', 'withdraw and push', 'wave hand like clouds', 'brush knee twist step', and 'separate right and left legs' – are based on the Cheng Man-Ch'ing's Yang-style short form [7]. The style of TC we employed has an emphasis on a soft, non-focused gaze [47]. This characteristic of practice distinguishes it from VOR-based VR exercises, which do require focused gaze. Participants in this study were specifically instructed to not focus their gaze during the exercise, and this along with all other aspects of the intervention was monitored at each session. In addition to the five formal TC movements described above, the intervention also included a short set of traditional TC warm-up exercises to complement the TC set. These warm-up exercises focused on loosening up the physical body and incorporating mindfulness and imagery into movement. Warm-up exercises included the following traditional exercises: a) tai chi swinging: repetitively shifting of weight from side to side with waist turn and free arm swing; b) drumming the body: gentle tapping palms to eight locations on torso to stimulate blood and chi flow; c) standing meditation: guided imagery while standing w/ feet at hip width; d) sitting breathing meditation emphasizing diaphragmatic breathing; and e) ankle and wrist rotations while seated. The approximate breakdown of the 70 minute session was as follows: 20 minutes tai chi warm-up and meditation; 40 minutes tai chi practice; 10 minutes discussion.

Vestibular Rehabilitation Intervention: The VR intervention used in this study is a comprehensive exercise program designed to improve the problems specifically associated with damage to the peripheral vestibular system and includes two major components: vestibular adaptation exercises and specific balance exercises [22]. The VR approach we used is based on the concept that the remaining intact vestibular system is able to adapt to the changes in demand and changes in sensory information received [12]. Vestibular adaptation exercises to promote gaze stability include such activities as gaze fixation performed during head movements, combined eye and head movements performed in various directions at various speeds, and various balance activities performed in combination with labyrinthine-stimulating eye and head movements [13,18]. For example, right and left head horizontal rotation is performed initially with eyes on a stationary target, and later performed with eye movements following a moving target in the direction opposite to the head movement. Subjects progress to performing these eye-head exercises with the target on a more complex background (to simulate real world activities), at increasingly faster speeds of head movements (eg, 2–3 Hz), and during more dynamic standing and locomotor activities. A unique feature of the VR program is use of a metronome to pace head movement during gaze fixation exercises. Over time the patient is progressed by increasing the speed (frequency and amplitude) of head movement to more appropriately train the VOR at speeds consistent with everyday locomotor activities. For patients with little or no remaining vestibular function, these activities are practiced during the performance of alternative (substitution) strategies for gaze stability (e.g., rapid saccadic eye movements). Another main component of the VR program is balance retraining exercises that enhance the use of various sensory cues for gaining posture control [9,13,18]. Examples of these exercises include subjects maintaining their balance while walking on various floor surfaces (such as foam) or with eyes closed. These tasks require enhanced use of visual, neck, and residual vestibular, inputs to compensate for the somatosensory system that has been challenged or suppressed during the activity. All exercises are performed with progressing levels of difficulty.

2.3. Measurements

Subjects performed an overground locomotor task best described as a repeated up/down bench stepping activity [10,15,36,37]. Subject stepped repeatedly up and forward then down and backward from a 7.5 cm step for 30 seconds at a cadence of 80 or 100 steps

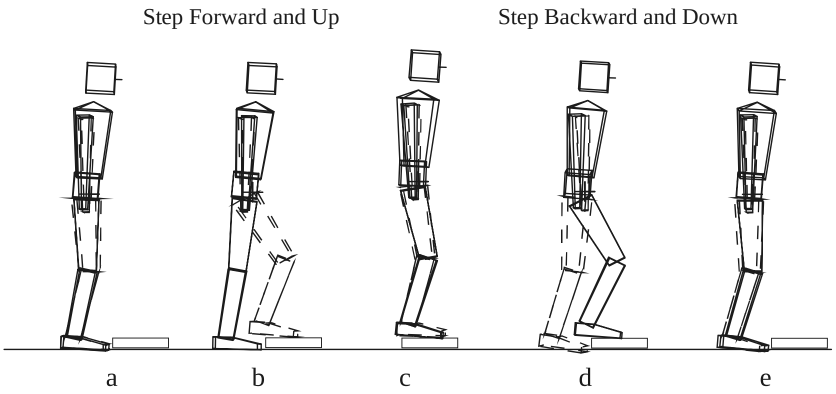

Fig. 1. Wire-model of a representative subject performing the stepping task. (a-b-c) The subject steps forward onto the platform with their dominant leg; (c-d-e) steps backward off the platform with their dominant leg. The task is repeated multiple times over a 30 second period (approximately 12 cycles).

per minute (depending on the patient's ability). For all trials, subjects were instructed to fix their gaze on a small light mounted on a wall at a distance of 4 m from the step. All subjects performed the test while wearing athletic shorts and in bare feet. A warm up trial was given to subjects prior to data collection, followed by at least two trials (each 30 seconds long) of data capture.

Kinematics of the body segments were acquired using a SELSPOT II kinematic data acquisition system (Selective Electronics, Partille, Sweden); four SELSPOT II optoelectric cameras were used to measure the position of infrared light emitting diodes (irLEDs) embedded on flat plastic disks and rigidly fixed to eleven body segments (both feet, shanks, thighs, and arms, and pelvis, trunk, and head). Body segment displacements and angles were then computed using TRACK software (Massachusetts Institute of Technology, Cambridge, MA). Kinematic data were sampled at 152 Hz and low-pass filtered (Butterworth 4th-order, 6 Hz cutoff).

Eye movement data were recorded with an ISCAN video pupil tracking system (Model RK-726PCI, ISCAN Inc., Burlington, MA). The ISCAN video camera with infrared illuminator was mounted on a plastic visor strapped firmly to the head (which also contained the irLED array for head motion tracking). The lens of the camera was aimed at a diachrotic mirror positioned approximately one inch in front of the subject's eye at a 45 degree angle. ISCAN image processing software calculated the center of the pupil and cornea reflection from the video image at 60 Hz in both vertical (pitch) rotation and horizontal (yaw) rotation planes. The resolution was $\sim$ 0.1 degree, and linear within a measurement range of ± 20 degrees for horizontal, and ± 10 degrees for vertical. The eye tracking system was calibrated for each subject by having them stand and gaze at three small lights arranged to represent -10, 0, $+10$ degree horizontally, and then -5, 0, $+5$ degree vertically, while keeping their head fixed in space. Eye kinematics were computed, and blinks detected, as described elsewhere [36].

Whole-Body Stability: Whole-body stability was assessed using High Curvature Analysis (HCA), details of which are published elsewhere [14,15]. Briefly, the analysis involves computing the curvature of a planar trajectory of a point in space at discrete intervals, and counting the frequency of curves exceeding a predefined curvature (angle) threshold. As such, smooth movements tend to have few high curvature intervals, whilst unstable movements tend to have numerous high curvature intervals. Representative data for a patient in the TC treatment group is shown in Fig. 2. Our past studies have found this technique to be a sensitive measure of stability for repeated locomotor activities [14, 15]. For the whole body stability analysis, HCA was applied to the whole-body center of mass. The center of mass was computed as described in previous reports [11,40]. HCA scores for trajectories in the frontal plane (HCA_{Z-Y}), transverse plane (HCA_{X-Z}), and sagittal plane (HCA_{X-Y}) were computed using a curvature threshold of 80 degrees, normalized by the step frequency (80, 100 or 120 steps/minute), and combined into a single whole-body stability (WBS) score using the following formula:

$$\text{WBS} = \sqrt{\text{HCA}^2_{X-Y} + \text{HCA}^2_{\text{X-Z}} + \text{HCA}^2_{\text{Z-Y}}} \quad (1)$$

Gaze Stability: Gaze stability was assessed by computing the intersection of the gaze vector with the target plane (wall, 4 m distant), and analyzing the phase

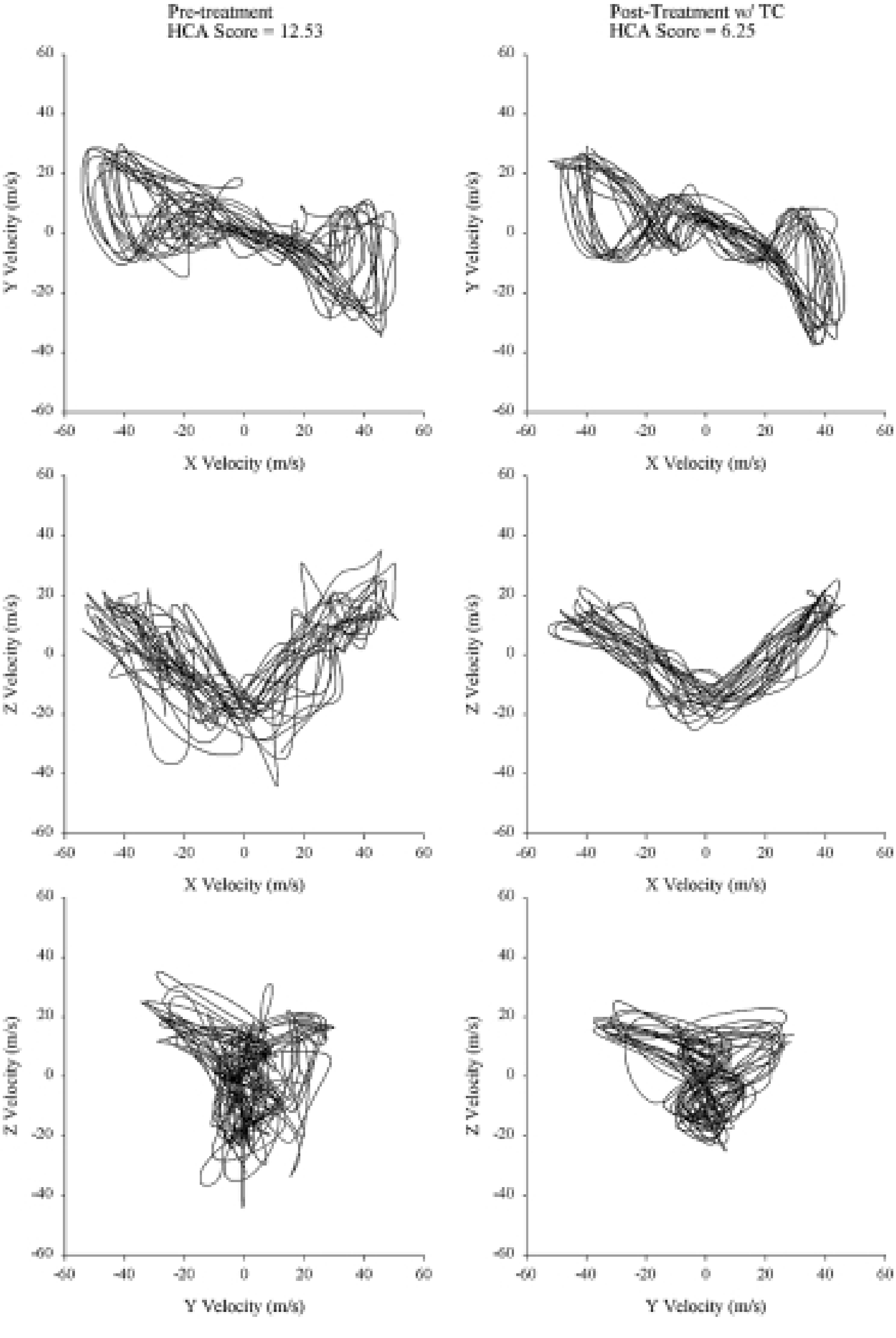

Fig. 2. Whole-body center of mass velocity in three-dimensions during the stepping task, displayed as velocity-velocity plots as used for the High Curvature Analysis (HCA), for a representative subject randomized to the TC treatment group. X is anterior-posterior, Z is mediolateral and Y is vertical. Left panels: XY, XZ and YZ velocity-velocity plots pre-treatment. Right panels: XY, XZ and YZ velocity-velocity plots post-treatment. In this subject (41 year old male), the improvement in whole-body stability is characterized by smoother movements of the center of mass.

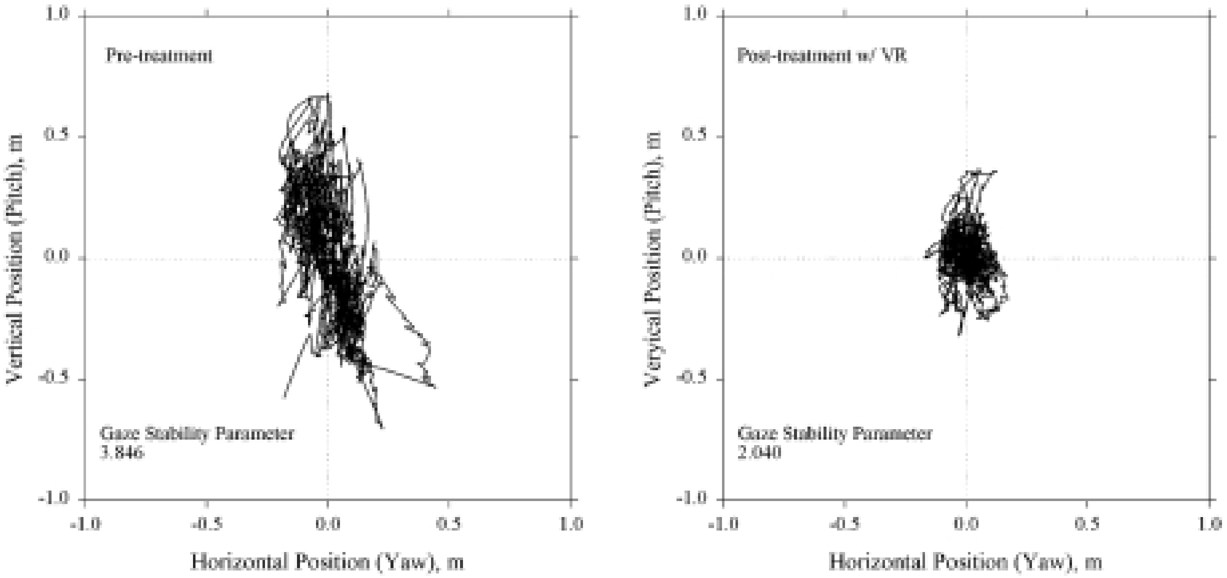

Fig. 3. Location of the gaze vector intersection with the plane of the wall mounted target (0,0) during the stepping task for a representative subject randomized into the VR treatment group. Left panel: Pre-treatment trace of the gaze vector. Right panel: Post-treatment trace of the gaze vector. In this subject (52 year old female), the improvement in gaze stabilization is primarily in the vertical (Y) dimension, representing the pitch plane.

plane of the intersection trajectory. The gaze vector was computed by transforming eye-in-head angular coordinates, as output from the ISCAN device, into eye-in-room coordinates. Because the gaze target was a fixed point in space, a stable gaze would result in a trajectory concentrated at the target location. A failure to stabilize gaze would result in deviations of the gaze intersection from the target, causing large displacements and/or velocities. Representative data for a patient in the VR group is shown in Fig. 3. Gaze stability was analyzed by numerically computing gaze velocity from the gaze displacement data, and then computing the standard deviation in displacement (s_{DISP}) and velocity (s_{VEL}) as orthogonal components of the phase plane. The gaze phase plane stability parameter in yaw (GZS_{YAW}) and pitch (GZS_{PITCH}) was then computed as previously described for anterior-posterior and medio-lateral standing balance assessments, and combined into a single parameter (GZS) [3,39].

$$\mathrm{GZS}_{\mathrm{YAW}} = \sqrt{s^2_{\mathrm{DISP,YAW}} + s^2_{\mathrm{VEL,YAW}}} \quad (2)$$

$$\mathrm{GZS}_{\mathrm{PICTH}} = \sqrt{s^2_{\mathrm{DISP,PITCH}} + s^2_{\mathrm{VEL,PITCH}}} \quad (3)$$

$$\mathrm{GZS} = \sqrt{\mathrm{GZS}^2_{\mathrm{YAW}} + \mathrm{GZS}^2_{\mathrm{PITCH}}} \quad (4)$$

Footfall Stepping Stability: Stepping stability of footfalls was measured by examining the consistency of footfalls during the stepping trial. First, the intervals of time that each foot was in weight support, for both left and right feet, in the forward (on the step) and back (off the step) positions were computed. Then the coefficient of variation (CoV, standard deviation divided by mean) of the intervals across the 30 second trial was calculated. The ankle joint center was used to represent the distal lower-extremity displacement during stepping. For stepping consistency, the CoV will have low values – meaning that the stepping pattern was invariable throughout the trial. Large CoV values indicate a variable stepping pattern, which would suggest an unstable stepping pattern. Representative data for a patient in the TC treatment group is shown in Fig. 4. CoV's were computed separately for left and right feet, in the forward and back positions, and then averaged to arrive at a single value for footfall stepping stability (FSS).

$$\mathrm{CoV}_{\mathrm{LEFT,FORWARD}} = \frac{s_{\mathrm{LEFT,FORWARD}}}{\bar{\chi}_{\mathrm{LEFT,FORWARD}}} \quad (5)$$

$$\mathrm{CoV}_{\mathrm{LEFT,BACKWARD}} = \frac{s_{\mathrm{LEFT,BACKWARD}}}{\bar{\chi}_{\mathrm{LEFT,BACKWARD}}} \quad (6)$$

$$\mathrm{CoV}_{\mathrm{RIGHT,FORWARD}} = \frac{s_{\mathrm{RIGHT,FORWARD}}}{\bar{\chi}_{\mathrm{RIGHT,FORWARD}}} \quad (7)$$

$$\mathrm{CoV}_{\mathrm{RIGHT,FORWARD}} = \frac{s_{\mathrm{RIGHT,FORWARD}}}{\bar{\chi}_{\mathrm{RIGHT,FORWARD}}} \quad (8)$$

$$\begin{aligned}\mathrm{FSS} = (&\mathrm{CoV}_{\mathrm{LEFT,FORWARD}} + \mathrm{CoV}_{\mathrm{LEFT,BACKWARD}} \\ &+\mathrm{CoV}_{\mathrm{RIGHT,FORWARD}} \\ &+\mathrm{CoV}_{\mathrm{RIGHT,BACKWARD}})/4\end{aligned} \tag{9}$$

2.4. Data analysis

The three outcomes variables, WBS, GZS and FSS were evaluated at pre- and post-treatment visits. For 12 of the initial sample of 38 subjects who completed the intervention, stepping data for both visits were not available. The final sample included in the analysis consisted of 13 patients in the TC treatment group and 13 patients in the VR treatment group.

Statistical analyses were hypothesis driven and one-tailed. To evaluate treatment effects, the change scores for WBS, GZS and FSS were compared between-groups using independent samples t-test. We were also interested in how each group changed with respect to themselves, therefore paired sample t-tests were conducted comparing pre- and post-test scores for each treatment group separately. Finally, we were also interested in the relationship among the three outcomes variables for the two different treatment groups, and thus Pearson product moment correlations were conducted. All statistical analyses were conducted with SPSS version 10 (SPSS Corp., Chicago, IL), at an alpha of 0.05.

3. Results

3.1. Demographics

There were no significant differences in age ($p = 0.43$), height ($p = 0.53$) and weight ($p = 0.21$) between the TC and VR groups (Table 1). There were 4 males and 9 females in the VR group, and 7 males and 6 females in the TC group, and there were 8 subjects with unilateral VSP and 5 subjects with bilateral VSP in each treatment group. Proportions between treatment groups were non-significant from Chi-square analysis for gender ($p = 0.23$) and side (unilateral vs bilateral) of VSP impairment ($p = 1.0$).

3.2. Treatment effects

Outcomes variables are summarized in Table 2. There were no significant between-groups differences at baseline (first visit) in outcomes variables WBS ($p = 0.11$), GZS ($p = 0.28$) and FFS ($p = 0.15$). There were, however, significant differences between groups following the interventions:

Whole-body stability: WBS improved significantly more for the TC group than the VR group ($p = 0.04$). Within-groups comparisons showed a significant improvement post-treatment for the TC group ($p = 0.01$), and borderline significant improvement in the VR group ($p = 0.05$).

Gaze Stability: GZS improved significantly more for the VR group than the TC group ($p = 0.005$). Within-groups comparisons showed a significant improvement post-treatment for the VR group ($p = 0.009$) and no significant change in the TC group ($p = 0.08$).

Footfall Stepping Stability: FFS improved significantly more for the TC group than the VR group ($p = 0.02$). Within-groups comparisons showed a significant improvement post-treatment for the TC group ($p = 0.02$), and no significant change for the VR group ($p = 0.19$).

3.3. Correlations

For the VR group, there were significant correlations between change in WBS and GZS ($r = 0.60, p = 0.01$), between change in FSS and GZS ($r = 0.71, p = 0.003$), and between changes in FSS and WBS ($r = 0.646$, $p = 0.008$). A partial correlation analysis between FSS and WBS when controlling for GZS, indicated no significant relationship between FSS and WBS ($r = 0.39$, $p = 0.11$).

For the TC group, there was no significant correlation between change in WBS and GZS ($r = -0.19$, $p = 0.27$), between change in FSS and GZS ($r = -0.03$, $p = 0.46$), but there was a significant correlation between changes in FSS and WBS ($r = 0.578$, $p = 0.020$). A partial correlation analysis between FSS and WBS when controlling for GZS, indicated the significant relationship between FSS and WBS ($r = 0.58$, $p = 0.02$) was maintained.

4. Discussion

While the value of vestibular rehabilitation (VR) has been aptly demonstrated [18,21,29,41,42], the benefits of VR are by no means ubiquitous [28]. Alternative therapies, such as TC, have also shown promise for improving balance, especially in older adults and also within non-specifically diagnosed, balance-impaired populations [17,51,55]. Neither the direct benefits of TC for VSP, nor the relative benefits of TC versus VR

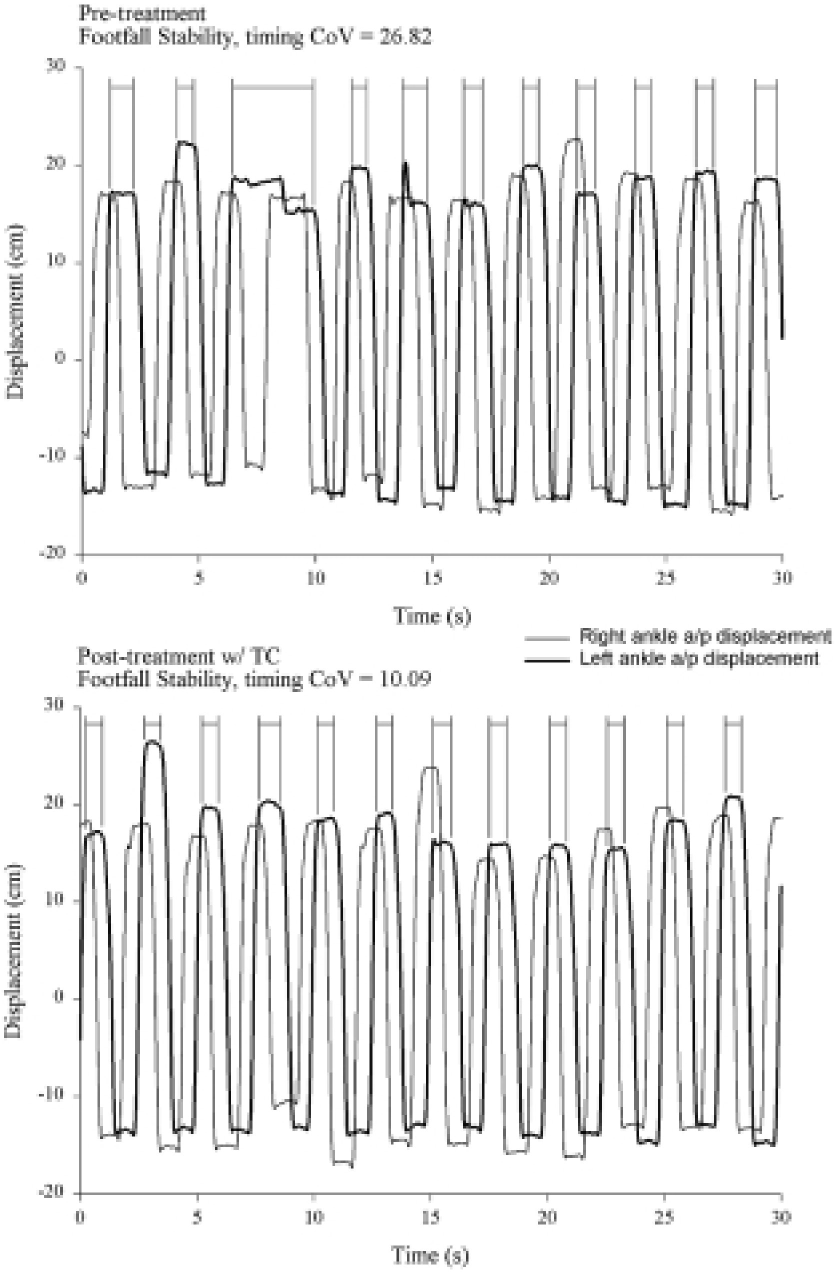

Fig. 4. Footfall pattern for right (thick line) and left (thin line) ankle centers during the stepping task for a representative subject randomized to the TC treatment group. Timing intervals of each foot during weight bearing (shown for the right ankle trajectory only) in both the forward (negative values) and backward (positive values) are analyzed to compute the coefficient of variation (CoV) of time intervals. Top panel: Pre-treatment footfall trajectory. Bottom panel: Post-treatment footfall trajectory. In this subject (72 year old male) the improvement in stepping stability is characterized by a more consistent stepping pattern.

have been thoroughly explored [46]. In this study, we examined the changes in gaze stability (GZS), whole-body stability (WBS) and foot-fall stability (FFS) following 10 weeks of VR or TC treatment in elderly persons with VSP. Our data suggest TC may indeed improve postural control in VSP patients, using different mechanisms from those that improve balance with standard VR.

The mechanisms responsible for improved balance in people with VSP are currently unknown, but im-

Table 1
Demographic data for subjects included in the analysis

	VR ($N = 13$)		TC ($N = 13$)	
	Mean	(SD)*	Mean	(SD)
Age	54.5	(11.2)	58.0	(11.2)
Height (m)	1.68	(0.12)	1.71	(0.10)
Mass (kg)	77.9	(17.8)	85.5	(11.8)
Gender	Males = 4,	Females = 9	Males= 7,	Females = 6
VSP side	Unilateral = 8,	Bilateral = 5	Unilateral = 8,	Bilateral = 5

*Standard deviation.

Table 2
Outcomes variables for subjects included in the analysis

Outcome Variable*	VR		Within groups p-value	TC		Within groups p-value	Between groups p-value
	Baseline† Mean (SD)	Change§ Mean (SD)		Baseline† Mean (SD)	Change§ Mean (SD)‡		
WBS	4.93 (2.18)	− 0.756 (1.57)	0.054	7.19 (4.32)	−3.30 (4.70)	0.013	0.005
GZS	3.56 (2.98)	− 0.915 (1.20)	0.009	2.49 (0.64)	0.670 (1.62)	0.081	0.042¶
FSS	9.77 (5.33)	1.19 (4.69)	0.189	12.8 (4.90)	−2.62 (4.23)	0.023	0.020

**WBS* = whole-body stability; *GZS* = Gaze stability; *FSS* = Footfall Stability.
†No significant between-groups difference ($p > 0.05$) in baseline scores; p-values not shown.
†SD = Standard deviation.
§Change score: negative value indicates improvement.
¶Computed for unequal variances (Levene's test, $p < 0.05$); all other between-groups comparisons computed assuming equal variances (Levene's test, $p > 0.05$).

proved gaze stabilization has been theorized to be an important factor. Indeed, gaze stabilization is a fundamental component of most contemporary VR protocols [18]. The present data clearly suggest that VR indeed improves GZS, but TC does not. Conversely, patients receiving TC had greater improvements in WBS and FFS than did the patients who received VR. While both groups demonstrated significant correlations between the change in WBS and FFS, this relationship appears to be mediated by changes in GZS, but only in patients receiving VR. Therefore, coupled with the non-significant improvement in gaze stability for the TC group, we are led to conclude that the mechanism whereby TC subjects improve whole body stability is not influenced by gaze stability. More concisely, patients receiving TC can improve movement stability without a measurable improvement in dynamic VOR function.

Although VR improves gaze stability (GZS) and may improve or enhance whole body stability (WBS) beyond the benefits engendered by balance training alone [13,18], the relationship between VOR and VSR function is not well understood. It may be that for some patients, especially those who are visually dependent, improvements in gaze stability following VR occur concurrently with improvements in postural control, but as our data indicate, such concurrency does not necessarily transpire. Indeed, our data are completely consistent with motor control theory, specificity of training tenets: patients improved most what they practiced most. The argument, therefore, that patients with vestibulopathy have impaired WBS, which is caused by foveation impairment, is logical but perhaps overly general. Vestibulospinal reflexes, along with the more obvious vestibulo-ocular reflexes (VOR), are impaired following vestibular insult [38], and the vestibulospinal system may respond to treatment, or compensate naturally, independently of the more frequently studied VOR. Indeed, VOR control has been accepted as being independent of balance control; for example, spinning skaters and dancers maintain superb equilibrium while systematically suppressing VOR gains [8]. Our findings support this assertion. Indeed, patients who received VR had significantly improved GZS, but despite having a significant correlation between changes in WBS and GZS, did not demonstrate greatly improved WBS (or FFS).

To our knowledge, these data are the first to test the assumption that improving gaze control among patients with VSP perforce improves postural stability. Our results suggest that gaze and whole-body stability are controlled by separate mechanisms, at least in VSP patients, despite the role of the vestibular apparatus in controlling both eye (via VOR) and body (via VSR) movements. In VSP patients with diminished (unilateral patients) or absent (bilateral patients) vestibular function, different compensatory mechanisms may be recruited to reestablish eye and body control. That both groups improved WBS (TC significantly more so than VR) may be explained by several mechanisms. First, both groups practiced posturally-challenging exercises, although the VR group focused much more on VOR-challenging exercises. Second, TC is designed to stimulate flowing, controlled motion both during weight transfers with fixed stances (foot placements) and during stepping, whereas VR has no such emphasis.

The TC-related improvements previously reported in musculoskeletal strength [25,31–33,49], flexibility [25, 31,32,43,45], limb control and kinesthetic sense [25, 57,58], and single stance times [17,20] may provide mechanisms that bypass the rapid demand-oriented typical function of the VOR, emphasizing proprioceptive and CNS adaptations. Improved strength, flexibility, and single stance times, for example, have been correlated with improved dynamic postural stability and reduced falls [29,34]. The improved FFS demonstrated among those patients who participated in the TC intervention, suggests that TC may enhance ankle and foot neuromuscular control.

TC's emphasis on mental concentration may have also led to improved postural control [46]. TC encourages practitioners to be focused and concentrated when practicing, and by so doing exclude other distractions and stressors, thus improving self-awareness of body movements [48]. A growing body of evidence suggests that attention control may be an important factor in posture and gait [54]. For example, older adults challenged with cognitive demands require longer periods of time to recover from postural perturbations than those without simultaneous cognitive demands [54]. Moreover, these effects are greatest for older individuals with balance impairments [5].

TC may also improve VSP patients' postural control by promoting general relaxation, reducing anxiety, and improving overall mood, optimism, and expectancy [6, 26,27]. Long-term chronic health problems and limited ADL, such as those associated with VSP, may lead to poor psychological profile, with further negative feedback on function [35]. Generally, fear/anxiety of falling is known to predict subsequent falls [1,2,30]. For example, among transitionally frail older adults, Kressing et al. [30] found an association between fear of falling and depression. Indeed, Wolf et al. [48] have demonstrated that changes in probability of falling in elders were highly correlated with a decreased fear of falling.

There are several limitations with our study. Our selection of outcomes variables was not exhaustive; we chose only to examine single measures of gaze stability, whole-body stability and foot-fall stability. Other biomechanical measures affected by the interventions could help explain the differences observed between groups. However, the variables we selected were chosen to be most consistent with our hypotheses, and we expect these variables are reflective of the gross neurobiomechanical changes embedded within the interventions. We also did not examine effects due to gender, age or diagnosis (whether unilateral or bilateral vestibular hypofunction, for example). Although there were no significant differences in these variables between treatment groups, we cannot preclude their effect in a larger study. One factor which may be important is the differential emphasis some VSP patients may place upon visual versus proprioceptive sensory input: an uneven distribution of such patients in the two different treatment groups may affect the outcomes. However, given the similar baseline values of each group (non-significant differences), we must conclude that this was not a factor in this study. Finally, the VR intervention was somewhat unconventional in that a group treatment approach was used to provide a better match with the group treatment approach to TC; however, the treatment effects we measured in the VR group may not be generalized to other, more traditional, VR approaches.

5. Conclusions

We conclude that VR most improves gaze and TC most improves whole-body stability, and the relationship between whole-body and footfall stability is mediated by gaze stabilization, for those receiving VR. Those receiving TC, however, have greater improvements in whole-body and footfall stability without improving gaze stability, suggesting they rely on non-gaze related mechanisms that may include training in alternative biomechanical strategies, improved body awareness, reduced distraction, and reduced anxiety/improved confidence.

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