



ELSEVIER

Contents lists available at ScienceDirect

Gait &amp; Posture

journal homepage: [www.elsevier.com/locate/gaitpost](http://www.elsevier.com/locate/gaitpost)

Full length article

# Vestibular training promotes adaptation of multisensory integration in postural control

KO Appiah-Kubi<sup>a</sup>, WG Wright<sup>a,b,\*</sup>

<sup>a</sup> Neuromotor Sciences Program, Department of Physical Therapy, Temple University, Philadelphia, PA, USA

<sup>b</sup> Department of Bioengineering, Temple University, Philadelphia, PA, USA

## ARTICLE INFO

### Keywords:

Vestibular training  
Headshake activity  
Sensory organization test  
Multiscale entropy

## ABSTRACT

**Background:** Postural stability depends on the integration of the multisensory system to produce motor outputs. When visual and somatosensory input is reliable, this reduces reliance on the vestibular system. Despite this, vestibular loss can still cause severe postural dysfunction. Training one or more of the three sensory systems through vestibular habituation and adaptation can alter sensory weighting and change postural behavior.

**Aim:** The purpose of this study was to assess sensory reweighting of postural control processing after combined vestibular activation with voluntary weight shift training in healthy adults.

**Methods:** Thirty-three healthy individuals (18–35 y.o.) were randomly assigned to one of three groups: No training (control), visual feedback weight shift training (WST) coupled with an active horizontal headshake (HS) activity to elicit a vestibular perturbation, or the same WST without HS (NoHS). Training was performed 2x/day, every other day (M, W, F), totaling six sessions. Pre- and post- assessments on the Sensory Organization Test (SOT) were performed. Separate between- and within- repeated measures ANOVAs were used to analyze the six SOT equilibrium scores, composite scores, sensory ratios and center of pressure (COP) variables by comparing baseline to post-training. Alpha level was set at  $p < .05$ .

**Results:** There was a significant group x session x condition change ( $p = .012$ ) in the COP multiscale entropy (MSE) velocity sway in the HS group during SOT conditions 5 and 6. Similarly, COP medio-lateral standard deviation sway (ML Std) showed group x session x visual condition ( $p = .028$ ), due to HS in condition 6 relative to other two groups.

**Conclusion:** Postural training can alter sensory organization after a visual feedback-vestibular activation training protocol, suggesting a possible sensory reweighting through vestibular adaptation and/or habituation.

**Significance:** Translating these findings into a vestibular-impaired population can stimulate the design of a rehabilitation balance protocol.

## 1. Introduction

Postural stability is maintained by the integration of somatosensory, visual and vestibular inputs to produce motor output. The vestibular system helps maintain visual fixation on an object during head and body movements, and integrates with the visual and somatosensory systems to maintain postural balance [1,2]. The postural control system prioritizes the somatosensory and visual systems for balance control; however, when there is reduced, inaccurate or unavailable information from these systems the postural system relies more heavily on vestibular input [3]. Although the vestibular system tends to be weighted less than the other two sensory systems during quiet stance [4], vestibular loss can cause severe postural dysfunction. The importance of vestibular input is further highlighted by how balance and locomotor function

improves with vestibular rehabilitation; it decreases dizziness and visual symptoms and corrects for overdependence on visual and somatosensory inputs [5]. The mechanisms driving this may include adaptation, substitution and/or habituation, which calibrate and reweight sensorimotor processes.

The vestibular system interacts with oculomotor, cervicocollic and spinal functions. The vestibulo-ocular reflex (VOR) coordinates with the vestibulo-collic reflex (VCR) and vestibulo-spinal reflex (VSR) to produce appropriate responses for postural maintenance [6–8]. By analyzing these vestibular responses through postural assessment, one may understand the sensory reweighting induced by vestibular training. The benefits of vestibular training have been shown for disorders such as vestibular hypofunction and Meniere's disease [9–11]; however, an optimal training protocol has not been established in clinical practice.

\* Corresponding author at: Neuromotor Sciences Program, Department of Physical Therapy, Temple University, Philadelphia, PA, USA.

E-mail address: [wrightw@temple.edu](mailto:wrightw@temple.edu) (W.G. Wright).

<https://doi.org/10.1016/j.gaitpost.2019.07.197>

Received 12 March 2019; Received in revised form 19 June 2019; Accepted 15 July 2019

0966-6362/ © 2019 Elsevier B.V. All rights reserved.

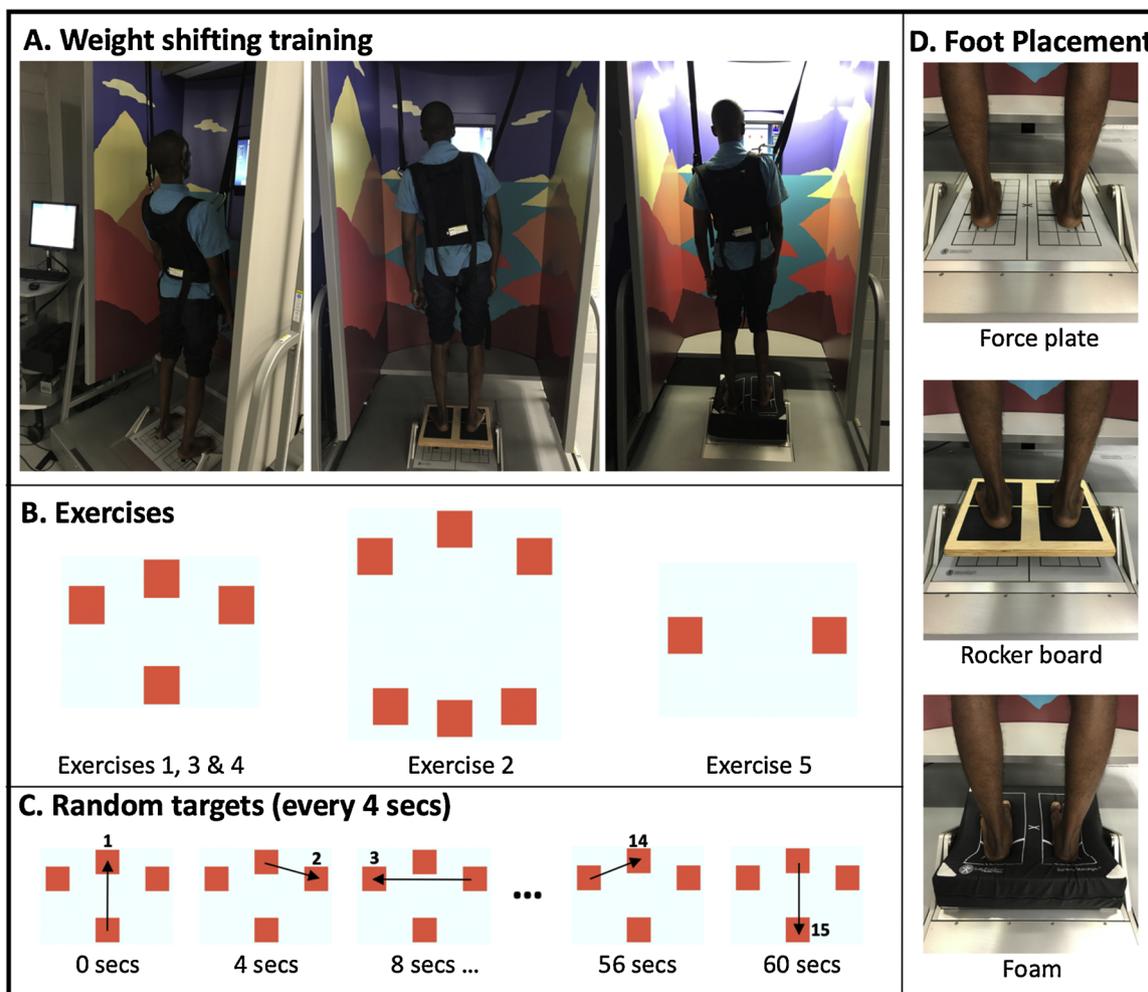


Fig. 1. Training protocol. A. Weight shifting exercises on force plate, rocker board and foam; B–C. Screen interface showing exercise targets of LOS, which changes randomly every 4 s; D. Foot placement during exercises (NeuroCom, 2014).

Engaging participants in horizontal headshake (HS) activities, which predominantly stimulate the lateral semicircular canals (SCC) [12], is useful in the assessment of vestibular imbalance during standing, walking-in-place and running-in-place [13,14]. Through the mechanisms of habituation and/or adaptation, performing repeated HS activities may also help relieve vestibular symptoms, while improving gaze stabilization and balance, as has been previously shown [9–11].

One way to enhance vestibular rehabilitation is by combining horizontal vestibular activation and postural training. Postural training involving active weight shift training (WST) and/or vestibular rehabilitation has proven to be effective in improving VOR function, balance and gait performance among individuals with vestibular impairments and chronic stroke [15–17]. In the current study, we combined headshake with WST, thereby concurrently training the multiple sensorimotor systems involved in postural control. This approach could be used to improve overall outcomes while reducing the duration of training sessions needed to realize gains. From a practical perspective this creates a more manageable training regimen leading to greater patient compliance. These considerations drove the design of a succinct, pragmatic vestibular-activation postural training regimen that could be used to induce sensory reweighting and change balance in healthy young adults.

To investigate this, we will use traditional postural metrics in addition to nonlinear analytics, which may reflect the temporal dynamics of the complex network of physiological systems that underlie postural stabilization [18]. We hypothesize the proposed training protocol will

cause changes to the highly adaptable network of neuromuscular connections controlling posture, which will be evident by less variability and greater complexity in the postural response.

## 2. Methods

### 2.1. Subjects

Thirty-three young healthy individuals (18 males; 24.5±4.4 years [18–35 years]; 1.7±0.2m) with no evidence of neurological/musculoskeletal impairments were randomly assigned to three groups: No training (control), visual feedback WST coupled with an active horizontal headshake (HS) activity, or the same WST without HS (NoHS). Participants self-reported having no ear infection or vestibular, oculomotor or balance issues for the past month. All participants gave written informed consent prior to participation.

### 2.2. Instrumentation and assessment procedure

A clinical musculoskeletal examination was performed by a physical therapist. Participants' posture was assessed in standing and lying positions to rule out signs of spinal, pelvic and leg length discrepancies. Pain and limited neck range of motion were also assessed and used as an exclusion criterion. The sensory organization test (SOT; NeuroCom® Smart Balance Master, Natus Medical Inc., Pleasanton, CA) was used to assess quiet standing balance at baseline and post-training. The SOT

**Table 1**  
Characteristics of Participants.

Variable	Control (n = 10)	Headshake (n = 12)	No Headshake (n = 11)	p
Age (yrs)	22.6 ± 2.9	27.5 ± 4.5	22.9 ± 3.8	0.007*
Height (m)	1.7 ± 0.1	1.8 ± 0.1	1.7 ± 0.1	0.160
Weight (kg)	79.3 ± 24.3	73.0 ± 17.9	67.0 ± 17.3	0.377
BMI (kg/m <sup>2</sup> )	27.4	22.5	23.2	0.143
Sex				
Male (%)	6 (60%)	7 (58%)	5 (45%)	0.775
Female (%)	4 (40%)	5 (42%)	6 (55%)	

Age, height, weight and BMI (mean±std); sex (frequency).

\*  $p < 0.05$ .

requires participants to stand upright as stably as possible for 20 s under six different testing conditions: Cond1– eyes open (EO) on stable support (SS), Cond2 – eyes closed (EC) on SS, Cond3 – sway-referenced visual surround (SRv) on SS, Cond4 – EO on SR support, Cond5 – EC on SR support, Cond6 – SRv on SR support [19].

### 2.3. Training protocol

The HS and NoHS groups performed training twice a day (3–4 hours apart) every other day amounting to three training days in one week, for a total of six training sessions. Before training, a baseline SOT measurement was collected. All training was performed using the NeuroCom® WST protocol. at level 3-forward and backward directions with 65%–70% limits of stability (LOS), and level 5-forward direction with 85%–90% LOS. Level 5 exercises required wider, more challenging LOS excursions than level 3. Five exercises were used for each level. The exercises include: (1) center 3-forward/backward on the force plate, (2) pin-wheel forward/backward on the force plate, (3) center forward/backward on a rocker board placed on the force plate, (4) center 3-forward/backward on foam placed on the force plate, and (5) forward/backward left/right on foam placed on the force plate, successively. Exercises 1, 3 and 4 have four targets, exercise 2 has six targets, and exercise 5 has just two targets (i.e., left and right). Each of the 15 exercises was administered for one minute. The exercises entailed participants leaning towards the specific direction related to the exercise number (i.e., forward, backward, diagonal or sideways) to reach a target that lights up randomly on the screen every 4 s (Fig. 1). Participants were instructed to quickly move towards the highlighted target as soon as possible and maintain that position until the next target lit up. Foot placement was standardized based on height and NeuroCom's heel alignment markings (participants 1.41–1.65 m used the M-line and > 1.66 m used the T-line). Foot placement on the rocker-board was estimated by ensuring ankle joint alignment with rocker-board fulcrum.

Participants in the HS group were instructed to rhythmically rotate their heads horizontally approximately 30° at 80 beats/min during WST exercises 1, 2 and 5 of level 3-forward direction, and at 100 beats/min for exercises 1, 2 and 5 of level 5-forward direction (Fig. 1B). The training protocol was a novel combination of center of mass shifting activities while standing in place on a flat surface, rocker board or foam and concurrently performing horizontal headshake activities. This protocol was designed to challenge sensorimotor coordination, while activating the vestibular system by encouraging gaze stability and smooth pursuit. Such headshake approaches have been used for postural assessment (e.g. HS SOT, [20]), but in this study we proposed to use it for training purposes. There were rest periods of 30 s between each exercise and 2 min. between each level. After the last exercise on the final training day, participants were seated for 5 min. to rest and recover, then a post-SOT assessment was performed. The control group only performed pre- and post-SOT assessments on day one and day five, respectively. Exercises were demonstrated and monitored by a physical therapist.

### 2.4. Data analysis

COP time series from the SOT were low-pass filtered at 30 Hz then analyzed to measure postural changes including COP sway area (using principal component analysis), sway velocity, medio-lateral (ML) standard deviation (Std), antero-posterior (AP) Std and multiscale entropy (MSE) sway velocity (MathWorks, 2016). The composite MSE was calculated as a mean across all  $\tau = 10$  time scales with  $m = 2$  and  $r = 0.2$ . The sampling rate for the SOT was 100 Hz, resulting in 2000 data points. This allowed for the data to be analyzed using MSE, since the minimum number of samples required to calculate the complexity of a time series is 200 [21]. A mixed model repeated measures analysis of variance (rmANOVA) was used to analyze SOT composite scores and sensory ratios (3 groups x 2 sessions). The sensory ratios were also used to analyze the relative sensory reweighting due to training. Similarly, rmANOVA was used to analyze the COP sway variables and equilibrium scores for the six SOT conditions (3 visual x 2 surface x 3 groups x 2 sessions), with the three visual and two surface levels representing the independent variables for sensory input. If significance was found in the omnibus ANOVA, then planned comparisons were evaluated using a follow-up rmANOVA. Bonferroni post-hoc adjustments were used to adjust for multiple between-group comparisons. All statistical analysis was conducted using SPSS software (v24.0; IBM Corp.) and significance set at  $\alpha \leq 0.05$ .

## 3. Results

### 3.1. Demographics

The thirty-three young adult participants were similar in all aspects except age, which showed a < 5 yr difference between groups (Table 1).

### 3.2. Standard deviation of medio-lateral COP

The mixed-model rmANOVA of the COP ML Std showed two main effects: *surface* ( $F_{1,30} = 79.8, p < .0001$ ) and *visual* ( $F_{2,29} = 62.1, p < .0001$ ). With respect to the study intervention, there was one significant group x session main effect: *group x session x visual* ( $F_{4,60} = 2.94, p = .028$ ). None of the other *group x session* effects were significant. There was also one other significant interaction: *visual x surface* ( $F_{2,29} = 37.2, p < .0001$ ). Generally, HS group showed decreased ML Std pre- to post-training. The other groups did not show any decrease in sway, with NoHS showing relatively increased sway. Planned comparisons of this *visual training* effect revealed group effects between HS & control in EO & SRv conditions (conditions 1,4 & 3,6;  $F_{1,20} = 6.07, p = .023$ ) and in EC & SRv conditions (conditions 2,5 & 3,6;  $F_{1,20} = 5.74, p = .027$ ; Fig. 2A & B). Similarly, visual effects were found between NoHS & control in the EC & SRv conditions ( $F_{1,20} = 7.19, p = .015$ ; Fig. 2A & C). However, ML Std did not reveal training effect between HS & NoHS.

### 3.3. Multiscale entropy of COP sway velocity

The mixed-model rmANOVA of this nonlinear metric showed three main effects: *surface* ( $F_{1,30} = 32.0, p < .0001$ ), *visual* ( $F_{1,30} = 8.28, p = .001$ ) and *session* ( $F_{1,30} = 8.13, p = .008$ ). With respect to the study interventions, there were two significant group x session effects: *group x session x visual* ( $F_{4,60} = 3.71, p = .009$ ) and *group x session x visual x surface* ( $F_{4,60} = 3.50, p = .012$ ). There was no significant difference in the group x session x surface ( $F_{2,30} = .17, p = .845$ ). Two other significant interactions were *session x surface* ( $F_{1,30} = 8.73, p = .006$ ) and *visual x surface* ( $F_{2,29} = 7.69, p = .002$ ). Generally, all the groups showed an increase in MSE sway velocity pre- to post-training, with HS exhibiting the greatest change. Planned comparison of the *group x session x visual x surface* effect showed effects between HS &

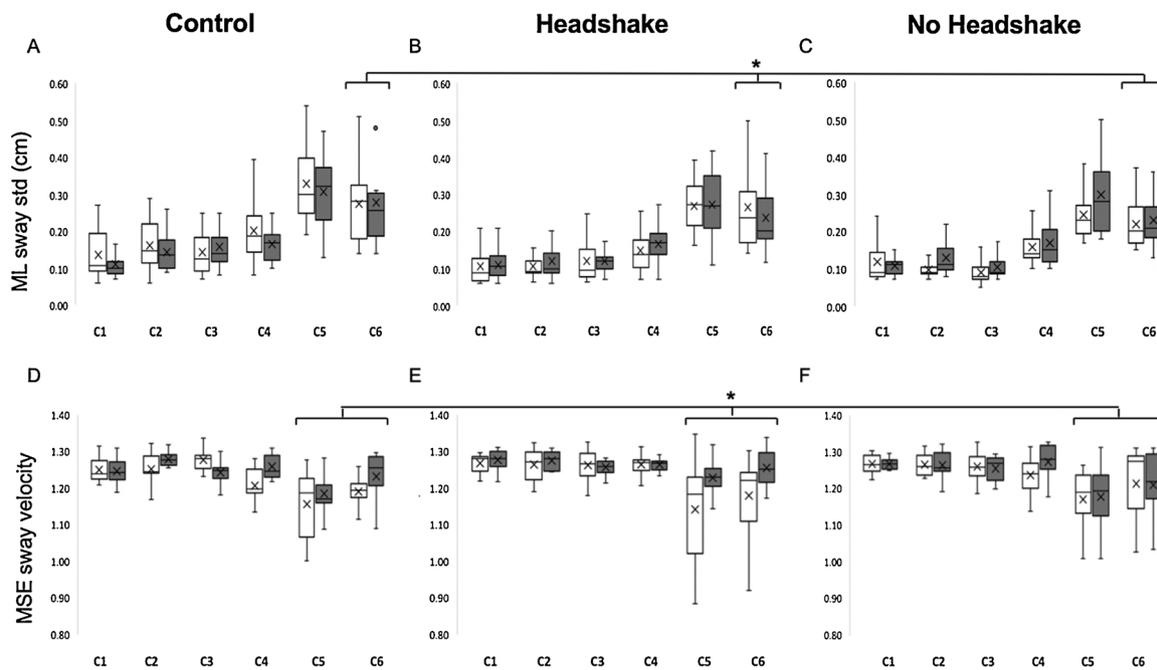


Fig. 2. ML sway Std (top row) and MSE sway velocity (bottom row) of the three groups after combined WST and vestibular training. White bar = pre-training measurements; gray bar = post-training measurements. X-marks on box plots indicate means. \* $p < 0.05$  for group  $\times$  session difference.

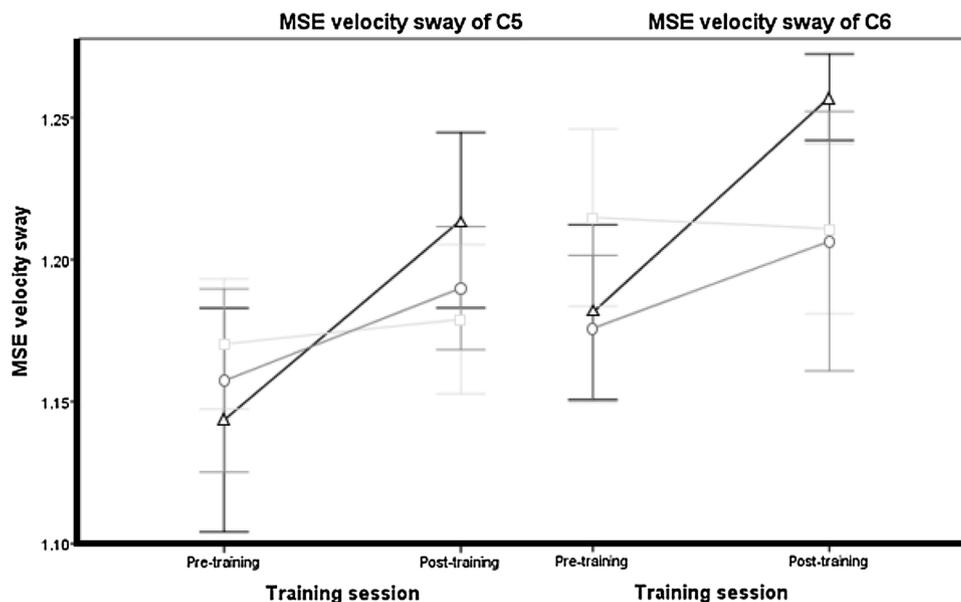


Fig. 3. Conditions 5 and 6 of MSE velocity of the three groups after combined vestibular training. Black/triangle = HS, light-gray/circle = NoHS, dark-gray/square = Control.

control ( $F_{1,20} = 5.32, p = .032$ ; Fig. 2D & E) and HS & NoHS ( $F_{1,21} = 10.75, p = .004$ ; Fig. 2E & F) in the EO & visual SR conditions. Similarly, the *group  $\times$  session  $\times$  visual* effect was found between HS & NoHS in the EO & EC conditions ( $F_{1,21} = 7.73, p = .011$ ) and EO and SRv conditions ( $F_{1,20} = 7.02, p = .015$ ). The *group  $\times$  session  $\times$  visual* effect was also found between HS & control in the EC & SRv conditions ( $F_{1,20} = 6.98, p = .016$ ; Fig. 3).

### 3.4. SOT scores

There was a significant *group  $\times$  session* interaction in somatosensory ratio ( $F_{2,30} = 4.43, p = .021$ ) from pre- to post-training (Table 2).

Significant differences between HS and NoHS groups were found ( $F_{1,21} = 7.43, p = .013$ ), with HS showing an increase in the somatosensory ratio. For SOT equilibrium and composite scores, none of the *group  $\times$  session* effects were significant ( $p > .10$ ) (Table 2).

### 3.5. Other sway variables

None of the *group  $\times$  session* effects were significant for COP sway area, COP velocity and AP Std ( $p > .10$ ). Negative COP Std values indicate decreased sway variability, positive SOT values indicate decreased sway range and positive sensory ratios indicate increased sensory weighting (Table 2).

**Table 2**  
Sway variables and sensory ratios of the three groups after vestibular balance training.

Sway variables	Control			Headshake			No Headshake		
	Pre	Post	Post – Pre	Pre	Post	Post – Pre	Pre	Post	Post – Pre
<i>COP AP standard deviation (cm)</i>									
EO - SS	0.41	0.29	-0.12±0.31	0.24	0.23	0.00±0.07	0.26	0.24	-0.02±0.11
EC - SS	0.51	0.46	-0.05±0.15	0.39	0.34	-0.04±0.10	0.32	0.45	0.13±0.27
SRv- SS	0.51	0.44	-0.07±0.15	0.41	0.36	-0.05±0.21	0.33	0.33	0.00±0.13
EO - SR	0.85	0.75	-0.10±0.40	0.88	0.63	-0.25±0.07	1.22	1.26	0.03±0.79
EC - SR	1.82	1.69	-0.13±0.50	1.63	1.37	-0.25±0.58	1.67	1.66	0.00±0.63
SRv- SR	2.05	1.86	-0.19±0.46	1.94	1.37	-0.56±0.95	1.81	2.04	0.23±0.81
<i>SOT equilibrium scores (100%)</i>									
EO - SS	92.2	94.1	1.9±5.3	95.0	95.5	0.1±1.7	94.9	94.8	-0.0±1.7
EC - SS	90.1	90.8	0.6±2.8	92.6	93.4	0.9±1.6	93.6	90.8	-2.8±4.1
SRv- SS	89.7	91.3	1.6±2.2	92.6	93.4	0.8±3.6	93.1	93.3	0.2±2.7
EO - SR	84.5	85.4	0.9±7.6	85.1	89.3	4.3±8.9	79.4	78.3	-1.1±11.5
EC - SR	67.1	67.6	0.5±7.0	70.0	73.9	3.9±7.5	68.8	67.9	-0.9±9.7
SRv- SR	63.6	69.9	6.3±6.2	69.7	76.4	6.7±13.7	67.7	64.4	-3.3±13.8
Composite	78.3	80.5	2.2±4.2	81.1	84.8	3.7±4.9	79.6	78.5	-1.1±6.7
<i>Sensory ratios</i>									
SOM	0.97	0.96	-0.01±0.02	0.97	0.98	0.01±0.02	0.99	0.96	-0.03±0.04
VIS	0.91	0.91	-0.01±0.07	0.89	0.94	0.04±0.1	0.84	0.83	-0.01±0.1
VES	0.73	0.72	-0.01±0.07	0.73	0.77	0.04±0.1	0.72	0.72	-0.01±0.1
PREF	0.97	0.98	0.01±0.05	0.97	0.98	0.01±0.1	0.98	0.97	-0.01±0.0

EO– eyes open, EC– eyes closed, SR– sway-referenced surface, SRv– sway-referenced visual, SS– stable surface, SOM– somatosensory ratio, VIS– visual ratio, VES– vestibular ratio, PREF– visual preference ratio.

\* p < 0.05 for group x session difference.

**4. Discussion**

Concurrent vestibular activation and weight shift training (i.e., HS group) showed significant changes in postural control relative to the NoHS group (i.e., WST only without headshake) and the control group. These changes were evident in the nonlinear measure of postural variability (MSE of COP sway velocity) and the medio-lateral COP variability (ML Std) during the visual and visual-vestibular conditions of the SOT. The results suggest that following rhythmic horizontal headshake training postural stability increases and that these changes are specific to the type of sensorimotor stimulation. The theoretical and clinical relevance of these findings are discussed below.

**4.1. Vestibular training improves postural stability**

The NeuroCom® SOT standard output of the Equilibrium Scores is only a measure of balance in the AP direction. Because we analyzed both AP and ML COP, we were able to detect changes in ML sway standard deviation and MSE sway velocity following training. The ML sway changes could be explained by the effect of the horizontal headshake activity that produced vestibular activation primarily along the medio-lateral axis potentially causing greater adaptation in lateral postural responses. Because SOT conditions that mainly rely on visual (i.e., Cond4), vestibular (i.e., Cond5), and visual-vestibular processing (i.e., Cond6) were affected the most, this points to the targeted effects of headshake activities on postural behavior. The vestibular system directly impacts the visual system through the VOR and sensory adaptation leading to gaze stabilization, and thus, can improve postural balance [18]. While the changes observed were most prominent in the HS group, whether this was due to specific adaptation of only the horizontal SCC pair could not be addressed, since no direction-specific measures of VOR were taken.

MSE analysis has been shown to be sensitive to systematic changes in physiological processes that underlie postural sway during quiet standing; processes that traditional measures such as COP standard deviation may miss [18,22]. While higher entropy values have been found to be associated with more automatic postural control and fewer constraints on the balance control strategies, i.e., higher entropy reflects more efficient balance [22], MSE has also been associated with inability to direct attentional control

during postural tasks or with age-related changes in postural control [22]. Rather than take a stance on whether the change in MSE reported here is “good” or “bad” noise, we will simply provide three reasons supporting the validity of using this metric for detecting change following our intervention. First, the MSE pattern of change across the six SOT conditions was similar to the well-established pattern of SOT equilibrium scores. Second, depending on the training intervention, MSE of COP sway velocity was significantly altered. Third, MSE was found to be even more sensitive in detecting subtle physiologic postural changes than other metrics, in that it was the only variable that revealed significant changes in both conditions 5 and 6 in the HS group. These two conditions heavily rely on the vestibular input and visual-vestibular interaction, so it appears that MSE was able to detect that headshake activities influenced these sensory processes, when comparing pre-post changes across groups. While a small change was seen in the control group, only the HS group showed significant changes, when compared with controls and the NoHS group.

**4.2. Sensory reweighting during vestibular training**

The headshake activities coupled with WST incorporates several mechanisms. These include gaze stability and smooth pursuit, which changed with headshake and visual tracking, and somatosensory inputs which changed with surface conditions. A significant group by session interaction in the somatosensory ratio was found between HS and NoHS, with the HS showing somatosensory up-weighting. While there was not a significant change in the other sensory ratios, we did find significant vestibular and visual-vestibular changes using MSE analysis. Together this may suggest that while the vestibular training group showed up-weighting of the somatosensory input, there was a simultaneous down-weighting in the vestibular system.

These findings may be explained by vestibular habituation and/or adaptation. The actual neural mechanisms supporting the effectiveness of vestibular adaptation and habituation exercises are still debated [23]; however, they may each be involved during these head movement exercises. Habituation involves learned suppression of vestibular symptoms such as dizziness using repeated exposure to provocative movements [9,24]. During habituation, the excitatory postsynaptic potential transmitted from the sensory receptor to the motor neuron is

gradually reduced in amplitude due to the low amount of calcium ions in the presynaptic membrane. After further exposures to repetitive sensory input, the synaptic connections decrease in number leading to long-term structural changes, which can contribute to decreased dizziness [25,26]. Relating this to our current training protocol, vestibular habituation occurs during repetitive headshake suppressing dizziness (i.e. the provocative stimulus) [24]. As a result, the vestibular signal driving oculomotor control goes down reducing VOR, but this also reduces the vestibular inputs driving potentially destabilizing VCR and VSR responses. If vestibular gain is gradually reduced, vestibular down-weighting may drive compensatory up-weighting of the somatosensory and/or visual channels.

We also considered the alternative mechanism of adaptation as the driver of these postural changes. During adaptation exercises, the task of foveating a visual target while performing horizontal headshake and WST provides a visual error signal which can be used to calibrate eye-in-head and head-on-body sensorimotor control [27,28]. The bottom-up signals from the somatosensory channel and spinal reflexes are triggered by the soles of the feet and the ankle joint, which are also used during this adaptation process [28,29]. As the individual adapts to the demands of standing on an unstable surface, integrating dynamic visual and vestibular inputs, while coordinating volitional head movements with automatic stabilization responses, the postural response may become more efficient and less variable.

#### 4.3. Limitations and further studies

One limitation of the study is whether these findings can be generalized to vestibular impaired populations. Moreover, the absence of a vestibular-impaired cohort in the current study made it difficult to induce large changes in otherwise healthy behavior. Another limitation is that sensory reweighting was inferred only from COP measures on the SOT. Future studies will include other postural tests (e.g. reactive postural perturbations), and measurement techniques, such as electromyography, electro-oculography and video head impulse test for recording vestibular responses. Also, by adding vertical headshake, the involvement of otoliths and descending vestibulo-spinal pathways can be better assessed. Finally, our immediate follow-up assessment did not allow us to ascertain whether the gains would lead to long-term retention, however, future studies will include delayed post-training assessments (> 24 h).

#### 4.4. Conclusion

Combined vestibular activation and weight shift training produce significant changes in the vestibular and visual-vestibular processes as evidenced in two postural stability metrics; a traditional (i.e., ML Std) and non-traditional (i.e., MSE velocity) measure. These changes can, in part, be explained by an interaction of high-level sensory reweighting processes and lower-level adaptation or habituation processes. The current findings may help guide the development of a vestibular rehabilitation intervention in impaired neurological populations, such as those with vestibular disorders or sensory integration problems as seen in traumatic brain injury. Furthermore, the exercise protocol can be modified for home-based training with virtual reality goggles or using smart-phone solutions, which will increase portability, accessibility and affordability.

#### Declaration of Competing Interest

The authors have no conflicts of interest to declare at this time.

#### References

- [1] L. Nashner, A. Berthoz, Visual contribution to rapid motor responses during

- postural control, *Brain Res.* 150 (1978) 403–407, [https://doi.org/10.1016/0006-8993\(78\)90291-3](https://doi.org/10.1016/0006-8993(78)90291-3).
- [2] L.M. Nashner, Adaptation of human movement to altered environments, *Trends Neurosci.* 5 (1982) 358–361, [https://doi.org/10.1016/0166-2236\(82\)90204-1](https://doi.org/10.1016/0166-2236(82)90204-1).
- [3] A. Shumway-Cook, F.B. Horak, Assessing the influence of sensory interaction on balance. Suggestion from the field, *Phys. Ther.* 66 (1986) 1548–1550, <https://doi.org/10.1093/ptj/66.10.1548>.
- [4] R.J. Peterka, Sensorimotor integration in human postural control, *J. Neurophysiol.* 88 (2002) 1097–1118, <https://doi.org/10.1152/jn.00605.2001>.
- [5] F.O. Black, S.C. Pesznecker, Vestibular adaptation and rehabilitation, *Curr. Opin. Otolaryngol. Head Neck Surg.* 11 (2003) 355–360, <https://doi.org/10.1097/00020840-200310000-00008>.
- [6] T.C. Hain, J.O. Helminsky, *Anatomy and physiology of the Normal vestibular system, Chapter 1. Vestibular Rehabilitation*, 3rd ed., FA Davis Company, Philadelphia USA, 2007.
- [7] T.C. Hain, Postural, Vestibulospinal and Vestibulocollic Reflexes, (2014) (07/12/2017), <http://www.dizziness-and-balance.com/anatomy/vspine.htm>.
- [8] V.J. Wilson, R. Boyle, K. Fukushima, P.K. Rose, Y. Shinoda, The vestibulocollic reflex, *J. Vestib. Res. Equilib. Orientat.* 5 (1995) 147–170 (accessed August 7, 2018), <http://ci.nii.ac.jp/naid/10006160906/en/>.
- [9] S.A. Telian, N.T. Shepard, M. Smith-Wheelock, J.L. Kemink, Habituation therapy for chronic vestibular dysfunction: preliminary results, *Otolaryngol. Head Neck Surg.* (1990), <https://doi.org/10.1177/019459989010300113>.
- [10] E.E. Hansson, Vestibular rehabilitation - for whom and how? A systematic review, *Adv. Physiother.* 9 (2007) 106–116, <https://doi.org/10.1080/14038190701526564>.
- [11] Y.J. Lee, J.E. Shin, M.S. Park, J.M. Kim, B.R. Na, C.H. Kim, H.J. Park, Comprehensive analysis of head-shaking nystagmus in patients with vestibular neuritis, *Audiol. Neurotol. Extra* 17 (2012) 228–234, <https://doi.org/10.1159/000336958>.
- [12] F. Spoor, B. Wood, F. Zonneveld, Implications of early hominid labyrinthine morphology for evolution of human bipedal locomotion, *Nature* 369 (1994) 645–648, <https://doi.org/10.1038/369645a0>.
- [13] C.H. Kim, J.E. Shin, C.I. Song, M.H. Yoo, H.J. Park, Vertical components of head-shaking nystagmus in vestibular neuritis, Meniere's disease and migrainous vertigo, *Clin. Otolaryngol.* 39 (2014) 261–265, <https://doi.org/10.1111/coa.12286>.
- [14] M.S. Panosian, G.D. Paige, Nystagmus and postural instability after headshake in patients with vestibular dysfunction, *Otolaryngol. Head Neck Surg.* 112 (1995) 399–404, [https://doi.org/10.1016/S0194-5998\(95\)70273-3](https://doi.org/10.1016/S0194-5998(95)70273-3).
- [15] B.A. Alsalaheen, A. Mucha, L.O. Morris, S.L. Whitney, J.M. Furman, C.E. Camiollo-Reddy, M.W. Collins, M.R. Lovell, P.J. Sparto, Vestibular rehabilitation for dizziness and balance disorders after concussion, *J. Neurol. Phys. Ther.* 34 (2010) 87–93, <https://doi.org/10.1097/NPT.0b013e3181d5e568>.
- [16] K. Jung, Y. Kim, Y. Chung, S. Hwang, Weight-Shift Training Improves Trunk Control, Proprioception, and Balance in Patients with Chronic Hemiparetic Stroke, *Tohoku J. Exp. Med.* 232 (2014) 195–199, <https://doi.org/10.1620/tjem.232.195>.
- [17] T. Mitsuake, M. Sakamoto, K. Ueta, S. Oka, E. Horikawa, Effects of vestibular rehabilitation on gait performance in poststroke patients, *Int. J. Rehabil. Res.* 40 (2017) 240–245, <https://doi.org/10.1097/MRR.0000000000000234>.
- [18] M.A. Busa, R.E.A. van Emmerik, Multiscale entropy: a tool for understanding the complexity of postural control, *J. Sport Heal. Sci.* 5 (2016) 44–51, <https://doi.org/10.1016/j.jshs.2016.01.018>.
- [19] L.M. Nashner, J.F. Peters, Dynamic posturography in the diagnosis and management of dizziness and balance disorders, *Neurol. Clin.* (1990), [https://doi.org/10.1016/S0733-8619\(18\)30359-1](https://doi.org/10.1016/S0733-8619(18)30359-1).
- [20] J.A. Honaker, K.L. Janky, J.N. Patterson, N.T. Shepard, Modified head shake sensory organization test: sensitivity and specificity, *Gait Posture* 49 (2016) 67–72, <https://doi.org/10.1016/j.gaitpost.2016.06.024>.
- [21] J.M. Yentes, N. Hunt, K.K. Schmid, J.P. Kaipust, D. McGrath, N. Stergiou, The appropriate use of approximate entropy and sample entropy with short data sets, *Ann. Biomed. Eng.* 41 (2) (2013) 349–365, <https://doi.org/10.1007/s10439-012-0668-3>.
- [22] F.G. Borg, G. Laxåback, Entropy of balance—some recent results, *J. Neuroeng. Rehabil.* 7 (2010) 38, <https://doi.org/10.1186/1743-0003-7-38>.
- [23] R. Clendaniel, The effects of habituation and gaze-stability exercises in the treatment of unilateral vestibular hypofunction—preliminary results, *J. Neurol. Phys. Ther. JNPT.* 34 (2010) 111–116, <https://doi.org/10.1097/NPT.0b013e3181deca01.The>.
- [24] N.T. Shepard, S.A. Telian, A. Raj, M. Smith-Wheelock, Vestibular and balance rehabilitation therapy, *Ann. Otol. Rhinol. Laryngol.* 102 (3) (1993) 198–205, <https://doi.org/10.1177/000348949310200306>.
- [25] A. Shumway-Cook, M.H. Woollacott, *Motor Control: Theory and Practical Applications*, Williams and Wilkins Google Scholar, Philadelphia, 2001.
- [26] L.H. Tee, N.W.C. Chee, Vestibular rehabilitation therapy for the dizzy patient, *Ann. Acad. Med. Singapore* 34 (2005) 289–294.
- [27] S.J. Herdman, Role of vestibular adaptation in vestibular rehabilitation, *Otolaryngol. Head Neck Surg.* 119 (1) (1998) 49–54, [https://doi.org/10.1016/S0194-5998\(98\)70195-0](https://doi.org/10.1016/S0194-5998(98)70195-0).
- [28] S.J. Herdman, Vestibular rehabilitation, *Curr. Opin. Neurol.* 26 (2007) 608, <https://doi.org/10.1097/WCO.0b013e3181d5e564>.
- [29] A.A. McCall, B.J. Yates, Compensation following bilateral vestibular damage, *Front. Neurol.* (December) (2011) 1–13, <https://doi.org/10.3389/fneur.2011.00088>.