EFFECTS OF VESTIBULAR TRAINING ON POSTURAL CONTROL OF HEALTHY ADULTS

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by
Kwadwo Osei Appiah-Kubi, MS, PT
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Examining Committee Members:
W. Geoffrey Wright, PhD, Health & Rehabilitation Sciences Dept., Temple University, Chair
Ryan Tierney, PhD, ATC, Health & Rehabilitation Sciences Dept., Temple University
Richard Lauer, PhD, Health & Rehabilitation Sciences Dept., Temple University
Anne Galgon, PhD, PT, NCS, Physical Therapy Department, University of the Sciences
Laurie King, PhD, PT, External Member, Department of Neurology, Oregon Health & Science University
ABSTRACT

**Background:** Postural stability is maintained by the central integration of the multisensory inputs to produce motor outputs. When visual and somatosensory input is available and reliable, this reduces the postural control system’s reliance on the vestibular system. Despite this, vestibular loss can still cause severe postural dysfunction. Training one or more of the three sensory systems can alter sensory weighting and change postural behavior. Exercises to activate the vestibular system is one form of training which resolves symptoms of vestibular impairments. Vestibular activation exercises, including horizontal and vertical headshaking, influences vestibular-ocular and -motor responses and have been showed to be effective in vestibular rehabilitation. However, no study has employed a concurrent vestibular activation and weight shift postural training to realize a more effective rehabilitation method by positively influencing sensory reweighting mechanisms and vestibular reflexes. Our pilot study (n=33) has demonstrated significant postural stability improvement in the center of pressure (COP) medio-lateral standard deviation sway (ML Std) and multiscale entropy (MSE) sway velocity among the horizontal headshake group. This improvement was found in the vestibular and visual-vestibular conditions of the Sensory Organization Test (SOT) assessment when compared to a non-headshake training group and no training group (control).

**Aims:** The main aim of this study was to assess sensory reweighting of postural control processing and vestibular-ocular and -motor responses after combined vestibular activation with postural training in healthy young adults. It was hypothesized that the effect of this training would significantly alter the pattern of sensory weighting by changing the ratio of visual, somatosensory and vestibular dependence needed to maintain postural stability, and significantly decrease vestibular responses.
**Methods:** Forty-two young healthy individuals (22 females; 23.0±3.9 years [18-35 years]; 1.6±0.1 meters) were randomly assigned into four groups: 1) visual feedback weight shift training (WST) coupled with an active horizontal headshake (HHS), 2) same WST with vertical headshake (VHS), 3) WST with no headshake (NHS) and 4) no training/headshake control (CTL) groups. The headshake groups performed an intensive body weight shift training (WST) together with horizontal or vertical rhythmic headshake 30° in both directions in accordance to the beat of a metronome ranging from 80 to 120 beats per minute. The NHS group performed the WST with no headshake while the control did not perform any training. Five 15-minute training sessions were performed on consecutive days for one week with the weight shift exercises involving upright limits of stability activities on a flat surface, foam or rocker board. All groups performed baseline- and post-assessments including SOT and force plate platform up and down unpredictable ramp perturbations, coupled with electromyographic (EMG) and electro-oculographic (EOG) recordings. The video head impulse test (vHIT) system was also used to record horizontal VOR gain.

**Statistical analysis:** A between- and within-group repeated measures ANOVA of 6 (3 visuals x 2 surfaces) conditions x 4 groups x 2 sessions was used to analyze five COP sway variables, the equilibrium and composite scores and sensory ratios of the SOT as well as EMG (onset, duration, peak amplitude, peak time and power spectral densities) signals and horizontal VOR gain. The five COP variables were: sway area, sway velocity, antero-posterior (AP) standard deviation, ML Std and MSE sway velocity. Similarly, COP variables, EMG, as well as EOG (angle in degrees) and vestibular reflex (vertical VOR, VCR and VSR gain) data during ramp perturbation trials were analyzed. Pearson product-
moment correlation was used to evaluate the relationships between outcome measures. Alpha level will be set at p<.05.

**Results:** The concurrent vestibular and WST showed a significant somatosensory downweighting ($p = .050$) in the headshake groups compared to the other groups. The training also showed a significant decreased horizontal VOR gain ($p = .040$), faster automatic postural response ($p = .003$) with improved flexibility ($p = .010$) in the headshake groups. Muscle activation pattern in medial gastrocnemius ($p = .033$) and eye movement variability ($p = .024$) were significantly decreased in the headshake groups following training. Pearson correlations showed moderate associations between postural sway, eye movement variables and vestibular reflex gains. Specifically, there were negative associations between VOR gain versus postural sway ($r = -0.460 - 0.553; p \leq .008$), and eye movement variability versus postural sway ($r = -0.404 - 0.521; p \leq .015$), and positive associations between EMG peak amplitude versus postural sway ($r = 0.435 - 0.498; p \leq .004$) and eye movement variability ($r = 0.467; p = .007$).

**Conclusion:** The concurrent vestibular activation and weight shift training modifies vestibular-dependent responses after the training intervention as evidenced in somatosensory downweighting, decreased VOR gain, decreased eye movement variability and better postural flexibility and faster automatic postural response. The findings suggest this is predominantly due to vestibular habituation and adaptation of VOR, VCR and VSR which induced sensory reweighting. The study also found moderate associations between postural measures and vestibular responses in vestibular reflex gains, eye movement variability and muscle activations. These findings may help predict postural changes through vestibular habituation and also provide insight into the behavior of eye movements and muscle activations following vestibular training. In addition, the
findings may be used to guide development of a vestibular-postural rehabilitation intervention in impaired neurological populations, such as with vestibular disorders or sensory integration problems present in traumatic brain injuries.
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CHAPTER 1
INTRODUCTION AND REVIEW OF THE LITERATURE

Public Health Implications of Postural Instability

Postural stability is essential to performing many activities of daily living. One of the common causes of postural imbalance is vestibular dysfunction; assessing and treating vestibular function is often integral to postural balance rehabilitation. Vestibular dysfunction can be described as a peripheral (inner ear, VIIIth nerve) or central (e.g., vestibular nuclei, cerebellum, vestibular cortical center) disorder of the vestibular system that can cause problems with postural stability and positional or movement-related dizziness. Vestibular disorders have an enormous societal impact since it is found across all ages in the population. Within a period of five years, an alarming 69 million US adults aged 40 years and older experienced vestibular dysfunction. Those who exhibited clinical symptoms had a 12-fold increase in odds of marked postural imbalance. Vertigo among school-age children has been found for at least one episode in the last year in 15% of the population. Sun and colleagues found an annual average economic burden of $13,019 per bilateral vestibular deficiency and $3,531 per unilateral deficiency per patient. Other studies have established the effects of vestibular disorders across ages and different global populations. Most of the symptoms are due to vestibular processing disorders arising from either peripheral or central vestibular system problems. However, vestibular impairment is not assessed routinely by medical personnel and thus does not receive adequate attention for its management. This research will investigate the underlying sensory weighting mechanisms affecting the integration of vestibular, visual and somatosensory channels by using various postural training protocols that can alter postural behavior through the vestibular ocular and vestibular postural systems.
Evidence and Effectiveness of Current Management of Vestibular Deficits

is Insufficient

Vestibular rehabilitation research studies have shown evidence that it can be effective in improving primary and secondary vestibular symptoms. Some research studies focus on vestibular training methods only without including postural stability activities. Evidence has shown that studies that employed combined programs such as vestibular activation activities (including gaze stabilization training and habituation exercises) and balance training yielded significant improvement in subjective dizziness, oculomotor control, balance and gait for concussed and mild traumatic brain injury participants. However, a review study showed that some groups of patients may not show improvement, probably due to the type of vestibular rehabilitation employed. Although using sensory reweighting to explain the benefits of training protocols in improving the vestibular system has been established, there remain open questions regarding the neural structures, pathways and processes that drive the effectiveness of sensory reweighting mechanisms specific to improving vestibular impairment through vestibular activation and postural rehabilitation. The focus of this study is to identify the specific underlying postural mechanisms mainly along the vestibular pathways following our vestibular activation intervention. Vestibular activation is referred to headshaking activities, which may or may not include visual focus leading to a potential vestibular adaptation and/or habituation.

Combined Postural and Vestibular Retraining Can Be Useful in Managing Vestibular Deficits

Postural stability is maintained by the central 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 stability 18,19. The postural system prioritizes the somatosensory and visual systems for balance control, however, when there is reduced, inaccurate or unavailable information from these systems the central nervous system (CNS) will depend on the information provided by the vestibular input 20. Although the vestibular system tends to be weighted less than the other two sensory systems during quiet stance 21, vestibular loss can cause severe postural dysfunction, and thus its importance in postural stability should not be underestimated. At the same time, vestibular rehabilitation can be very effective for improving balance following vestibular loss. Vestibular rehabilitation can decrease dizziness and visual symptoms, correct overdependence on visual and somatosensory inputs, improve neuromuscular conditioning and increase balance and walking functions 9,22. The mechanisms are based on the principles of neuroplasticity using adaptation, substitution and habituation to reinforce already existing sensorimotor processes and reflexes (e.g., vestibulo-ocular reflex– VOR). Adaptation uses an error-driven motor learning process to account for predictable changes through a sensory feedforward system until accurate outcomes are attained 23. Adaptation, therefore, uses both feedback and feedforward mechanisms. Adaptation exercises are designed to regulate and adapt sensory neural processing to improve the VOR, which can improve gaze stabilization and reduce symptoms. Substitution exercises are aimed at promoting alternative strategies, such as, the use of other eye movements for impaired vestibular function. For instance, one can be trained to use saccades, which produces quick eye movements, to replace the slow phase of the VOR component following vestibular dysfunction to assist in the maintenance of gaze stability 24. Habituation exercises involve repeated exposure to provocative stimuli or head
movements to desensitize and consequently resolve symptoms of vestibular impairment such as dizziness and vertigo $^{24,25}$.

The VOR coordinates together with the vestibulo-colic reflex (VCR) and vestibulo-spinal reflex (VSR) during postural maintenance. When the vestibular system is challenged as a result of a body perturbation, the VOR is stimulated and coordinates the eyes and head movements for gaze stabilization. The VCR responds to maintain head-on-body stability by decreasing the vestibular disturbance and producing neck muscular contractions opposite to the side of the perturbation $^{26}$. At the same time, the VSR also generates compensatory body movements by transmitting motor impulses via medial and lateral vestibulo-spinal, and reticulo-spinal tracts to axial and appendicular muscles to respond and maintain postural stability $^{27,28}$.

The VOR, VCR and VSR have been traditionally measured using electro-oculography (EOG) and electromyography (EMG). These bioelectric signals show how the nature of these vestibular reflexes are transmitted. The EOG has been shown to measure all types of eye movements with precision $^{29,30}$ including smooth pursuits and VOR such as fixating on a static visual or head sway-referenced moving target during upright postural stability $^{31}$. Similarly, the EMG method can be used to assess muscle latency responses and synergies $^{32}$, and power spectral densities $^{33,34}$ during postural activities. By analyzing eye movement variability of eye muscles and EMG peak amplitude and spectral densities of postural muscles during balance tasks, one may understand the eye movement variability and EMG onset, duration, peak amplitude and frequency changes, which may be
influenced by vestibular postural training over time and potentially relate to effects of vestibular activation.

Postural training using weight shift training (WST), where the limits of stability (LOS) is challenged, can enhance postural stability and functional activities. LOS is the amount of maximum excursion of the center of mass over the base of support in any direction from the vertical without losing balance or taking a step \(^{35}\). In a study of individuals with chronic hemiparetic stroke, WST involving balance pad and a dynamic ball cushion on unstable surface, was used to investigate the effects of the training on trunk control, proprioception and balance. Significant improvements were reported in all three-balance measures (trunk reposition error, Trunk Impairment Scale, and TUG) in the WST group (compared to controls), indicating that WST is beneficial for improving trunk control and proprioception in chronic hemiparetic stroke, and thus postural stability \(^{36}\). Cheng et al. \(^{37}\) found significant improvement in dynamic balance control in chronic hemiplegic patients (main training group) compared to controls (conventional training group) during a visual feedback rhythmic WST on the NeuroCom\textsuperscript{®} Balance Master. The improvement in dynamic balance was sustained over six months, however, there was no significant effect on the static balance function. Vestibular rehabilitation has also been found to significantly improve patients' condition in all self-report, as well as gait and balance performance measures \(^{13,38}\). Using a retrospective chart review of concussed children and adults (aged 8 to 73 years; \(n = 114\)) referred for vestibular rehabilitation, Alsalaheen et al. \(^{13}\) found improvements in measures including dizziness severity, Dizziness Handicap Inventory (DHI), sensory organization test (SOT), Dynamic Gait Index (DGI) and gait speed at the time of discharge. The vestibular rehabilitation intervention used in the study were
customized programs targeted at each patient’s impairments and functional limitations that related to dizziness, ocular motor function, and balance and gait function.

Combined vestibular activation and postural training can also enhance vestibular rehabilitation. Stroke patients were found to have benefited from vestibular rehabilitation coupled with weight shift balance exercises \(^{39}\). The authors found that the experimental group significantly improved in gaze stabilization test (GST) and DGI in at least three weeks of rehabilitation compared to their baseline measurements. The aged-sex-matched cohort controls showed no significant difference in any of the outcome measures. Improvements in the GST indicate a better VOR function and improvements in DGI indicate a better dynamic balance function. Improvements in both functions indicate that vestibular rehabilitation coupled with the WST positively influences the sensory reweighting mechanism by facilitating the reflex mechanism related to vestibular function. Though both groups received conventional physical therapy (with the experimental group receiving vestibular rehabilitation in addition), the control group did not show the same level of improvement in the GST or DGI. This points to the importance of vestibular rehabilitation with respect to improving VOR and possibly facilitating sensory reweighting for gait balance control. These findings indicate the possibility of using a combined vestibular and postural training program to rehabilitate the vestibular postural system effectively. The current study was similar; however, our protocol incorporated a concurrent balance training (with the vestibular activation), thereby training the visual, somatosensory and vestibular systems of postural balance. This protocol was also made to also reduce the duration of training sessions resulting in a more manageable treatment regiment, which may help reduce compliance issues. To assess whether or not the training had a
positive influence on the sensory systems, the SOT was used to measure participants’ balance before and after the combined vestibular and postural training.

**Sensory Organization Test (SOT)**

The sensory organization test (SOT), one of the assessment protocols of the NeuroCom® SMART Balance Master, has been used in many studies to assess postural balance deficits. During the SOT assessment, the force plates in the SMART Balance Master measure vertical ground reaction and share forces produced by the feet during quiet stance as the body’s center of gravity (COG) moves around a fixed base of support. The test systematically disrupts the sensory selection process and tasks the postural system to use the reliable sensory systems. Through sensory reweighting, the test alters the available somatosensory, visual and/or vestibular information while measuring the ability to minimize postural sway in the anterior-posterior direction. Sensory reweighting is the ability to adjust the relative contributions of the multisensory systems that are available to maintain postural balance depending on current environmental conditions. The SOT can test this principle of reweighting by manipulating the availability of the sensory inputs in each condition and then comparing the results of these conditions to one another. The comparisons are computed into sensory ratios. These ratios give information on the ability of the postural system to rely on a sensory channel (visual, somatosensory or vestibular) for balance when there is a sensory perturbation or impairment.

The SOT protocol requires participants to stand upright as stably as possible for 20 seconds 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)
The NeuroCom® system calculates the SOT composite score as a weighted average of all six conditions to determine the overall level of performance as a percentage from 0-100, with better performance represented as a higher score and a fall scored as 0. The NeuroCom® also indicates the sensory ratios, which estimates the participants’ ability to utilize each type of sensory input to maintain balance. The vestibular ratio represents the degree to which a participant relies on the vestibular system to maintain balance even if the visual and somatosensory inputs are unreliable. The somatosensory ratio is the degree to which a participant relies on the somatosensory input to maintain balance. The visual ratio is the ability of the participant to rely on visual input for balance control. The preference ratio is the degree to which a participant relies on the visual input even when it is inaccurate.

**Measures of Postural Sway**

The postural analysis performed by NeuroCom® SOT is based on equilibrium and composite scores in the anterior-posterior (AP) direction. This is because the sensory manipulating inputs (i.e., surface and visual) of the test are delivered in the AP direction. Thus, interpretation of results using the equilibrium and composite scores should be done with caution because postural regulation is multidirectional. To overcome the unidirectional limitation of the SOT, the recorded COP output data can be transformed into other linear measures, which can be meaningful in interpreting various dimensions of postural control. These measures include sway area, sway velocity and AP and medio-lateral (ML) sway standard deviations. However, these traditional linear measures may be
insensitive to variability across time and focus only on a single time scale, thus reducing the ability to assess physiological changes on the control and coordination of postural patterns 41. Moreover, postural regulation behavior during quiet stance is non-linear and complexities in COP changes over time has been previously identified 41. These complexity changes are usually subtle and are missed by the traditional measures. Due to the physiological nature of quiet stance, assessment of postural control changes by examining complexity over multiple timescales has also been shown to be a reliable and sensitive method 42.

**Multiscale Entropy (MSE) Measure**

Using multiscale entropy (MSE) to measure complexity in a COP times scale may be a better method to identify changes in vestibular reflexes (VCR and VSR) and sensory reweighting following training in a healthy population. MSE, a non-linear measure, is a complexity measure of a time series over different temporal scales. MSE uses a coarse-graining procedure constructed through an averaging of the data points to generate new time series 41. This measure provides insight into the point-to-point fluctuations of the postural signals over a range of time scales and therefore may be sensitive to detect the process of sensory reweighting during quiet standing 43,44. The COP time series data of postural balance measurement during quiet stance from the NeuroCom® SOT possess some elements that makes the application of non-linear metrics such as entropy important during analysis and interpretation of results. The time series has a large number of data points (2000) with physiological noise due to the various integrating processes, control and coordination of muscular contractions patterns employed during balance control 44. It is sampled at a high frequency (100Hz) and has a lengthy data set that is above the
minimum number of samples (200) required to estimate the complexity of a time series 44,45.

Complexity measures such as approximate entropy (ApEN) and sample entropy (SampEN) have shown that higher entropy values are indicative of a system exhibiting an automatic postural control and a less constrained strategy for balance control, thus an individual’s ability to balance more effectively 46. In an analysis of 136 participants from ten studies (including two case studies) comprising various balance impaired populations such as labyrinthine deficit, elderly, ballet dancers, track athletes, diabetes and infants with delayed developmental stages compared to healthy participants, higher entropy values were found to correspond with an individual’s ability to balance more effectively 46. Since MSE serves a more robust technique in accessing postural balance than ApEN and SampEN 43,47, it is expected to reveal the subtle fluctuations that are exhibited in healthy young adults after vestibular rehabilitation. For instance, Fino and colleagues 48 found that multi-variate composite MSE was the most consistent variable (among ApEN, SampEN and multi-variate SampEN) to identify differences between concussed athletes and their healthy cohorts. The concussed athletes showed a lower complexity measure over a high frequency COP time-series, suggesting a decline in postural control complexity.

MSE has also been found to identify differences in complexities in postural control in a female multiple sclerosis (MS) population 47,49. A lower MSE was observed in the MS group compared to age-matched controls in the AP and ML directions, depicting an impaired postural control in the MS patients. These reductions were observed due to impaired cutaneous sensation on the plantar surface of the feet, and partly due to the limited visual
information from the postural task manipulation, indicating that MSE is a reliable non-linear metric for identifying changes in postural control among balance impaired populations such as MS. In our previous study (see Pilot study below; Fig. 1.1) significant differences were found in MSE sway velocity in condition 5 and condition 6 of the SOT in the headshake group following training as compared to the control group. Among four other traditional measures only the COP ML Std sway showed a significant change in the headshake group following training, and this was found in condition 6 of the SOT. Therefore, we suggest that our complexity measure (MSE) will be more sensitive to differences in the training groups after vestibular activation compared to the linear measures.

**Vestibular Headshake Activities**

The benefits of vestibular activation including headshaking activities in assessments of several vestibular impairments have been well-documented. Apart from horizontal headshake (HS) that has been employed in standing, walking-in-place and running-in-place, vertical HS has also been found to be a relatively important component when combined with horizontal HS. This is also important because vertical HS activates the otolith organs (i.e., saccules) in addition to the anterior and posterior semicircular canals, whereas horizontal HS mainly activates the lateral semicircular canals. Vertical head movements are an essential component of upright bipedal behavior and body movements, and such movements activate the vestibular pathways which can be detected by measuring the VSR. In this current study, vertical HS activities will be included in training participants, together with horizontal HS which was used in the pilot study.
The assessment benefits derived from headshaking activities as found in the literature \textsuperscript{51–54} could be structured into a rehabilitation protocol by the activation of the vestibular system to provoke vestibular symptoms. With repeated exposure to rhythmic headshaking overtime, the symptoms can become desensitized and consequently be resolved, leading to vestibular habituation \textsuperscript{53,58}. Similarly, since headshaking activities spontaneously require oculomotor control through eye fixation, the benefits of gaze stabilization, a form of vestibular adaptation, can be obtained \textsuperscript{10,59}. Hence, our vestibular activation protocol through horizontal and vertical headshake activities may yield both vestibular habituation and adaptation changes in the central nervous system.

The actual neural mechanisms behind vestibular habituation and adaption exercises is not well understood \textsuperscript{59,60}. However, it is known that during habituation, the excitatory postsynaptic potential (EPSP) which is transmitted from the sensory receptor to the interneurons, then eventually to the motor neuron is gradually reduced in amplitude due to the low amount of calcium ions in the presynaptic membrane. The gradual reduction of the EPSP along the sensory-motor pathway leads to temporary reduction of dizziness. After further exposures to the provocative movements overtime, the synaptic connections between the sensory-, inter- and motor- neurons decrease in number leading to long-term structural changes and permanent decrease in symptoms such as dizziness \textsuperscript{9,61}.

Vestibular adaptation exercises are generally more clearly described in most studies compared to habituation. Adaptation exercises typically involve eye fixation on a static or dynamic target during body and/or head movements. Habituation exercises in various forms may be described as repeated positional exercises \textsuperscript{62}, optokinetic exercises or
virtual reality environments \(^{10}\) and Brandt-Daroff exercise \(^{63}\). Headshaking activities with concurrent trunk flexion-extension and lateral flexion has also been related to vestibular habituation \(^{59}\). Our pilot study, which involved horizontal rhythmic head movements, eye fixation and postural training, showed significant training effects in the COP ML Std sway and MSE sway velocity of the SOT across three groups (n=33), with the horizontal HS (treatment) group exhibiting better postural stability. These changes were found in the vestibular and visual-vestibular dependent sensory systems suggesting the positive influence of the headshake activities to recalibrate the visual-vestibular systems in a healthy population. The benefits of this combined postural balance and vestibular activation (including habituation and/or adaptation) demonstrated by the outcome measures cannot be attributed to a practice effect of the SOT pre- and post-assessments because the no headshake group exhibited little or no change relative to the control group.

**Vestibular Rehabilitation**

Vestibular rehabilitation studies have shown evidence that it can be effective in improving primary and secondary vestibular symptoms and/or impairments \(^{10,11}\). A Cochrane Review on 39 studies (n = 2,441) found moderate to strong evidence for the effectiveness of vestibular rehabilitation therapy in patients with unilateral vestibular hypofunction or loss \(^{64}\). There was also moderate evidence that the improvements were sustained for months post treatment. The studies compared various forms of vestibular rehabilitation therapy to no or sham treatments. Also, in a three-year systematic review, \(^{65}\) positive effects of vestibular rehabilitation was found for a wider range of vestibular disturbances including unilateral/bilateral vestibular hypofunction, chronic dizziness, vestibular or imbalance symptoms, benign paroxysmal positional vertigo (BPPV), dizziness from central origin and
dizziness related to aging. Among several vestibular rehabilitation protocols, the most frequently used ones are the Cawthorne-Cooksey protocol, Shepard and Telian protocol, and the Norre protocol $^{53,66-69}$.

The Cawthorne-Cooksey exercises, which provides a general approach to vestibular rehabilitation, were the original vestibular exercises developed in the 1940’s $^{66,67}$. The Cawthorne-Cooksey protocol entails active eye movements, head movements and upper and lower bodily functional mobility exercises categorized into four progressive levels. These levels include exercising in bed or sitting, solely in sitting, standing and moving about. The patient is instructed to perform horizontal, vertical and vergence eye movements. This is followed by horizontal and vertical head movements with eyes open and then eyes closed, which will be used in our protocol. In the sitting position, shoulder movements and bending forwards or sideways to pick up objects from the ground are added to the eye and head movements. Levels one and two are repeated in standing and ball throwing exercises are performed, which include patient throwing a ball from hand to hand at eye level and under the knee. Sit-to-stand activities and turns are also included. At the final level, ambulatory activities across a room, up and down a slope and steps, hand to hand eye-ball coordination exercises with eyes following the ball, and stooping and stretching activities are performed $^{66,67}$.

Although the Cawthorne-Cooksey vestibular training protocol is effective in improving balance disorders, it may have some limitations in improving certain aspects of vestibular and balance impairments. In a systematic review $^{65}$, four clinical studies (experimental group = 143, control group =139; ages > 60 years) showed that the Cawthorne-Cooksey
vestibular training protocol resulted in a significant improvement in dynamic balance and in activities of daily living as compared to controls. However, there were no differences in the limits of stability, tandem position, psycho-cognitive scales or visual analog scale (VAS) outcome measures for subjective perception of vestibular symptoms. Our training protocol considers the principles behind the Cawthorne-Cooksey exercises, together with current vestibular rehabilitation approaches. The approaches are targeted at patients’ impairments and functional limitations, and include gaze stability exercises, habituation exercises, balance and gait training, and walking for endurance. By employing headshaking activities, gaze stabilization, smooth pursuit and total body weight shift activities on a flat surface, foam or a rocker board, our design should yield similarly effective outcomes.

Among the vestibular rehabilitation studies, some focus on vestibular training methods only without including postural balance activities. Evidence has shown that the studies that employed combined protocols such as gaze stabilization training, balance training and habituation exercises yielded significant improvement in subjective dizziness, gaze stability, balance and gait. However, some groups of patients with vestibular hypofunction may not show improvement, probably due to the type of vestibular rehabilitation employed. Although evidence of using sensory reweighting to explain the benefits of training protocols in improving the vestibular system has been established, there is paucity of knowledge about the effectiveness of sensory reweighting mechanisms for improving vestibular impairment through vestibular activation and postural rehabilitation. The vestibular rehabilitation protocol used in this current study investigated the underlying sensory weighting mechanisms affecting the reweighting and
integration of vestibular, visual and somatosensory systems by using various postural and vestibular training protocols that can alter ocular and postural behaviors. This training protocol comprises COM shifting activities while standing in place, on foam or rocker board and concurrently performing horizontal or vertical headshake activities to activate the vestibular system.

The purpose of this current study was to assess the effect of combined weight shift training (WST) and vestibular activation on sensory reweighting in the postural control processing system among young adults. Healthy individuals were randomly assigned into four groups, viz: 1) visual feedback WST coupled with an active horizontal headshake (HHS), 2) same WST with vertical headshake (VHS), 3) WST with no headshake (NHS) and 4) no training/no headshake control (CTL) groups. In reference to our pilot study, the inclusion of a fourth training group (i.e. VHS) allowed for examining the changes in VOR, VCR and VSR independently from the changes associated with horizontal HS.

In order to show the changes and differentiate vestibular pathways of the VOR (head-centered sensorimotor pathways) from those that are more neck and trunk centered (VCR and VSR) after the vestibular/postural training, the video head impulse test (vHIT), EOG and EMG were used as outcome measures. First, we hypothesized that the effect of the training protocol on the vestibular system will significantly alter the pattern of SOT sensory dependence. The postural control system may alter dependence on visual and somatosensory input to compensate for the changes in vestibular dependence to maintain postural stability. Second, we hypothesized that vestibular-motor responses related to VOR, VCR, and VSR will be differentially affected depending on which training is
employed. VOR gain is the ratio of eye movement velocity to head velocity. Since the head movement and eye-target distance were approximately the same pre- and post-assessments (as tested by the vHIT system in our study), VOR gain was determined by the eye movement only. Normal VOR ranges from 0.80 to 1.00\(^7\). If the VOR gain decreases post-training, then vestibular-ocular habituation has occurred. If it stays the same or increases, then vestibular adaptation has occurred. The reduction in VOR gain in a healthy population is related to reduction in symptoms in a vestibular impaired population leading to a possibility of vestibular habituation. Similarly, the VSR response was assessed as the ratio of trunk angular velocity to ramp velocity. If the trunk velocity response decreases post-training, it connotes that a VSR habituation has occurred; if there is an increase or no change, then an adaptation has occurred. Additionally, the VCR response (i.e., ratio of neck angular velocity to ramp velocity) was treated similar to VSR. Findings from this training protocol may guide the development of a rehabilitation method for postural balance control in neurological populations with sensorimotor control impairment.

**The Use of Multiple Outcome Measures in Detecting Vestibular Changes**

Several methods have been used to assess vestibular-motor responses during postural control and vestibular rehabilitation studies. These methods include: the sensory organization test (SOT), electro-oculography (EOG), electromyography (EMG), video head impulse test (vHIT) and accelerometry. The SOT is an objective gold standard tool used for assessing postural stability during quiet stance by systematically disrupting the postural sensory selection process to analyze relative sensory weighting\(^40\). The EOG has been shown to measure all types of eye movements with precise measurements accuracy.
including coordinated smooth pursuits and VOR which occurs when fixating on a
static visual or head sway-referenced moving target during upright postural control 31. The
EMG method can be used to assess muscle latency responses and synergies 32 and
power spectral densities 33,34 during postural activities. The vHIT system is used to test the
function of the semicircular canals (SCCs) by measuring the ratio of the compensatory
eye movement velocity to a head movement velocity during a rapid head rotation
performed passively along the planes of the specific canal 71,72. The output of the ratio is
recorded as the VOR gain. Accelerometry has been used to measure the relative head-
trunk and trunk-lower limbs movements during pitch and roll ramp perturbations, linking
these motions to the influence of the vestibular system 32,73,74.

By analyzing changes in the eye movements and the VOR gain during balance tasks, one
may understand the eye movement variability and specific SCC function, which may be
influenced by vestibular postural training over time and potentially relate to effects of
vestibular activation. Furthermore, changes in the EMG and accelerometry signals can
give insights into the EMG onset, peak amplitude, duration and average power frequency
changes, and relative movement of body segments.

Many studies have employed several of the aforementioned posturography, bioelectrical
and accelerometric kinetic and kinematic measurement tools to investigate postural
behavior with respect to sensory reweighting across different populations. Horak et al. 75
used a SOT principle-based method, EMG and kinematic data to study the roles of
somatosensory and vestibular information in the coordination of postural responses
between bilateral vestibular loss patients and normal controls during surface translation
displacements. Authors showed that the postural system typically selects either hip
strategy (for somatosensory loss) or ankle strategy (for vestibular loss) depending on either reduced/impaired sensory information. However, both the sensory loss and vestibular loss participants could perform voluntary ankle-like and hip-like movement strategies when asked to do so. Also, Horak & Hlavacka 76 used galvanic vestibular stimulation and kinematics to show that when the somatosensory system is impaired or somatosensory information is disrupted it leads to an increase in vestibulospinal sensitivity. In addition, the participants with diabetic peripheral neuropathy showed larger center of pressure (COP) with increasing galvanic vestibular stimulation compared to age-matched controls.

Another study conducted by Amiridis and colleagues 77 employed force plate instrumentation, EMG and two-dimensional kinematic data to explore how young and older adults respond to increased postural demands (i.e., bipedal, Romberg-sharpened and one-legged stances) during quiet stance. Results showed that compared to young adults, the older adults exhibited greater COP, EMG and mixed hip-ankle displacements. Meanwhile, the young adults adapted to the increased postural requirements by demonstrating only ankle movement strategy. Furthermore, Gauchard et al. 78 investigated the effects of physical activities on VSR and ocular movements of visual and vestibular origins in the elderly using various vestibulo-ocular and vestibulo-motor tests and EMG analyses. The study revealed that relative inactivity correlated with poor vestibular sensitivity, reduced visual detection and poor reaction time. Furthermore, being physically active significantly increased gaze and postural stabilization by improving VSR, VOR and visuo-ocular reflexes.
Other studies with direct clinical focus have been conducted to assess the vestibular changes that occur following vestibular rehabilitation. In assessing the effects of specific vestibular exercises on central compensation in acute/subacute unilateral vestibular lesion patients, Strupp et al. 79 used laser ophthalmoscope (for testing ocular torsion), subjective visual vertical test (for perception) and force plate technology (for total sway path). Results showed that, there was a significant improvement in the total sway path for the therapy group compared to the controls on the 30th day of training. Both groups were encouraged to engage in regular daily activities, such as walking. In addition, the therapy group received intensive physiotherapy and vestibular training with components of Cawthorne-Cooksey 66,67 and Norre exercises 80. There were no differences in the ocular torsion (for the vestibulo-ocular system) or the subjective visual vertical (for perception) between the groups. Furthermore, using a motion analysis kinematic technique, Patten and colleagues 81 investigated the effects of a 16-week protocol of vestibular rehabilitation on head and body coordination during unconstrained, paced and in-place gait between vestibulopathic individuals and their age-matched healthy counterparts. The vestibular rehabilitation protocol involved a program of habituation and compensation exercises for vertigo, gaze and balance. The vestibular training group demonstrated more normal patterns in pitch and improvements towards normal in yaw and roll.

The above studies employ multiple tools to examine postural reactions and provide insights into postural sensory systems, with or without vestibular intervention. However, some of the studies use only posturography via COP measures. While this method does not directly measure vestibular changes, changes in the COP have been attributed to recalibration of the vestibular system 76. The studies 75,77 which used several measurement
tools do not provide any statistical correlation between the measures. Computing such information to show possible correlations between measures can assist clinicians to identify related outcome measures which can be used as predictors during the assessment of vestibular dysfunction, and also serve as monitoring tools for vestibular rehabilitation protocols. That is, the assessment of one outcome measure, e.g., COP sway velocity, can be used to predict another, e.g., the EMG amplitude. It is only the Gauchard et al. study \(^78\) that correlated the vestibulo-ocular and vestibulo-motor tests and EMG outcome measures used in its investigation. However, the participants in the active group did not engage in any specific vestibular training. Moreover, at the moment, no study has investigated the correlation between postural balance variability and vestibular-ocular and motor responses after vestibular training by using a rhythmic headshaking intervention.

Investigating the correlations of the bioelectrical signals and posturography data after vestibular training can be a valuable method to predict the outcome of a vestibular protocol and also can provide substantive evidence for its efficacy. For instance, in the current study, if the COP or EMG amplitude during ramp perturbation assessments are lower after training in the headshake groups, it could suggest a lower acceleration in the relative head-to-trunk movement (due to controlled postural control). Moreover, the use of several assessment methods to identify vestibular changes in the current study can enhance the clinician’s ability to make proper diagnosis and monitor the effects and progress of a vestibular training program. Furthermore, the correlations can show which of the outcome measures will be more sensitive in determining vestibular changes after vestibular training, and thus, guide clinicians in making decisions for a better assessment tool.
Innovation and Significance

Rehabilitation of vestibular dysfunction has become a vital area in the management of balance problems. Vestibular loss alone can cause severe postural imbalance leading to prolonged decrease in activities of daily living and productivity, increase in risk of exposure to further injury/s and huge economic cost. An underlying factor of vestibular dysfunction is vestibular processing impairments, which can occur in the either peripheral or central vestibular system. One way to resolve symptoms associated with the disorders is through vestibular habituation, which utilizes sensory weighting mechanisms and sensory integration processes of the multisensory postural systems.

The benefits of vestibular training have been shown, however an optimal training protocol has not been established. Engaging participants in horizontal headshake activities in standing, walking-in-place and running-in-place and also in vertical headshake have been found to be useful in vestibular assessments. Horizontal HS activity predominantly stimulates the lateral semicircular canals, while vertical HS stimulates the anterior and posterior semicircular canals and otolith organs. These assessment methods can be incorporated into exercise activities that can relieve vestibular symptoms and/or improve gaze stabilization. However, no study has investigated the horizontal and vertical HS activities in the same cohort groups or by using our training protocol. Our study examined these two head directional activities in four groups: horizontal headshake, vertical headshake, no headshake and control groups.

Several of the vestibular rehabilitation methods established in research studies and clinics do not include postural balance activities. The few studies which have included postural
training may not exhibit improvement. The combined vestibular activation and postural training protocol in this present study was designed to place emphasizes on sensory weighting and integration by employing headshaking activities to potentially activate habituation and/or adaptation in the CNS through headshaking activities. The headshaking activities therefore included aspects of dynamic gaze stabilization to change the VOR gain and habituation. The weight shift postural training was purported to improve the limits of stability, somatosensory and proprioceptive components necessary for postural balance control.

Moreover, the vestibular activation training exercises in our study were slightly different compared to the traditional vestibular rehabilitation exercises such as used in the Cawthorne-Cooksey, the Norre and Brandt-Daroff protocols. Our training was different because it combined several principles for vestibular rehabilitation (gaze stabilization, smooth pursuit, vestibular habituation and body shifting) simultaneously. Also, evidence from a systematic review showed that the Cawthorne-Cooksey protocol did not show significant differences in the limits of stability, tandem position or VAS outcome measures (for subjective perception of vestibular symptoms) in patients compared to healthy cohorts, although improvement in dynamic balance and activities of daily living occurred. This suggests that the Cawthorne-Cooksey protocol may have some limitations. Our pilot study showed significant training effects in the COP ML Std sway and MSE sway velocity in the horizontal headshake group as assessed by the SOT. Before we could validate our approach on individuals with vestibular impairment, this research was conducted to validate the underlying principles and its ability to effect change in a healthy young population.
Furthermore, patients' compliance to rehabilitation schedules is a major challenge for clinicians mostly due to the prolonged time stipulated per training session. Unlike several of the rehabilitation methods that entail both vestibular activation and postural training separately, our protocol was designed to be more efficient in promoting changes in the postural system, thus obtaining more relevant benefits within a relatively shorter training session of 20 minutes per session in only five sessions.

As part of testing this method on healthy participants, the vestibular rehabilitation protocol in our study was designed to positively influence the underlying physiological processes and to determine whether the protocol may cause changes in vestibular response and balance. Outcomes of the benefits of our combined vestibular activation and postural training were quantitatively assessed by using electrophysiological and balance assessment tools including EMG, EOG, SOT and vHIT. These quantitative tools have been validated and thus provide evidence of possible positive changes in the vestibular system after training using underlying changes that occur in vestibular (postural) reflexes and sensory weighting. Moreover, no study has investigated sensory weighting and vestibular reflexes using different measurement tools to study the sources of underlying mechanisms in order to confirm the effectiveness of a training protocol.

The NeuroCom® SOT system assesses postural balance in linear measures and only in AP directions using the equilibrium scores. Since sway does not occur in only AP direction, the COP outcome data of the SOT was transformed into other forms of measures including sway area, sway velocity, AP Std and ML Std sways. Additionally, as non-linear measures are recently being used to analyze physiological variables such as quiet standing, our
study employed an entropy measure (i.e., MSE sway velocity), which has been shown to detect subtle physiological sway changes that the traditional linear measures fail to detect.

The outcome of this postural and vestibular training protocol can better inform clinicians on how to tailor their rehabilitation methods in treating conditions with associated vestibular symptoms. This may further help resolve lingering symptoms that persist when current management guidelines are followed. It can also facilitate return to activities of daily living, reduce the risk of exposure to subsequent injuries and consequently reduce economic costs of health care.

Summary

Our vestibular activation and postural training protocol is novel by training vestibular habituation and/or gaze stabilization, and postural control simultaneously. It is targeted on specific physiological aspects such as vestibular reflexes and sensory weighting/integration to potentially produce a more effective method to relieve vestibular symptoms and improve the vestibular and postural systems. We proposed that this training strategy would show improved outcomes over traditional training methods. The findings of this study may guide clinicians to develop rehabilitation methods for vestibular postural control in neurological populations with vestibular and/or sensorimotor control impairment.
Pilot Study

The aim of our pilot study was to assess sensory weighting mechanisms of postural control processing after combined vestibular activation and weight shift training. We hypothesized that the effect of this training on the vestibular system will significantly alter sensory reweighting by upweighting the somatosensory system and downweighting the vestibular system. Thirty-three young healthy individuals (18 males; 24.5±4.4 years [18-35 years]; 1.7±0.2 meters) with no evidence of neurological or musculoskeletal impairments were randomly assigned to one of three groups: visual feedback WST coupled with an active horizontal headshake (HHS) activity, or the same WST with no HS (NHS) or No training (control). The HHS and NHS groups were trained on the NeuroCom® WST balance training protocol twice per day, for every other day, for a week. The HS group performed rhythmic horizontal head rotations (approximately 30°) in each direction to the beat of the metronome at 80 to 100 beats per minute. All three groups performed pre- and post-assessments on the SOT. Separate between- and within-group repeated measures ANOVA of six conditions (3 visuals x 2 surfaces) x 3 groups x 2 sessions, were used to analyze the SOT equilibrium scores, composite scores, transformed COP variables and sensory ratios by comparing baseline to post-training.

The mixed-model rmANOVA of the COP ML Std sway showed two main effects: surface ($F_{1,30} = 79.80, p < .0001$) and visual ($F_{2,29} = 62.10, p < .0001$). 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 ($F_{2,29} = 37.20, p < .0001$). Generally, HHS group showed decreased ML Std sway pre- to post-training. The other
groups did not show any decrease in sway, with NHS showing relatively increased sway. Planned comparisons of this visual training effect revealed group effects between HHS & control in the eyes open (EO) & visual sway-referenced (SR) conditions (conditions 1,4 & 3,6; $F_{1,20} = 6.07, p = .023$) and in the eyes closed (EC) & visual SR conditions (conditions 2,5 & 3,6; $F_{1,20} = 5.74, p = .027$; Fig. 1.1A & 1.1B). Similarly, the visual effect was found between NHS & control in the EC & visual SR conditions ($F_{1,20} = 7.19, p = .015$; Fig. 1.1A & 1.1C). However, there was no visual training effect between HHS & NHS.

The mixed-model rmANOVA of the nonlinear metrics 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 x surface ($F_{4,60} = 3.50, p = .012$) and group x session x visual ($F_{4,60} = 3.71, p = .009$). There was no significant difference in the group x session x surface ($F_{2,30} = .17, p = .845$). There were also two other significant interactions: 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 HHS exhibiting the largest change, followed by control. Planned comparison of the group x session x visual x surface effect showed effects between HHS & control ($F_{1,20} = 5.32, p = .032$; Fig. 1D & 1E) and HHS & NoHS ($F_{1,21} = 10.75, p = .004$; Fig. 1.1E & 1.1F) in the EO & visual SR conditions. Similarly, the group x session x visual effect was found between HHS & NHS in the EO & EC conditions ($F_{1,21} = 7.73, p = .011$) and EO and visual SR conditions ($F_{1,20} = 7.02, p = .015$). The group x session x visual effect was also found between HHS & control in the EC & visual SR conditions ($F_{1,20} = 6.98, p = .016$).
There was a significant *group x session* interaction in somatosensory ratio ($F_{2,30} = 4.43$, $p = .021$) from pre- to post-training (Table 1.1). This was found between HHS and NHS groups ($F_{1,21} = 7.43$, $p = .013$), with HHS showing an increase in the somatosensory ratio. For SOT equilibrium and composite scores, none of the *group x session* effects were significant ($p > .100$). None of the *group x session* effects were significant for COP sway area, COP sway velocity and AP Std ($p > .10$).

In summary, combined vestibular activation and weight shift training produce significant changes in the vestibular and visual-vestibular processes (i.e. SOT conditions 5 and 6) as
evidenced in two postural stability metrics; a traditional (i.e., standard deviation of mediolateral COP sway) and a non-traditional (i.e., COP multiscale entropy sway 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. While these findings represent some interesting new results, still many questions remain, regarding underlying mechanisms, dosage, and generalizability to other populations. Some of these open questions were investigated in this dissertation. This was, in part, conducted by the addition of new tests and outcome measures (vHIT, EMG, EOG and ramp perturbations). The questions were also addressed, in part, by the addition of a new training condition with vertical HS, which may better isolate the sources of these training-induced changes by providing insights into VOR, VCR, VSR and muscles activation pattern responses.

Specific Aims

Aim 1. To assess the effect of a vestibular training protocol on sensory weighting during postural control among young healthy adults. Rhythmic horizontal and vertical headshake movements, coupled with the weight shift training (WST), will be used to perturb and activate the vestibular system. We hypothesize that the vestibular training protocol will significantly alter sensory weighting, due to vestibular activation.

Independent variables:

- 4 groups (HHS, VHS, NHS and controls)
- 3 eye conditions (eyes open, eyes closed or sway referenced vision)
- 2 surface conditions (fixed or sway-referenced surface)
Table 1: Sway variables and sensory ratios of the three groups after vestibular balance training

<table>
<thead>
<tr>
<th>Sway variables</th>
<th>Headshake</th>
<th></th>
<th></th>
<th>No Headshake</th>
<th></th>
<th></th>
<th>Control</th>
<th></th>
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<tbody>
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<td>Pre-</td>
<td>Post-</td>
<td>Difference</td>
<td>Pre-</td>
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<td>Difference</td>
<td>Pre-</td>
<td>Post-</td>
<td>Difference</td>
<td></td>
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<tr>
<td>COP Antero-posterior standard deviation (cm)</td>
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<td></td>
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<tr>
<td>EO - SS</td>
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<td>0.23±0.05</td>
<td>0.00±0.07</td>
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<td>0.24±0.13</td>
<td>-0.02±0.11</td>
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<td>0.29±0.12</td>
<td>-0.12±0.31</td>
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<tr>
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<td>0.39±0.16</td>
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<td>-0.05±0.15</td>
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<td>-0.05±0.21</td>
<td>0.33±0.08</td>
<td>0.33±0.11</td>
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<td>0.51±0.18</td>
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<td>94.9±1.5</td>
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<td>94.1±2.5</td>
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<td>0.9±1.6</td>
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<td>SRv- SS</td>
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<td>93.4±2.2</td>
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<tr>
<td>Composite</td>
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<td>79.6±7.6</td>
<td>78.5±10.4</td>
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<td>78.3±4.8</td>
<td>80.5±5.1</td>
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<td>Sensory ratios</td>
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<td></td>
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<tr>
<td>SOM *</td>
<td>0.97±0.02</td>
<td>0.98±0.02</td>
<td>0.03±0.02</td>
<td>0.99±0.01</td>
<td>0.96±0.04</td>
<td>-0.03±0.02</td>
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<td>0.96±0.02</td>
<td>-0.01±0.05*</td>
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<td>0.98±0.02</td>
<td>0.01±0.05</td>
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</tbody>
</table>

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 = eye preference ratio, * p<0.05 for group x session difference
Dependent variables:

- SOT equilibrium scores (six conditions), composite scores and sensory ratios from SOT scores
- COP sway variables (sway area, velocity, anterior-posterior standard deviation, medio-lateral standard deviation and multiscale entropy velocity) – from SOT-COP time series

Hypotheses:

1. SOT equilibrium and composite scores will significantly increase in the headshake groups post-training compared to the other two groups.
   a. SOT conditions 5 and 6 will significantly increase in the headshake groups post-training.
2. Sensory weighting will change significantly in the headshake groups by changing the ratios of visual, somatosensory, and vestibular dependence post-training.
3. Postural stability will improve (i.e. COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation sways will decrease) in the headshake groups post-training.
4. COP multiscale entropy velocity will significantly increase in the headshake groups post-training.

Aim 2. To assess changes in vestibular -ocular and -motor responses after vestibular training of postural balance control. Center of pressure (COP), electro-oculography (EOG), electromyography (EMG) and the video head impulse test (vHIT) will be used to investigate three vestibular -ocular and -motor responses pre- and post-training. The outcome measures, apart from the vHIT, were obtained by up and down platform ramp
rotations during standing. We hypothesize that vestibular responses will significantly change after the vestibular postural training, but not postural training alone, resulting in improved postural and gaze stability.

**Independent variables:**

- 4 groups (HHS, VHS, NHS and controls)
- Ramp rotations (up and down)
- Left & right passive head rotations (vHIT)

**Dependent variables:**

- COP sway variables from ramp perturbation trials (sway area, sway velocity, anterior-posterior standard deviation sway and medio-lateral standard deviation sway)
- EMG onset, duration and peak amplitude (VCR and VSR), EMG power spectral density (PSD) – from Inertia Measurement Unit (IMU)
- Head and trunk acceleration profiles – from IMU (head and trunk accelerometers)
- Eye movement variables (horizontal and vertical variability, area of eye excursion, velocity, anterior-posterior and medio-lateral standard deviation) – from EOG
- Horizontal VOR gain – from video head impulse test (HIT)
- Vertical VOR, VCR and VSR gains will also be obtained from EOG velocity, head velocity, trunk velocity and ramp velocity – from EOG and IMU (head accelerometers)
- Levels of headache, dizziness and nausea – from Visual analog scale (VAS) symptoms rating tool

Eye movement area and velocity refers to the area of excursion covered by eye movements and eye movement velocity, respectively. Anterior-posterior standard
deviation and medio-lateral standard deviation of eye movements refers to eye movements in the up & down and left & right directions, respectively.

**Hypotheses:**

1. Vestibulo-ocular reflex (VOR), vestibulo-colic reflex (VCR) and vestibulo-spinal reflex (VSR) responses during platform ramp rotations will significantly decrease in the headshake groups post-training (as recorded as EOG and EMG onset, duration and peak amplitudes).
   a. VOR gain (recorded by the vHIT system) will significantly change post-training in the headshake groups.
   b. VCR (in sternocleidomastoid and cervical erector spinae EMGs) will significantly decrease post-training in the horizontal headshake group compared to vertical headshake group.
   c. VSR (in trunk axial and lower limb muscles EMGs) will significantly decrease post-training in the horizontal headshake group compared to vertical headshake group.
   d. Similarly, vertical VOR, VCR and VSR gains will significantly decrease post-training in the headshake groups compared to the other two groups.

2. EMG peak amplitude in other postural muscles during platform ramp rotations will significantly decrease in the headshake groups post-training. The habituation of vestibular reflexes due to rhythmic headshake activity will improve VOR in particular, and thus improve gaze stabilization to assist in maintaining balance during the ramp trials. Therefore, lower EMG activation compared to pre-ramp assessment will suffice to ensure appropriate postural control during the post-ramp assessment.
3. EMG onset and duration in postural muscles during platform ramp rotations will significantly change in the headshake groups post-training. Headshake groups, mainly the VHS group, will habituate the VSR due to training, which will significantly change the EMG onset and duration. HHS group, on other hand, will mainly habituate the horizontal VOR and VCR.

4. EMG power spectral densities (PSD) during platform ramp rotations will significantly change in the headshake groups post-training. Due to the hypothesized significant reduction in EMG amplitude, the PSD will consequently change significantly (i.e., leading to a reduced PSD in the headshake groups).

5. Head and trunk accelerations during platform ramp rotations will significantly decrease in the vertical headshake group post-training. As the VCR and VSR are habituated, it will lead to well-controlled head and trunk movements, thus, resulting in significant decrease in head and trunk acceleration.

6. Peak horizontal and vertical eye movement variability during platform ramp rotations will significantly decrease post-training in the horizontal and vertical headshake groups, respectively.

7. Eye excursion/movement area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation during platform ramp rotations will significantly decrease in the headshake groups post-training. Habituation/adaptation of the horizontal and vertical VORs will improve gaze stabilization and consequently decrease eye sway area, velocity and variability.

8. Postural stability will improve (i.e. COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will decrease) during platform ramp rotations in the vestibular groups post-training.
Aim 3. To perform an exploratory analysis between postural balance variables and EOG-EMG signals. We hypothesize that improvements in postural balance variables will significantly correlate with lower EOG signal variability and lower EMG signals (including lower power spectral densities) post-training in the vestibular groups.

Independent and dependent variables as stated in Aims 1 and 2.

Hypotheses:

1. SOT equilibrium and composite scores will be negatively correlated with EMG peak amplitude, EMG power spectral densities post-training in the headshake groups.

2. COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will be positively correlated with EMG peak amplitude post-training in the headshake groups.

3. SOT equilibrium and composite scores will be negatively correlated with horizontal and vertical eye movement variability, eye movement area and velocity post-training in the headshake groups.

4. Vestibular ratio will be positively correlated with horizontal and vertical eye movement variability, eye movement area and velocity post-training in the headshake groups.

5. COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will be positively correlated with horizontal and vertical eye movement variability, eye movement area and velocity post-training in the headshake groups.
6. SOT equilibrium and composite scores, vestibular ratio and multiscale entropy velocity will be negatively correlated with VOR, VCR and VSR gains post-training in the headshake groups.

7. COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will be positively correlated with VOR, VCR and VSR gains post-training in the headshake groups.

Summary of Outcome Measures
The various outcome measures with their respective measuring equipment were related to the predicted underlying mechanisms and directional changes with regards to our main training groups (i.e., the vestibular groups). For some of the measures with no clear directions, we did not specify the directions (Table 1.2).
Table 1.2 Summary of outcome measures proposed underlying mechanisms and predicted directional change wrt HS groups

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measuring tool</th>
<th>Output</th>
<th>Underlying mechanism</th>
<th>Directional change</th>
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<td>NeuroCom SOT</td>
<td>Postural stability</td>
<td>Changing COM</td>
<td>Increase</td>
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<tr>
<td>Equilibrium</td>
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<td></td>
<td>Gaze stabilization, smooth pursuit, optokinetic reflex, proprioception, spinal reflex</td>
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<tr>
<td>Composite</td>
<td></td>
<td></td>
<td></td>
<td>Increase</td>
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<tr>
<td>- Visual Preference</td>
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<td>Decrease</td>
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<tr>
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<td>NeuroCom ramp and Trigno EMG</td>
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<td>Modified VCR and VSR</td>
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<td>Frequency power of signal</td>
<td>Modified vestibular reflexes</td>
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<td>EOG, IMU sensors, vHIT and NeuroCom ramp platform</td>
<td>Vestibular reflexes</td>
<td>Vestibular reflex downweighting and compensatory reweighting of the other sensory systems</td>
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AP = anterior-posterior, APR = automatic postural response, COM = center of mass, COP = center of pressure, EM = eye movement, EMG = electromyography, MSE = multiscale entropy, ML = medio-lateral, PSD = power spectral density, SOT = sensory organization test, Std = standard deviation, VCR = vestibulo-colic reflex, VOR = vestibulo-ocular reflex, VSR = vestibulo-spinal reflex
Sensory Reweighting Relevance

The dependent variables were related to the principle of sensory reweighting. For example, if there was a decrease in VOR gain in headshake groups during ramp rotation reassessment, it would indicate vestibular downweighting, hence, habituation. Consequently, this was hypothesized to lead to a compensatory upweighting process in vision and/or somatosensory inputs. As vestibular habituation occurs, it would lead to a slower head-on-trunk response. Faster and stronger coordinated response from distal lower limb muscles would occur as a compensatory mechanism to the reduced VSR response. Somatosensory, proprioceptive inputs and spinal reflexes, triggered by the ankle, would drive these compensatory responses and soles of the feet, producing a bottom-up approach (Fig. 1.2).

![Figure 1. 2 Sensory reweighting relevance](image)
CHAPTER 2
EFFECT OF A VESTIBULAR TRAINING PROTOCOL ON SENSORY WEIGHTING DURING POSTURAL CONTROL AMONG HEALTHY YOUNG ADULTS

Introduction

Vestibular dysfunction is a prevalent public health concern in various clinical rehabilitation settings. In the US, 69 million adults aged 40 years and older experience the condition. Several studies have found vestibular disorders in different populations over the world and across all ages, from children to the elderly. Due to the wide range of the affected populations, the total annual mean economic burden of both unilateral and bilateral vestibular deficiency in the US per patient in 2012 was $16,550.

Vestibular rehabilitation has been shown to effectively resolve vestibular impairments of associated conditions including mild traumatic brain injury and unilateral/bilateral peripheral vestibular dysfunctions such as Meniere’s and benign paroxysmal positional vertigo (BPPV). Furthermore, individuals with unilateral vestibular hypofunction or loss showed moderate to strong evidence for improvements in vestibular symptoms and other outcome measures. Follow up of the patients showed moderate recovery that was sustained after months. Specifically, outcomes measures such as symptom reduction (dizziness), visual acuity, gait, activities of daily living and quality of life were improved with vestibular rehabilitation. One other important measure that was improved by the vestibular rehabilitation was postural balance.
Poor postural balance is a critical sequela of vestibular dysfunction and requires much attention during rehabilitation. The postural system organizes and integrates accurate and reliable somatosensory, visual and vestibular inputs to produce motor output for efficient balance control. When information from the somatosensory and visual systems is reduced, inaccurate or unavailable, the central nervous system relies on the vestibular system for balance control. As the vestibular system is responsible for linear/angular orientation and equilibrium, a vestibular impairment can result in severe postural dysfunction. Vestibular rehabilitation may, therefore, be necessary to help individuals with balance and gait problems.

The physiologic mechanisms used in achieving effective resolution of vestibular impairments include vestibular adaptation, habituation, substitution and sensory reweighting. Vestibular adaptation involves exercises combining continuous, rhythmic head movements and opposite conjugate eye movements on either a fixed or a moving visual target to produce significant changes in the vestibulo-ocular reflex (VOR) gain. By performing this activity, gaze stabilization is improved with subsequent balance control.

With regards to habituation exercises, the focus is on repetitive head movements that provoke the vestibular symptoms (such as dizziness) until the symptoms are gradually resolved and the individual no longer responds to the stimuli. For vestibular substitution, the eyes are trained to use alternative eye movement patterns in improving gaze stabilization. Sensory reweighting is another important mechanism the postural system uses during vestibular rehabilitation to achieve efficient balance control. Sensory reweighting is the postural system’s ability to regulate its dependence on each of the
sensory systems (i.e., somatosensory, vision and vestibular) proportionate to their reliability and accuracy.

Several vestibular rehabilitation protocols and techniques, such as the Epley’s maneuver, Herdman, Norre & Brandt-Daroff and the Cawthorne-Cooksey, have been used over the years. Some of the vestibular rehabilitation studies that have shown effective improvements focused on vestibular training methods only without including postural balance activities. Evidence has shown that studies that employed combined programs such as gaze stabilization training, balance training, adaptation and habituation exercises yielded significant improvement in subjective dizziness, gaze stability, balance and gait following concussion or blast-induced head trauma 13,14. However, some groups of patients with vestibular hypofunction may not show improvement 11, probably due to the type of vestibular rehabilitation employed. Although evidence of using sensory reweighting to explain the benefits of training protocols in improving the vestibular system has been established 15–17, there is paucity of knowledge about the effectiveness of sensory reweighting mechanisms for improving vestibular impairment through vestibular activation and postural training. Furthermore, patients’ compliance with rehabilitation schedules is a major challenge for clinicians mostly due to the prolonged time stipulated per training session. Unlike several of the rehabilitation methods that entail both vestibular activation and postural training separately, our protocol is designed to train both systems simultaneously, thus obtaining two relevant benefits within a relatively shorter training session of 20 minutes per session in only five sessions. This is intended to reduce the duration of training sessions, make the treatment regimen more manageable, and thus, reduce compliance issues.
Our pilot study utilized a concurrent vestibular and postural training protocol which showed that the vestibular (or headshake) group compared to age-matched controls demonstrated a significant upweighting of the somatosensory system with a compensatory downweighting of the vestibular and visual-vestibular systems. These reweighting mechanisms were shown primarily by sensory ratios as obtained by the sensory organization test (SOT) on the NeuroCom® SMART Master (Natus Medical Inc., Pleasanton, CA). Specifically, the vestibular changes were found on the center of pressure (COP) standard deviation sway of the mediolateral sway, while the COP multiscale entropy sway velocity showed both vestibular and visual-vestibular changes. The control group and no headshake group exhibited either little or no vestibular changes post-training.

This current study focuses on vestibular activation to determine if sensory reweighting in the postural control system occurs in healthy young adults. This is an extension of the pilot study using new participants with the addition of a fourth group (i.e., the vertical headshake group) to allow for examining the changes in the sensory weighting that could be different from the changes associated with horizontal headshake activities. We hypothesized that for the vestibular training groups (i.e., the horizontal and vertical headshake groups) the effect of the training protocol on the vestibular system would significantly alter the pattern of the SOT sensory ratios. That is, the postural control system may alter dependence on visual and somatosensory input to compensate for the changes in vestibular dependence to maintain postural stability. For the non-vestibular training groups (i.e., the no headshake and control groups), we predicted a relatively little or no change in the sensory ratios,
particularly vestibular reweighting, since the vestibular system was not targeted in that training protocol.

**Methods**

The study design was a four group pre- and post-design with random group assignment to train healthy young participants for five sessions, within a week.

**Participants**

Forty-two healthy young individuals from Temple University were enrolled in the study. Each participant signed the University’s Institutional Review Board (IRB) approved consent form in accordance with the guidelines of the Helsinki Accords. Participants were recruited through flyers posted on Temple University main campus and contacted the researcher via email or phone. Monetary incentives for participation commensurate with their total number of sessions ($25-$75). The study was conducted at the Motion-Action-Perception (MAP) Lab, Temple University, Philadelphia, PA.

**Eligibility and Randomization Process**

Healthy, male and female individuals aged 18 to 35 years, with no evidence of neurological or musculoskeletal impairments were eligible to participate in the study. Participants completed a short biomedical background form to rule out evidence of concussion, vestibular or balance issues over the past six months, and ear infection and ocular-motor issues for the past month. The biomedical background also ruled out history of anxiety, depression and learning disability. A short clinical musculoskeletal examination was performed by a physical therapist; i.e., the researcher (Appendix A). Posture was assessed in standing and lying positions to rule out signs of obvious spinal deviations,
pelvic deviations and leg length discrepancies. Pain and limited neck range of motion were assessed and used as exclusion criteria. Eligible participants were then placed in four groups by blocked randomization taking into consideration equal group by gender. The four groups comprise: (i) visual feedback weight shift training (WST) coupled with active sinusoidal horizontal headshake (HHS), (ii) the same WST with vertical headshake (VHS) activity, (iii) WST with no HS (NHS) and (iv) no training (control).

**Procedures**

**Outcome Measures**

**Sensory Organization Test (SOT).** The SOT is one of the assessment protocols of the NeuroCom® SMART Balance Master (Natus Medical Inc., Pleasanton, CA). The SOT is designed to objectively identify abnormalities in an individual’s ability to use the multisensory systems—somatosensory (proprioception), visual and vestibular—that contribute to postural control. The test has six different conditions each repeated three times. Participants stood upright as still as possible with arms by the side and looked straight ahead for 20 seconds under each trial. The six conditions are: 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 SS. The NeuroCom® equipment calculates the SOT composite score as a weighted average of all six conditions to determine the overall level of performance as a percentage from 0-100, with better performance represented as a higher score and a fall scored as 0. The NeuroCom® also indicates the sensory ratios, which estimates the participants’ ability to utilize each type of sensory input to maintain balance. The vestibular
ratio represents the degree to which a participant relies on the vestibular system to maintain balance even if the visual and somatosensory inputs are unreliable. The somatosensory ratio is the degree to which a participant relies on the somatosensory input to maintain balance. The visual ratio is the ability of the participant to rely on visual input for balance control. The preference ratio is the degree to which a participant relies on the visual input even when it is inaccurate. Furthermore, the center of pressure (COP) time series data collected by the SOT can be transformed into other sway variables including, sway area, sway velocity, anterior-posterior (AP) and medio-lateral (ML) standard deviation sways and multiscale entropy (MSE) sway velocity.

The SOT was used to assess static balance at baseline and post-training. Before the exercises, baseline SOT was assessed on all participants (including the control group), and participants rested for 5 minutes. Reassessment of the outcome measure was performed 24 hours from the last training day (Fig. 2.3). The control group only performed pre- and post-assessment of the outcome measure on day one and day six, respectively.
A safety harness was used to support participants during assessments and training, and it has relatively loose straps enough so as not to interfere with movement of the body during normal postural sway, except to catch a fall or near fall.

*Visual Analog Scale (Symptoms).* A simple visual analog scale (VAS) rating tool was used to assess the levels of headache, dizziness and nausea for the HS training groups after each training session. This was used to monitor potential participants’ symptoms and it was then analyzed to identify any significant differences between vestibular groups (i.e., HHS and VHS). The VAS tool rates from “0”- no symptom, to “10”- worst symptom ever felt.

*Exercise Performance Accuracy.* The WST on the NeuroCom® recorded percentage of exercise performance accuracy at the end of each exercise. A score of performance accuracy is recorded when a target is reached successfully by a participant within the 4 seconds from a previous target. Total performance accuracy is, therefore, the number of successful reaches a participant makes in a 1-minute exercise. The maximum total performance accuracy is 15.

*Training*

*Weight Shift Training (WST).* WST is one of the training programs of the Sequence Training activities on the NeuroCom®. WST has six components, that is, levels 1 to 5 and weight bearing, in progressive order. Each level has four directions (i.e. right, left, forward and backward) and each direction has seven exercise activities that offer both static and dynamic “in place” center of gravity weight shift tasks (NeuroCom Clinical Operation Guide, 2014). In this study, levels 3 (forward and back directions) and 5 (forward) were
implemented because they serve to progressively challenge a healthy population and possibly alter sensory reweighting. Level 3 exercises has limits of stability (LOS) of 65%-70%, while level 5 has 85%-90% LOS. Hence, level 5 exercises required wider LOS excursions from participants than level 3 exercises and therefore were more challenging.

Five exercises were selected for each of level 3 forwards, level 3 backwards and level 5 forwards, amounting to a total of 15 exercises. The exercises included: (1) center 3 forward or backward on force plate, (2) pin-wheel forward or backward on force plate, (3) center forward or backward on rocker board place on force plate, (4) center 3 forward or backward on foam placed on force plate and (5) forward or backward left/right on foam placed on force plate, successively. Exercises 1, 3 and 4 have four targets, exercise 2 has six targets, while exercise 5 has two targets (i.e., left and right) (Fig. 2.2 A).

Training protocol. Visual feedback LOS balance training with the WST protocol of the NeuroCom® was implemented to train participants in the three training groups (HHS, VHS and NHS). 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 seconds (Fig. 2.2 B & C). Participants were instructed to quickly move toward the highlighted target as soon as possible and maintain that position until the next target lights up. Each exercise was administered for a period of one minute. Foot placement for the exercises were exact as the standardized foot placement for the SOT assessment (NeuroCom Clinical Operation Guide, 2014). That is, participants with heights 1.41 – 1.65 meters used the M-line, while those with heights 1.66 meters and above used the T-line (force plate and foam). Foot placement for the
Figure 2. 2 Training protocol. A. Weight shift exercises on force plate, rocker board and foam; B-C. Screen interface showing exercise targets of LOS, which changes randomly every 4 seconds; D. Foot placement during exercises (NeuroCom Clinical Operation Guide, 2014)

rocker board was estimated by ensuring that the ankle joint was aligned with the fulcrum of the board. A successful trial was defined as reaching the target within the 4 seconds period and maintaining the position until the next target comes up (although NeuroCom® records a trial as successful when a participant gets into the target and maintains position for one second). However, participants were not aware of this information, in order to ensure standardization in all participants and maintain control of movements.
In the HHS and VHS conditions participants were instructed to rhythmically rotate either their heads horizontally or vertically, respectively, approximately 30° in each direction to a beat of the metronome set from 80 to 120 beats per minute (bpm) as the sessions progressed. The headshake activities were performed concurrently in three out of five exercises for each level, except level 3 backwards. That is, exercises 1, 2, and 5 of levels 3 and 5 forwards. Exercises were performed for five sessions, in five consecutive days, with a weekend break. The training protocol involved center of mass shifting activities while standing in place on flat surface, rocker board or foam and concurrently performing horizontal or vertical headshake activities. Such headshake approaches have been used for postural assessment such as the HS SOT [88], but in this study we proposed to use it for training purposes. The design of our protocol was to challenge the somatosensory system (e.g. different surface stability and COM shifts in different directions), and encourage optokinetic-VOR calibration by incorporating visual feedback during headshake, which all
together would fine-tune postural responses, vestibular reflexes, gaze stability, smooth pursuit control, and multisensory reweighting.

There was a 15 second rest period between each exercise and a 1-minute rest period between each level. The average time of training for each session, including rest periods was 20 minutes. Exercises were monitored by a physical therapist (i.e., the researcher). One of the exercises was demonstrated by the researcher for the participant to see what was expected of him or her. For some of the exercises, participants were asked to adopt tiptoeing, heel, hip and ankle strategies, without lifting the entire foot off the surface, in order to reach farther targets.

Compared to the pilot study, parameters of the exercises of the current study were modified. The sessions were changed from twice a day to once daily to avoid the possibility that participants may miss one of the two daily sessions. The 24-hour reassessment used in the current study was used to ascertain whether training effects would be retained beyond immediate post experiment follow-up period.

**Power Analysis**

In comparing between four groups for the outcomes, a minimum of 36 healthy participants (Fig. 2.4) was considered sufficient to detect a significant difference at alpha 0.05 and 0.30 effect size at beta=0.8 (G*Power, Version 3.0.10). The effect size was based on the pilot study.
In this study, we recruited 42 participants to allow for attrition and lost data.

**Statistical Analysis**

In order to analyze the postural changes in different metric dimensions the COP time series data of the SOT were transformed into COP sway area (using principal component analysis), sway velocity (using path length divided by total time), medio-lateral (ML) standard deviation (Std), antero-posterior (AP) Std and multiscale entropy (MSE) sway velocity \((m = 2; r = 0.2, \tau = 10)\) (MathWorks, 2016). The sampling rate for the SOT was 100 Hz, resulting in 2000 data points, which allows 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 \(^{45}\). Data was filtered at 10 Hz before the calculations. A between and within-group
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 six conditions of the SOT-COP sway variables and equilibrium scores (3 visuals x 2 surfaces x 4 groups x 2 sessions). If significance was found in the omnibus analysis, then a follow-up rmANOVA was performed. Bonferroni post-hoc adjustments were used to adjust for multiple comparisons. The SOT condition was split into visual and surface components during the analysis in order to identify how the surface or visual inputs of the test influences specific sensory systems due to training. Analyzing the SOT data this way controls for the variability because of these known independent variables, i.e., the surface and vision. In addition, the total performance accuracy was computed for all the exercises for each day and an average found for the 5 days. These data were converted into percentages. A one-way ANOVA was used to analyze the percentage performance accuracy between groups for each exercise day and for the average for the 5 days. Bonferroni post-hoc adjustments were used to adjust for multiple comparisons. All statistical analysis was conducted using SPSS software (version 25.0; IBM Corporation, Armonk, NY) and significance set at alpha equal to 0.05.

**Results**

**Demographics**

All the forty-two young participants (20 males; 22 females; 23.0±3.9 years [18-35 years]; 1.6±0.1 meters) completed all the SOT pre- and post-assessments. Also, all thirty-two participants in the training groups completed all five training sessions. There were no significant differences in participant’s characteristics among all the groups (Table 2.1).
Table 2. Characteristics of Participants (n=42)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Horizontal Headshake (n=11)</th>
<th>Vertical Headshake (n=10)</th>
<th>No Headshake (n=11)</th>
<th>Control (n=10)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>22.9±3.4</td>
<td>22.1±3.1</td>
<td>22.5±4.1</td>
<td>24.8±4.9</td>
<td>0.422</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.7±0.1</td>
<td>1.6±0.1</td>
<td>1.7±0.1</td>
<td>1.7±0.1</td>
<td>0.633</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>65.3±13.7</td>
<td>64.8±8.8</td>
<td>71.4±19.2</td>
<td>68.5±19.2</td>
<td>0.754</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.3±3.2</td>
<td>24.1±3.0</td>
<td>25.0±4.9</td>
<td>23.9±5.2</td>
<td>0.833</td>
</tr>
<tr>
<td>Male (%)</td>
<td>5 (45%)</td>
<td>5 (50%)</td>
<td>5 (45%)</td>
<td>5 (50%)</td>
<td>0.994</td>
</tr>
<tr>
<td>Female (%)</td>
<td>6 (55%)</td>
<td>5 (50%)</td>
<td>6 (55%)</td>
<td>5 (50%)</td>
<td></td>
</tr>
</tbody>
</table>

Age, height, weight and BMI (mean±standard deviation); sex (frequency); * p<0.05

**SOT equilibrium and composite scores**

The mixed-model repeated measures analysis of variance (rmANOVA) for the SOT equilibrium and composite scores did not show any significant group x session differences following the vestibular-postural training. However, there were significant changes in the surface, vision and surface x visual interaction of the equilibrium scores (Table 2.2). The average composite scores indicated the following postural changes in the groups: HHS (0.7±2.8), VHS (1.4±3.3), NHS (-1.6±3.6) and control (2.3±0.6) (Table 2.3).

Table 2. 2 SOT condition effects after training

<table>
<thead>
<tr>
<th>Effect</th>
<th>F-test (df, error df)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>234 (1,38)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Vision</td>
<td>125 (2,37)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Surface x vision</td>
<td>40.9 (2,37)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Group x session</td>
<td>0.690 (3,38)</td>
<td>0.564</td>
</tr>
<tr>
<td>Group x session x surface x vision</td>
<td>0.264 (6,76)</td>
<td>0.952</td>
</tr>
</tbody>
</table>

**Sensory ratios**

The mixed-model rmANOVA did not show a significant group x session effect in the SOT sensory ratios pre- to post-training (Table 2.4). However, there was a trending group x session effect in the somatosensory ratio ($F_{3.38} = 2.66$, $p = .062$, n.s.), with HHS (0.023±0.027) and NHS (0.012±0.021) showing the biggest downweighting, followed by
Table 2. 3 SOT equilibrium and composite differences (mean±sd) due to training (Session 2 – Session 1)

<table>
<thead>
<tr>
<th>SOT Conditions</th>
<th>Horizontal Headshake</th>
<th>Vertical Headshake</th>
<th>No Headshake</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>EO - SS</td>
<td>0.8±0.5</td>
<td>-1.2±0.1</td>
<td>0.2±0.6</td>
<td>-0.9±0.3</td>
</tr>
<tr>
<td>EC - SS</td>
<td>-1.4±2.3</td>
<td>-1.3±1.7</td>
<td>-0.9±1.1</td>
<td>1.1±1.8</td>
</tr>
<tr>
<td>SRv- SS</td>
<td>0.1±1.7</td>
<td>0.3±1.2</td>
<td>1.2±0.2</td>
<td>0.7±2.4</td>
</tr>
<tr>
<td>EO - SRs</td>
<td>0.2±2.0</td>
<td>2.5±2.6</td>
<td>-6.0±3.9</td>
<td>1.1±2.2</td>
</tr>
<tr>
<td>EC - SR</td>
<td>0.3±6.8</td>
<td>3.8±1.7</td>
<td>-1.5±4.8</td>
<td>4.7±0.9</td>
</tr>
<tr>
<td>SRv- SRs</td>
<td>1.3±1.8</td>
<td>1.4±3.1</td>
<td>-3.1±6.7</td>
<td>2.6±1.3</td>
</tr>
<tr>
<td>Composite</td>
<td>0.7±2.8</td>
<td>1.4±3.3</td>
<td>-1.6±3.6</td>
<td>2.3±0.6</td>
</tr>
</tbody>
</table>

EO = eyes open, EC = eyes closed, SRs = sway-referenced surface, SRv = sway-referenced visual, SS = stable surface, *p<0.05

VHS (0.004±0.013) (Fig. 2.5). When both vestibular groups were pooled together (HHS & VHS), a significant group x session effect (F_{2,39} = 3.235, p = .050) was found when compared to NHS and CTL groups separately. Specifically, this comparison showed that there was a difference between the vestibular groups (i.e., HHS + VHS) and controls (-0.014 vs 0.019; F_{1,29} = 5.59, p = .025), and between NHS and controls (-0.012 vs 0.019; F_{1,19} = 5.973, p = .024). There were, however, no differences between the vestibular groups and NHS group (-0.014 vs -0.012; F_{1,30} = 0.02, p = .889). Additionally, another analysis between all training groups pooled together (i.e., HHS + VHS + NHS) and controls showed a significant group x session effect (F_{1,40} = 6.61, p = .014).

Table 2. 4 SOT sensory ratio difference (mean±sd) due to training (Session 2 – Session 1)

<table>
<thead>
<tr>
<th>SOT Ratio</th>
<th>Horizontal Headshake</th>
<th>Vertical Headshake</th>
<th>No Headshake</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Somatosensory</td>
<td>-0.023±0.027</td>
<td>-0.004±0.013</td>
<td>-0.012±0.021</td>
<td>0.019±0.011</td>
</tr>
<tr>
<td>Visual</td>
<td>-0.004±0.023</td>
<td>0.035±0.025</td>
<td>-0.066±0.039</td>
<td>0.017±0.030</td>
</tr>
<tr>
<td>Vestibular</td>
<td>-0.001±0.076</td>
<td>0.046±0.015</td>
<td>-0.017±0.053</td>
<td>0.056±0.014</td>
</tr>
<tr>
<td>Preference</td>
<td>0.009±0.026</td>
<td>-0.003±0.010</td>
<td>0.002±0.006</td>
<td>-0.005±0.015</td>
</tr>
</tbody>
</table>

Negative values indicate sensory downweighting
COP Sway of SOT Conditions

Generally, the mixed-model rmANOVA did not show a group x session effect for any of the COP sway variables due to training. There were, however, some sway variables (see below) that showed main and interaction effects for certain components of the test.

COP multiscale entropy sway velocity

The nonlinear metric (MSE sway velocity) showed no group x session effects. The typical main effects obtained during an SOT were found to be significant: surface \( (F_{1,38} = 147, p < .0001) \), visual \( (F_{2,37} = 61.4, p < .0001) \) and surface x visual \( (F_{2,37} = 48.9, p < .0001) \) (Fig. 2.6 E – H). Additionally, there was a session x surface main effect \( (F_{1,38} = 4.61, p = .038) \) and a trending session effect \( (F_{1,38} = 4.05, p = .051) \).

COP standard deviation sway velocity

The COP standard deviation sway velocity (velocity Std) showed no group x session effects. The typical main effects obtained during an SOT were found to be significant: surface \( (F_{1,38} = 71.6, p < .0001) \), visual \( (F_{2,37} = 21.5, p < .0001) \) and surface x visual \( (F \)
2.37 = 15.8, \( p < .0001 \)) (Fig. 2.6A & D). Additionally, there was a group x surface main effect (\( F_{3,38} = 3.41, p = .027 \)) not due to training.

**COP standard deviation mediolateral sway**

The COP standard deviation mediolateral sway (ML Std) showed no group x session effects. The typical main effects obtained during an SOT were found to be significant: surface (\( F_{1,38} = 124, p < .0001 \)), visual (\( F_{2,37} = 25.6, p < .0001 \)) and surface x visual (\( F_{2,37} = 16.9, p < .0001 \)). Additionally, there was a trending session x surface x visual main effect (\( F_{2,37} = 2.75, p = .077 \)) not due to training.

The COP standard deviation antero-posterior sway (AP Std) and sway area did not show any significant group x session differences due to training; however, they both showed the typical three main effects with regards to surface, visual and surface x visual differences.

**Exercise Performance Accuracy**

The one-way ANOVA showed significant differences of percentage performance accuracy between groups for exercise day 1 (\( F_{2,31} = 4.77, p = .016 \)), day 2 (\( F_{2,31} = 4.56, p = .019 \)) and day 3 (\( F_{2,31} = 3.48, p = .044 \)), but not days 4 (\( F_{2,30} = 2.50, p = .10 \)) and 5 (\( F_{2,27} = 2.74, p = .084 \)). Also, the average percentage compliance for the entire 5 exercise days showed a significance difference between the groups (\( F_{2,31} = 5.46, p = .01 \)). A Bonferroni post-hoc analysis showed that the differences were always between HHS and NHS. Thus, NHS group showed the highest exercise performance accuracy on exercise days 1–3 (\( p = .013 – .045 \)) and on the average (\( p = .008 \)) for all exercises (Fig. 2.7).
**VAS Symptoms during Exercise Training**

Five (46%) of the HHS participants expressed symptoms of dizziness or headache before and after training, while three (30%) VHS participants reported similar symptoms. Only one participant in the HHS group reported a pre-training symptom of 1 and 2 scores. No other participants had pre-training symptoms. Dizziness and headache change scores (due to training) were 11 and 2 for HHS, respectively. Similarly, dizziness and headache change scores were 6 and 1 for VHS, respectively.
Discussion

Concurrent vestibular activation and weight shift training (i.e., HHS and VHS groups) showed evidence of sensory reweighting relative to the groups that did the weight shift training only without headshake (i.e., NHS group) and the control group. This sensory reweighting was evident in somatosensory downweighting. However, the concurrent training did not show group-by-session (training) effect in the postural control measures. Possible explanations of the findings have been provided below.

**Sensory Reweighting May Occur Following Vestibular Training**

The headshake activities coupled with weight shift training (WST) incorporates several mechanisms. These include gaze stabilization, smooth pursuit and somatosensory inputs as head activation, eye movements and different surfaces were employed in this study.
The training protocol in the current study suggests somatosensory downweighting when the headshake (HS) groups considered as one large group is compared to the NHS group and control group. This somatosensory downweighting was contrary to our hypothesis and the results in our pilot study \cite{50}. It was hypothesized in the current study that the headshake activity would downweight the vestibular system, which would in turn drive compensatory upweighting of the somatosensory and/or visual channels. This inconsistent result suggests that it is less likely for the somatosensory downweighting to be driven by only the headshake activity, rather it may have also been under the influence of the sensory feedback. That is, there could be the central integration of the vestibular system during the headshake activity with sensory feedback from the somatosensory stimulation during WST performed on different surfaces such as flat, foam and rocker board surfaces.

In addition, somatosensory downweighting was also found in the NHS group, which provides an explanation behind the possible influence of WST on the sensory reweighting. Since this study did not have a headshake group with no WST, we cannot deduce the strength of influence of the WST on somatosensory reweighting or vestibular activation on somatosensory reweighting. However, the magnitude of the change in somatosensory reweighting was larger for the HHS group. It is therefore suggestive that the concurrent horizontal vestibular activation (i.e., HHS) and WST produces a better training effect compared to WST alone (i.e., NHS group). Also, future studies will investigate an HHS group with no WST to establish the proportion of contribution from the headshake activity.
The HHS group showed a larger somatosensory downweighting following training compared to VHS group. Horizontal HS activity predominantly stimulates the horizontal semicircular canals (SCCs), together with the utricular otolith organs, and also activates the vestibulo-colic reflex (VCR). Vertical HS activity on the other hand, stimulates the vertical SCCs (i.e., anterior and posterior SCCs), together with the saccular otolith organs, and also activates the vestibulo-spinal reflex (VSR) and changes the COM due to the movement of the head inertia shifting fore and aft. This may have contributed to the training difference between HHS and VHS groups.

The somatosensory downweighting in the headshake groups 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; however, the two mechanisms 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. 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 the provocative movements, the synaptic connections between the neurons decrease in number leading to long-term structural changes and a concomitant decrease in dizziness. Relating this to our current training protocol, vestibular habituation may have occurred during repetitive headshake suppressing dizziness (i.e. the provocative stimulus). As a result, the vestibular signal driving oculomotor control may go down reducing VOR, but this also reduces the vestibular inputs driving potentially destabilizing VCR and VSR responses. If
vestibular gain is gradually reduced, vestibular downweighting may drive compensatory upweighting of the somatosensory and/or visual channels. However, due to the nature of our protocol design, the contribution of the sensory feedback from the WST consequently downweighted the somatosensory system.

We also considered the alternative mechanism of adaptation as the driver of these potential sensory changes. During adaptation exercises, the task of foveating a visual target while performing headshake and WST provides a visual error signal which can be used to calibrate eye-in-head and head-on-body sensorimotor control 11,91. 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 11,92. 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 will become more efficient and less variable.

**Exercise Performance Accuracy**

The exercise performance accuracy, which indicated how well participants were able to shift their COM to reach targets on the screen during the training sessions, was highest in the NHS group. The NHS presumably achieved the best performance because they concentrated on only one type of exercise compared to the headshake (HHS and VHS) groups; i.e., it was a less complex sensorimotor task. The coordination of repeated rhythmic head movements during the WST in the headshake groups came at a cost to WST exercise performance, affecting accuracy in reaching some targets. Postural
performance has been shown to be negatively impacted by concurrent secondary cognitive tasks using the dual-task paradigm. Our concurrent headshake activity simulates the secondary cognitive task since the participants may have cognitively processed performing the rhythmic head movements concurrently and accurately with using visual feedback of the target to voluntarily control their COM. Furthermore, the finding that all the groups performed progressively well indicates the evidence of motor learning taking place. Although the HS groups generally exhibited lower exercise performance but similar pattern of improvements over the days compared to NHS group, they learned to combine the headshake with the WST probably more effectively. Specifically, the finding suggests that the HS groups continued to improve from day 3 to day 5 while NHS plateaued. Thus, motor learning may have been exhibited more effectively in the HS groups which was evident in the activation of the vestibular system through vestibular habituation/adaptation.

**Comparison to Pilot Study**

The results of the current study when compared to the pilot study did not show a clear effect of headshake training when we compared only the same dependent variables. This may be due to several reasons. The pilot study had six training sessions that were performed twice a day for every other day for a total of five days (i.e., Monday, Wednesday and Friday), while the participants in the current study performed five training sessions once a day for five days with a weekend break. In addition to an extra training dosage, the larger effect found in the pilot study may be influenced by the motor learning effects obtained through motor consolidation due to the resting days between training sessions. Another factor for the larger changes found in the pilot study was due to the immediate
reassessment performed after the last training session as compared to the 24-hour delay before reassessment in the current study.

The finding of the pilot study was different with regards to the direction of somatosensory reweighting. The pilot study showed somatosensory upweighting in the HS group. This difference could be explained by the increased frequency of headshake activities in the current study. The pilot study employed 80 – 100 beats/minute compared to 80 – 120 beats/minute in the current study. This suggests that the dosage of vestibular activation in the current study had a higher influence during the central integration of the somatosensory and vestibular signals following the concurrent vestibular training and WST in the HS groups. Hence, this resulted in a somatosensory downweighting in the current study but an upweighting in the pilot study. Future studies should investigate on how different dosages of vestibular activation could modify somatosensory reweighting and integration.

Unlike the pilot study, assessment of some outcome measures could impact the outcome of succeeding measures. Performing horizontal VOR using the vHIT device could have influenced the outcome performance of SOT sensory reweighting. During the assessment, the assessor rotates the participant's head at a high velocity to activate the VOR. At least forty head rotations are delivered in both left and right directions to complete the assessment. These number of rotations may influence the visual-vestibular systems before a baseline sensory ratio was obtained during SOT.
**Limitations**

One limitation of the study is the absence of vestibular impairment in the sample which made it difficult to induce large changes in otherwise functional behavior. From another perspective, the use of only healthy young participants for all the groups despite the different training manipulations made it difficult to cause large changes. Furthermore, the 20 minutes of training/day for only five sessions was relatively short to induce large vestibular changes. Typically, six to eight weeks of training would be used to show larger changes between the groups. Also, a follow-up was not performed to ascertain whether the gains would lead to long-term retention. In addition, it could be argued that multiple baseline assessments of the SOT may lead to a learning effect. However, the inclusion of a control group in our study allowed us to dissociate learning effects from vestibular training effects.

**Conclusion**

Combined vestibular activation and weight shift training (WST) produced significant somatosensory downweighting relative to the groups that did the WST only without headshake (and the control group. The magnitude of somatosensory downweighting was larger in the HHS than VHS group. Although the SOT equilibrium scores did not show any significant training effect, the above sensory change lends some support to the findings of the pilot study which found evidence of training effects following vestibular activation and WST. The findings can be explained, in part, by an interaction of vestibular habituation or adaptation processes. The outcome of this study may be used as basis for 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 may be modified for home-based training with virtual reality goggles or using smart-phone solutions, which will increase portability, accessibility and affordability.
CHAPTER 3

CHANGES IN VESTIBULAR-MOTOR RESPONSES OF POSTURAL CONTROL AFTER VESTIBULAR TRAINING AMONG HEALTHY YOUNG ADULTS

Introduction

Balance often relies on gaze stabilization mediated by the vestibular system which helps regulate appropriate postural muscle contractions to maintain upright stance. When externally perturbed, short-lived head movements activate the vestibular system, which activates the oculo-motor, cervico-motor and spino-motor pathways to maintain balance. Specifically, when the vestibulo-ocular reflex (VOR) is activated, motor output signals to the extraocular muscles produce fixation of the eyes. Eye fixation also helps to ensure head stabilization and contributes to maintaining head orientation \(^96,97\). Additionally, the vestibular system transmits motor impulses to neck muscles via the vestibulo-collic reflex (VCR) and the VCR contributes to head orientation by maintaining head-on-trunk stability \(^{26}\). Axial muscles below the neck region, which are the primary postural muscles, together with appendicular muscles, respond to maintain body postural balance through the vestibulo-spinal reflex (VSR) \(^{27,28}\).

Multiple methods, including the electro-oculography (EOG), electromyography (EMG), video head impulse test (vHIT) and accelerometry, have been used to assess vestibular-motor responses during postural control studies. The EOG has been shown to measure all types of eye movements with precise measurements accuracy \(^{29,30}\) including smooth pursuits and VOR such as fixating on a static visual or head sway-referenced moving target during upright postural control \(^{31}\). The EMG method can be used to assess muscle
latency responses and synergies \(^{32}\) and power spectral densities \(^{33,34}\) during postural activities. The vHIT system is used to test the function of the semicircular canals (SCCs) by measuring the ratio of the compensatory eye movement velocity to a head movement velocity during a rapid head rotation performed passively along the planes of the specific canal \(^{71,72}\). The output of the ratio is recorded as the VOR gain. Accelerometer studies have shown the relative head-trunk and trunk-lower limbs movements during pitch and roll ramp perturbations, linking these kinematics to the vestibular system \(^{32,73,74}\). By analyzing changes in the eye movement signals of extraocular muscles and the VOR gain during balance tasks, one may understand the eye movement variability and SCC function, which may be induced by vestibular postural training over time and potentially relate to effects of vestibular activation. Furthermore, changes in the EMG and accelerometry signals can give insights into the EMG onset, peak amplitude, duration and average power frequency changes, and relative movement of body segments. The above outcome measures can be used to determine the influence of vestibular training on postural balance control.

Maintaining postural balance is an essential outcome of vestibular rehabilitation. Vestibular rehabilitation is purported to decrease dizziness and visual symptoms, correct overdependence on visual and somatosensory inputs, improve neuromuscular conditioning and increase balance and walking functions \(^{9,22}\). The mechanisms of vestibular rehabilitation are based on principles of vestibular adaptation, habituation and substitution. Most of these principles change the gain of the vestibular system through the VOR, VCR and VSR to ensure that the appropriate motor impulses are transmitted to extraocular and postural muscles. Similarly, vestibular rehabilitation facilitates the use of
somatosensory and visual cues, and other postural strategies, such as hip, knee, ankle and stepping strategies.\textsuperscript{98,99}

Wrisley & Stephens\textsuperscript{100} demonstrated greater improvements in orientation to the vertical on a composite clinical score incorporating the Activities-specific Balance Confidence Scale (ABC), Dizziness Handicap Inventory (DHI), Vestibular Activities of Daily Living Scale (VADL) and Functional Gait Assessment (FGA) during balance training with repetitive ramp platform rotations. The vestibular group in the above study which trained with ramp rotations at vestibular velocities of 1, 2 and 4 deg/sec at 6 deg amplitude performed better than those which trained at non-vestibular velocities (0.5, 8 and 16 deg/sec) and the other group which underwent clinical balance training. The groups trained three times a week for two weeks. The ramp rotation exposures at vestibular velocities appeared to be specifically activating and training the vestibular system.

Keshner et al.\textsuperscript{32} examined the EMG onsets of lower limbs, trunk and neck muscle activation during platform rotations and translations in 10 healthy young adults. In the ramp up perturbations, participants demonstrated early response in the soleus (49 ms), followed by anterior tibialis (TA; 100 ms) and neck extensors (135 ms). Conversely, the ramp down perturbations showed early response in the TA (90 ms), followed by soleus (103 ms) and neck flexion (126 ms). The findings did not show a strong ascending pattern of muscle activation and therefore suggest that the vestibular system was mainly activated (i.e., descending pattern) during the ramp rotations. To identify possible origins of directionally specific triggering signals, Carpenter et al.\textsuperscript{73} performed rotations in both directions of the pitch and roll planes (n=14 healthy young adults). At short latencies as early as 15 ms, there were large vertical linear accelerations of head movement for the pitch perturbations.
and angular roll accelerations for the roll perturbations. The results suggest that these early head responses are due to activations of otoliths or vertical SCCs, transmitting VSR to the trunk and leg muscles for balance correction. The above studies indicate the influence of vestibular activation on postural control and how this activation through headshaking activities can be employed to enhance the vestibular system.

Although, vestibular rehabilitation research studies have shown its effectiveness in improving primary and secondary vestibular symptoms \(^{11,12}\), some studies focus on vestibular training methods only without including postural balance activities. Evidence has shown that studies that employed combined programs such as vestibular activation activities (including gaze stabilization training and habituation exercises) and balance training yielded significant improvement in subjective dizziness, oculomotor control, balance and gait \(^{13,14}\). However, some groups of patients may not show improvement \(^{11}\), probably due, to the type of vestibular rehabilitation employed. Furthermore, there is a paucity of knowledge about neural structures, pathways and processes that drive the effectiveness of sensory reweighting mechanisms for improving vestibular impairment through vestibular activation and postural rehabilitation. Postural training involving active weight shift training (WST) and/or vestibular rehabilitation have been shown to be effective in improving VOR function, trunk control, balance and gait performance among individuals with vestibular impairments and chronic hemiparetic stroke \(^{13,36,39}\). Apart from the benefits of vestibular and postural training, this current protocol was designed to reduce the duration of training sessions resulting in a more manageable treatment regiment, which may help increase compliance.
This study was conducted to assess the effect of a vestibular postural training on vestibulo-motor responses among healthy young adults. The responses include VOR, VCR, VSR and ocular and postural muscle activity using the vHIT system, IMU inertial sensors accelerometry, EOG and EMG measurements. These outcome tools, apart from the vHIT system, were utilized during ramp perturbation rotation trials. We hypothesized that vestibulo-motor responses will significantly change after training in the headshake groups resulting in reduced VOR, VCR and VSR reflexes and head and trunk accelerations. Similarly, we hypothesize that eye movement variability, EMG muscle activity and power spectral density would be significantly reduced after vestibular-postural training in the headshake groups compared to the other groups.

**Methods**

The study design was a four group pre- and post-design with random group assignment to train healthy young participants for five sessions, within a week.

**Participants**

Forty-two healthy young individuals from Temple University were enrolled in the study. Each participant signed the University’s Institutional Review Board (IRB) approved consent form in accordance with the guidelines of the Helsinki Accords. Participants were recruited through flyers posted on Temple University main campus and contacted the researcher via email or phone. Monetary incentives for participation commensurate with their total number of sessions ($25-$75). The study was conducted at the Motion-Action-Perception (MAP) Lab, Temple University, Philadelphia, PA.
Eligibility and Randomization Process

Healthy, male and female individuals aged 18 to 35 years, with no evidence of neurological or musculoskeletal impairments were eligible to participate in the study. Participants completed a short biomedical background form to rule out evidence of concussion, vestibular or balance issues over the past six months, and ear infection and ocular-motor issues for the past month. The biomedical background also ruled out history of anxiety, depression and learning disability. A short clinical musculoskeletal examination was performed by a physical therapist; i.e., the researcher (Appendix A). Posture was assessed in standing and lying positions to rule out signs of obvious spinal deviations, pelvic deviations and leg length discrepancies. Pain and limited neck range of motion were assessed and used as exclusion criteria. Eligible participants were then placed in four groups by blocked randomization taking into consideration equal group by gender. The four groups comprise: (i) visual feedback weight shift training (WST) coupled with active sinusoidal horizontal headshake (HHS), (ii) the same WST with vertical headshake (VHS) activity, (iii) WST with no HS (NHS) and (iv) no training (control).

Procedures

Outcome Measures

All outcome measures were collected immediately before the training exercises and 24 hours following the last (fifth) training session.

Video Head Impulse Test (vHIT) System. To measure the VOR gain, the Video Head Impulse Test (vHIT) system was used. The vHIT objectively measures eye movement response to rapid head rotation by assessing semicircular canal function during passive head rotation. Participants were asked to sit at 1.3 meters away from a target, keeping
head, neck and trunk as still as possible. The impulse conducting system (ICS; GN Otometrics, Taastrup, Denmark) was calibrated using a prescribed series of conjugate eye movements involving following a laser light from left to right without blinking for less than 10 seconds (sampling rate = 250Hz). During VOR testing, the researcher stood behind the participant and delivered small, unpredictable horizontal head impulse rotations to the left and right \(^{72}\). Twenty head impulses were performed to assess each of the two horizontal semicircular canals (Fig. 3.1). Our version of the ICS system was only capable of assessing the horizontal canals. To assess vertical VOR gain, an Inertial Measurement Unit (IMU; Delsys Inc., Boston, MA, USA) and electro-oculography (EOG) system (BlueGain; Cambridge Research Systems, 2012) was used. That is, the head accelerometer recorded head angular acceleration, which was used to calculate angular velocity and the EOG recorded eye movement which was converted to velocity.

Figure 3.1 VOR gain testing using the ICS impulse system

*Postural and Oculomotor activity during the Sensory Organization Test (SOT).* The EMG and EOG activity were assessed at baseline and post-training during SOT. The SOT is
one of the assessment protocols of the NeuroCom® SMART Balance Master (Natus Medical Inc., Pleasanton, CA). The SOT is designed to objectively assess an individual’s ability to use the multi-sensory systems—somatosensory, visual and vestibular—that contribute to postural control. The test has six different conditions each repeated three times (Fig. 3.2). Participants are instructed to stand upright with arms by the side, looking straight ahead, and minimizing extraneous movements for 20 seconds during each trial. The six conditions are: 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 SS.

Before the exercises, inertial measurement unit (IMU) sensors and electro-oculography (EOG) electrodes were placed on postural and ocular muscles of participants. Baseline SOT was then assessed on all participants (including the control group), and participants rested for 5 minutes. Reassessment of the outcome measures were performed 24 hours
after the last training day (Fig. 3.8). The control group only performed pre- and post-assessment of the outcome measures on day one and day six, respectively. A safety harness was used during assessments and training, setup as recommended so as not to interfere with movement of the body during normal postural sway, except to catch a fall or near fall.

**Inertial Measurement Unit (IMU) and Electromyography (EMG) System.** The Delsys Trigno IMU wireless system (Delsys Inc., Boston, MA, USA) consists of EMG, accelerometer, gyroscope and magnetometer sensors. The EMG measures the electrical activity of a muscle, while accelerometers measure the acceleration of body segments. The angular velocity and the orientation of a body segment relative to the direction of motion are measured by the gyroscopes and magnetometers. In the current study, the Trigno wireless system was used to assess EMG signals of eight postural muscles, namely: sternocleidomastoid, cervical erector spinae, rectus abdominis, lumbar erector spinae (L2/L3), rectus femoris, biceps femoris, medial gastrocnemius and tibialis anterior (sampling rate = 1100 Hz). Electrode placement followed standard guidelines \[102\] (Table 3.1). Participants were then asked to lay down on a mat, remain still and relaxed, and the resting EMGs of the eight muscles were collected for 20 seconds. With the Trigno sensors in place, all 18 SOT trials were collected according to SOT instructions (NeuroCom Clinical Operation Guide, 2014). Afterwards, three ramp up followed by three ramp down perturbation trials were collected. Two inertial sensors were placed on the forehead and on the first thoracic spinous process (T1) to assess head and trunk accelerations, respectively (sampling rate = 148 Hz). These sensors also aided in the calculation of vertical VOR, VCR and VSR gains during ramp trials. The acceleration of the forehead sensor was used to calculate vertical VOR gain by relating vertical head velocity to the
velocity of the vertical EOG signal. These two IMU’s were also used to calculate the velocity relationship of the neck relative to trunk movement. Thus, VCR gain was estimated from the head relative to trunk movement. Angular acceleration of the T1 sensor was used to calculate VSR gain by relating the trunk angular velocity to ramp velocity. The IMUs are sensitive to three DOF: AP (pitch), ML (roll) and up & down directions (Fig. 3.3).

Power spectral density was obtained during the SOT and ramp trials from the frequency content of the EMG signals by using the Yule-Walker method. The NeuroCom® (assessing SOT and ramp trials), EOG device and IMU systems were synchronized for simultaneous data capturing by sending pulses from NeuroCom® to the EOG device and IMU system.

Table 3. 1 Names of Postural Muscles and Position for IMU sensors. EMG placements were performed in accordance to the SENIAM Guidelines.

<table>
<thead>
<tr>
<th>Trigno Sensor</th>
<th>Muscle/Landmark</th>
<th>Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>R. Cervical erector spinae (ES)</td>
<td>1 cm lateral to right C3/C4</td>
</tr>
<tr>
<td>02</td>
<td>L. Cervical erector spinae (ES)</td>
<td>1 cm lateral to left C3/C4</td>
</tr>
<tr>
<td>03</td>
<td>R. Longissimus</td>
<td>3 cm lateral to right L1</td>
</tr>
<tr>
<td>04</td>
<td>L. Longissimus</td>
<td>3 cm lateral to left L1</td>
</tr>
<tr>
<td>05</td>
<td>R. Biceps Femoris (BF)</td>
<td>Midway between the right ischial tuberosity and right lateral epicondyle</td>
</tr>
<tr>
<td>06</td>
<td>Head accelerometer</td>
<td>Mid forehead</td>
</tr>
<tr>
<td>07</td>
<td>R. Medial Gastrocnemius (MG)</td>
<td>Most prominent bulge of right calf muscle after maximal contraction</td>
</tr>
<tr>
<td>08</td>
<td>Trunk accelerometer</td>
<td>T1</td>
</tr>
<tr>
<td>09</td>
<td>R. Sternocleidomastoid (SCM)</td>
<td>Midway between the right mastoid and the clavicle</td>
</tr>
<tr>
<td>10</td>
<td>L. Sternocleidomastoid (SCM)</td>
<td>Midway between the left mastoid and the clavicle</td>
</tr>
<tr>
<td>11</td>
<td>R. Rectus abdominis</td>
<td>Measure 1 cm above the umbilicus, then 2 cm lateral to right side of the midline</td>
</tr>
<tr>
<td>12</td>
<td>L. Rectus abdominis</td>
<td>Measure 1 cm above the umbilicus, then 2 cm lateral to left side of the midline</td>
</tr>
<tr>
<td>13</td>
<td>R. Rectus Femoris (RF)</td>
<td>Midway between right ASIS and superior aspect of the right patella</td>
</tr>
<tr>
<td>14</td>
<td>L. Rectus Femoris (RF)</td>
<td>Midway between left ASIS and superior aspect of the left patella</td>
</tr>
<tr>
<td>15</td>
<td>R. Tibialis Anterior (TA)</td>
<td>Upper 1/3 between tip of right fibula and tip of right medial malleolus</td>
</tr>
<tr>
<td>16</td>
<td>L. Tibialis Anterior (TA)</td>
<td>Upper 1/3 between tip of left fibula and tip of left medial malleolus</td>
</tr>
</tbody>
</table>
Electro-oculography (EOG) Device. The two channel BlueGain EOG Bio-signal Amplifier device (Cambridge Research Systems, 2012) was used to assess the horizontal and vertical eye movements directions (Table 3.2; sampling rate = 1k Hz) during SOT and ramp perturbations assessments. The wireless device was connected to the EOG software on a desktop computer via Bluetooth connectivity. After careful skin preparation using isopropyl alcohol wipes, two sets of two disposable “duck foot” surface gel-electrodes (20 x 15 mm, Ag/AgCl sensor; Ambu Neurolne 700, Denmark) were placed around the right eye. These electrodes were placed horizontally, near the lateral and medial canthi and vertically above the eyebrow and below the lower eyelid of the right eye, with the reference electrode on the center of the forehead. Electrodes were secured with 3M Durapore surgical silk tapes. The device was wrapped around participant’s upper arm via the armband case. The calibration of the EOG device was performed synchronously during the vHIT system calibration (Fig. 3.4).
During data collection, an external infrared light-emitting diode (IR LED) bulb affixed over the internal IR receiver on the BlueGain device. The IR LED was used as a sync pulse sent from NeuroCom® at the beginning and the end of a trial to serve as a trial marker (Appendix B).

Table 3.2 Names of Ocular Muscles

<table>
<thead>
<tr>
<th>EOG input channel</th>
<th>Muscles/Landmark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel 1</td>
<td>Near right lateral canthus</td>
</tr>
<tr>
<td>Channel 2</td>
<td>Above right eyebrow</td>
</tr>
<tr>
<td>Reference</td>
<td>Forehead just below IMU sensor</td>
</tr>
<tr>
<td></td>
<td>Near right medial canthus</td>
</tr>
<tr>
<td></td>
<td>Below right lower eyelid</td>
</tr>
</tbody>
</table>

*NeuroCom® Ramp Up and Ramp Down Rotations.* Reactive postural responses were tested using, ramp up and down support surface rotations on the NeuroCom® SMART Balance Master. Participants were instructed to stand as still as possible with eyes open on the force plate, arms by the side while ramp up and down perturbations were presented at random times for each trial. The angular velocity of the upward or downward rotations was $+50^\circ$/second with amplitude of $10^\circ$ and 0.2 seconds duration $^{32,73,74}$. Six trials (three ramp ups followed by three ramp downs) were performed with random delays of 1 or 2 seconds. These trials were performed pre- and post-training of the first and last training sessions. Data were collected at a sampling rate of 100 Hz for 5 sec each trial. EOG, EMG, and accelerometry was collected during each trial. COP time series data was...
transformed into various sway parameters including COP sway area, sway velocity, medio-lateral (ML) standard deviation (Std), antero-posterior (AP) Std and multiscale entropy (MSE) of sway velocity. Fig. 3.5 shows a participant’s set up.

**Figure 3. 5 Set up of a participant**

**Visual Analog Scale (Symptoms).** A simple visual analog scale (VAS) rating tool was used to assess the levels of headache, dizziness and nausea for the HS training groups after each training session. This was used to monitor participants’ potential symptoms and it was then analyzed to identify any significant differences between vestibular groups (i.e., HHS and VHS). The VAS tool rates from “0”- no symptom, to “10”- worst symptoms ever felt.
Figure 3. 6 Training protocol. A. Weight shift exercises on force plate, rocker board and foam; B-C. Screen interface showing exercise targets of LOS, which changes randomly every 4 seconds; D. Foot placement during exercises (NeuroCom Clinical Operation Guide, 2014)

**Training**

*Weight Shift Training (WST).* WST is one of the training programs of the Sequence Training activities on the NeuroCom®. WST has six components, that is, levels 1 to 5 and weight bearing, in progressive order. Each level has four directions (i.e. right, left, forward and backward) and each direction has seven exercise activities that offer both static and dynamic “in place” center of gravity weight shift tasks (NeuroCom Clinical Operation Guide, 2014). In this study, levels 3 (forward and back directions) and 5 (forward) were
implemented because they serve to progressively challenge a healthy population and possibly alter sensory reweighting. Level 3 exercises has limits of stability (LOS) of 65%-70%, while level 5 has 85%-90% LOS. Hence, level 5 exercises required wider LOS excursions from participants than level 3 exercises and therefore were more challenging.

Five exercises were selected for each of level 3 forwards, level 3 backwards and level 5 forwards, amounting to a total of 15 exercises. The exercises included: (1) center 3 forward or backward on force plate, (2) pin-wheel forward or backward on force plate, (3) center forward or backward on rocker board place on force plate, (4) center 3 forward or backward on foam placed on force plate and (5) forward or backward left/right on foam placed on force plate, successively. Exercises 1, 3 and 4 have four targets, exercise 2 has six targets, while exercise 5 has two targets (i.e., left and right) (Fig. 3.6 A).

Training protocol. Visual feedback LOS balance training with the WST protocol of the NeuroCom® was implemented to train participants in the three training groups (HHS, VHS and NHS). 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 seconds (Fig. 3.6 B & C). Participants were instructed to quickly move toward the highlighted target as soon as possible and maintain that position until the next target lights up. Each exercise was administered for a period of one minute. Foot placement for the exercises were exact as the standardized foot placement for the NeuroCom® equipment (NeuroCom Clinical Operation Guide, 2014). That is, participants with heights 1.41 – 1.65 meters used the M-line, while those with heights 1.66 meters and above used the T-line (force plate and foam). Foot placement
for the rocker board was estimated by ensuring that the ankle joint was aligned with the fulcrum of the board. A successful trial was defined as reaching the target within the 4 seconds period and maintaining the position until the next target comes up (although NeuroCom® records a trial as successful when a participant gets into the target and maintains position for one second). However, participants were not aware of this information, in order to ensure standardization in all participants and maintain control of movements.

Figure 3. 7 Study protocol. VOR = vestibulo-ocular reflex; SOT = sensory organization test; EMG = electromyography; EOG = electro-oculography
In the HHS and VHS conditions participants were instructed to rhythmically rotate either their heads horizontally or vertically, respectively, approximately 30° in each direction to a beat of the metronome set from 80 to 120 beats per minute (bpm) as the sessions progressed. The headshake activities were performed concurrently in three out of five exercises for each level, except level 3 backwards. That is, exercises 1, 2, and 5 of levels 3 and 5 forwards. Exercises were performed for five sessions, in five consecutive days, with a weekend break. The training protocol involved center of mass shifting activities while standing in place on flat surface, rocker board or foam and concurrently performing horizontal or vertical headshake activities. The design of this protocol was to challenge the somatosensory system, while activating the vestibular system by encouraging gaze stability and smooth pursuit. Such headshake approaches have been used for postural assessment such as the HS SOT, but in this study we proposed to use it for training purposes. There was a 15 second rest period between each exercise and a 1-minute rest period between each level. The average time of training for each session, including rest periods was 20 minutes. Exercises were monitored by a physical therapist (i.e., the researcher). One of the exercises was demonstrated by the researcher for the participant to see what was expected of him or her. For some of the exercises, participants were asked to adopt tiptoeing, heel, hip and ankle strategies, without lifting the entire foot off the surface, in order to reach farther targets.

**Power Analysis**

In comparing between four groups for the outcomes, a minimum of 36 healthy participants (Fig. 3.8) was considered sufficient to detect a significant difference at alpha 0.05 and 0.30 effect size at beta=0.8 (G*Power, Version 3.0.10). The effect size of
Aim 1 was used for the calculation of the sample size for the various outcome measures. In retrospect, we may have been underpowered for the dependent variables that we did not have pilot data for, which showed little or no significant effects. Had we assumed a smaller effect size (d < 0.3) for the other dependent variables, and increased our sample size, some of the small or trending effects may have reached significance.

![Figure 3. 8 Sample size determination (from G*Power)](image)

In this study, we recruited 42 participants to allow for attrition and lost data.
Data Management/Statistical Analysis

Video Head Impulse Test (vHIT) System

The ICS impulse system calculated two VOR gains for the left and right horizontal SCCs, respectively, from the twenty head impulses obtained on each side. These gains were calculated for both pre- and post-assessments. An average VOR gain was calculated from the left and right horizontal SCCs gain for each participant. A between and within-group repeated measures analysis of variance (rmANOVA) was used to analyze the VOR gains (4 groups x 2 sessions). If significance was found in the omnibus analysis, then planned between-group comparisons were performed to determine which groups differed. Bonferroni corrections were used to adjust for multiple comparisons.

NeuroCom® Ramp Up and Ramp Down Rotations (COP)

The NeuroCom® system produces a COP time series output data for the ramp perturbation trials. The trials were analyzed in two main ways: the entire trial and segmental components. For the entire ramp trials (which lasted for 5 seconds), the first-200 milliseconds (ms) after ramp onset was analyzed to reflect involuntary responses (Fig. 3.9 A – D). That is, the entire ramp trial analysis entailed trajectories from ramp onset to the next 200 ms, while the segmental component analysis entailed specific segments of the 200 ms trajectory. For the entire trial analysis, the COP data of the trials were transformed into four COP sway variables: COP sway area, sway velocity, medio-lateral (ML) standard deviation (Std) and antero-posterior (AP) Std sways. Each of the three trials with their respective averages were considered in the analyses.

For the segmental component analysis, the AP response for the ramp up trials typically has an initial maximum (max) followed by a minimum (min) peak. The trajectory from the
ramp onset to the next 200 milliseconds was divided into three segments (Fig. 3.9 A – B, B – C and C – D). Fig. 3.9 shows the various segments of the trajectory and the analyses that were considered:

a. A – B: Time between the ramp onset to the max peak, reflecting the biomechanical effects of the platform perturbation (reversal for ramp down trials).

b. B – C: Time between max peak and min peak, reflecting the reflexive response (reversal for ramp down trials). This is the automatic control mechanism mostly likely provided by the vestibular system (reflexes), which we will refer to as the automatic postural response. If the automatic postural response significantly changes in only the headshake groups, then it will be due to vestibular reflexes.

c. C – D: Time between min peak and next max peak, reflecting postural corrective adjustment (reversal for ramp down trials).

d. Matlab codes, together with visual inspection, were used to identify peak amplitudes (B and C) and the vertical distance between them.

e. Reaction times were identified at B and C.

f. COP sway velocity was calculated for B – C (velocity of APR).

g. Also, the COP sway area, velocity, AP Std and ML Std sway were calculated from ramp onset to next 200 ms.

The first and average trials of the ramp perturbations were considered for the analysis. The first trial represents participants’ first exposure to the assessment and thus, no influence of learning effects, while the average trials represent participants’ ability to demonstrate that the effect of the assessment is retained. A between and within-group repeated measures analysis of variance (rmANOVA) was used to analyze the four COP
sway variables (COP sway area, velocity, AP Std and ML Std sway; 4 groups x 2 sessions), the APR (velocity of B – C; 4 groups x 2 sessions) and peak up and down amplitudes of the APR (4 groups x 2 sessions) for the ramp up and ramp down trials. If significance was found in the omnibus analysis, then planned between-group comparisons were performed to determine which groups differed using a follow-up rmANOVA. Bonferroni corrections were used to adjust for multiple comparisons.

Figure 3. 9 Ramp up and down perturbation trajectories
Inertial Measurement Unit (IMU) and Electromyography (EMG) System

Electromyography during Sensory organization test (SOT). The middle 10 seconds time series data of the resting EMG of each participant was used to normalize the postural muscle activations during the SOT trials by expressing the EMG of the muscle of each participant as a percentage of the mean plus one standard deviation of the resting EMG, according to the equation below:

\[
\text{Normalized tibialis anterior EMG} = \left( \frac{\text{Tibialis anterior EMG}}{\text{mean} + \text{sd tibialis anterior of resting EMG}} \right) \times 100
\]

The longissimus and rectus abdominis muscles were excluded throughout all the analyses because they were contaminated with electrocardiogram wave signals. More importantly, excluding these muscles did not affect the primary aims of the study because the neck and lower limb muscles were the main focus of the study. The normalized signals were full wave rectified, low pass filtered and smoothed at 10 Hz using a Butterworth filter of the 4th order (MATLAB R2016a, Mathworks Inc., Natick MA, USA). The means of the filtered signals (from the time series trial) were calculated to obtain the muscle activations of the three SOT trials for all 6 conditions. The muscle activations of the 3 trials were averaged to obtain one value for each condition. A between- and within-group repeated measures analysis of variance (rmANOVA) was used to analyze the muscle activations of SOT conditions (4 groups x 2 sessions x 3 visuals x 2 surfaces). If significance was found in the omnibus analysis, then a follow-up rmANOVA was performed. Bonferroni post-hoc adjustments were used to adjust for multiple comparisons.

Ramp trials. Similarly, the middle 5 seconds time series data of the resting EMG was used to calculate the normalized postural muscle activation during the ramp perturbation trials. Signals were filtered as stated above. The means of the filtered signals of the ramp trials
were calculated accordingly starting from the ramp onset to the end of the 5 seconds trial to obtain the muscle activation during each ramp perturbation. Averages for ramp up and ramp down trials were calculated separately. For the EMG ramp segment analysis, EMG time onset response with corresponding time onset amplitude, and peak magnitude with corresponding peak time were extracted using Matlab “findpeaks” function. Where the locations were not correctly identified by Matlab, visual inspection with aid of Matlab data tip tool was used to identify them. A between- and within-group rmANOVA was used to analyze the EMG of individual trials and average trials for ramp up and ramp down (4 groups x 2 sessions). Similarly, a between- and within-group rmANOVA was used to analyze time onset response, time onset amplitude, peak magnitude and peak time separately (4 groups x 2 sessions). Bonferroni post-hoc adjustments were used to adjust for multiple comparisons.

*Head and trunk angular acceleration/velocity.* The head and trunk acceleration profiles during ramp trials were detrended and filtered with a Butterworth filter of 4th order and cut-off frequency of 6Hz using Matlab “filtfilt” function. Peak angular acceleration was calculated from the detrended data. Also, the detrended angular acceleration was converted to angular velocity using Matlab “cumtrapz” function and the average angular velocity was calculated. A between- and within-group rmANOVA was used to analyze the head and trunk angular accelerations and head and trunk angular velocities of individual trials and average trials for ramp up and ramp down (4 groups x 2 sessions). Bonferroni post-hoc adjustments were used to adjust for multiple comparisons.

*Power spectral density (PSD).* The Yule-Walker method was used to calculate the PSD. While the Welch method is used more frequently to estimate the PSD, two studies 106,107 have demonstrated superior performance of the Yule-Walker method over the Welch
method. The Yule-Walker method performs better for larger continuous data, with good statistical consistency and smooth nature, and shows clearer and sharper peaks. Moreover, the Welch method produces broader and misleading peaks, while the Yule-Walker method gives better frequency resolution. Therefore, in the current study, the Yule-Walker method, which estimates the autoregressive parameter, was used to find the PSD for the 5 seconds ramp perturbation trials. Similar procedures as stated above were used to normalize and filter signals. The normalized signal was then used to obtain the PSD, from the ramp time onset to the rest of the 5 seconds trial, using Matlab “aryule” function with a 4th order model. The mean PSD was calculated from the time series PSD data to obtain one PSD value for statistical analysis. A between- and within-group rmANOVA was used to analyze the PSD of individual trials and average trials for ramp up and ramp down (4 groups x 2 sessions).

Electro-oculography (EOG). Vertical EOG calibration. Since the EOG was calibrated synchronously with the vHIT (which measures only the horizontal VOR), the vertical calibration was not performed during testing. Due to this limitation during data collection, a vertical EOG calibration was tested on four other healthy participants (outside the study sample) whose demographics were within the study age range. This was performed by placing the two targets vertically and 1.3 meters away from the seated participants. Participants were asked to perform conjugate eye movements at 60 beats/minute to obtain vertical saccades. Similarly, a horizontal EOG calibration was performed on these four participants by placing the targets horizontally. Two trials were performed in each orientation. Matlab data tip tool was used to identify distances between saccades and averages were found. The distance represents eye movement between the two fixed points and was used for the EOG calibration. To statistically justify that this vertical EOG
calibration could be applied to the main study sample, a reliability statistic was conducted between the horizontal EOG calibration from 17 participants from the main study and vertical EOG calibration from the other four participants. The intrarater reliability was performed using the 2-way mixed-effects model and absolute agreement \(^{108,109}\). The intraclass correlation (ICC) for the horizontal calibration was 0.764 (CI = 0.367 – 0.914; p = 0.003), while that for the vertical calibration was 0.944 (CI = 0.838 – 0.981; p = 0.008). Thus, averages of the calibrations were used as baseline for the ramp trials. The average horizontal calibration factor was 0.005, whereas that for the vertical was 0.013. Matlab codes were used to locate the non-zero number and the beginning and end of a trial was extracted (Appendix B). The calibration factor was applied to the horizontal and vertical eye signals accordingly for the EOG ramp trials. Data was filtered using a Butterworth lowpass filter of 2\(^{nd}\) order and at 30 Hz cut-off frequency. Filtered data was detrended and the displacement was calculated for horizontal and vertical signals. The displacement was differentiated to velocity and acceleration. Averages of the three trials were found from the ramp onset to the end of the 5 seconds trials and also from ramp onset to the next 200 ms. Eye movement area, velocity, AP and ML Std were calculated. A between- and within-group rmANOVA was used to analyze the eye movement variables during ramp up and ramp down trials (4 groups x 2 sessions). Bonferroni post-hoc adjustments were used to adjust for multiple comparisons.

**VOR, VCR and VSR Gain.** The reflex gains were calculated using the assessments (session 1) and reassessments (session 2) of the eye velocity, head and trunk velocities and angular velocities, and ramp velocity.

The vertical VOR (VVOR) gain was calculated as:
\[ VVOR\ gain = \frac{Vertical\ eye\ velocity\ in\ Pitch}{Peak\ head\ angular\ velocity\ in\ Pitch} \]

The VCR gain was calculated as:

\[ VCR\ gain = \frac{Peak\ head\ angular\ velocity\ in\ Pitch}{Peak\ trunk\ angular\ velocity\ in\ Pitch} \]

The VSR gain was calculated as:

\[ VSR\ gain = \frac{Peak\ trunk\ angular\ velocity\ in\ Pitch}{Ramp\ velocity} \]

The above equations were used to find the respective gains of sessions 1 and sessions 2 separately. Repeated measures ANOVA was then used to find significant changes due to training between sessions 1 and 2 across the four groups (4 groups x 2 sessions). Bonferroni post-hoc adjustments were used to adjust for multiple comparisons.

All statistical analysis was conducted using SPSS software (version 25.0; IBM Corporation, Armonk, NY) and significance set at alpha equal to 0.05.

**Ramp falls**

The number of falls during ramp perturbation trials were recorded for pre- and post-assessments for each participant, and the total frequency of falls were obtained for each group. Simple frequency analysis was used to compare the frequency of falls for all groups.

**VAS Symptom Scores**

The total number of reported dizziness, headache and nausea were obtained for pre- and post-training for HS groups. Simple frequency analysis was used to compare the symptoms for HHS and VHS groups.
Results

Demographics

All the forty-two young participants (20 males; 22 females; 23.0±3.9 years [18-35 years]; 1.6±0.1 meters) completed most of the pre- and post-assessments. Some of the data were lost due to equipment failure that was not detected during data collection. Also, all the thirty-two participants in the training groups (HHS, VHS and NHS) completed all the five training sessions. There were no significant differences in participant's characteristics among all the groups (Table 3.3).

Table 3. 3 Characteristics of Participants (n=42)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Horizontal Headshake (n=11)</th>
<th>Vertical Headshake (n=10)</th>
<th>No Headshake (n=11)</th>
<th>Control (n=10)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>22.9±3.4</td>
<td>22.1±3.1</td>
<td>22.5±4.1</td>
<td>24.8±4.9</td>
<td>0.422</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.7±0.1</td>
<td>1.6±0.1</td>
<td>1.7±0.1</td>
<td>1.7±0.1</td>
<td>0.633</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>65.3±13.7</td>
<td>64.8±8.8</td>
<td>71.4±19.2</td>
<td>68.5±19.2</td>
<td>0.754</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.3±3.2</td>
<td>24.1±3.0</td>
<td>25.0±4.9</td>
<td>23.9±5.2</td>
<td>0.833</td>
</tr>
<tr>
<td>Male (%)</td>
<td>5 (45%)</td>
<td>5 (50%)</td>
<td>5 (45%)</td>
<td>5 (50%)</td>
<td>0.994</td>
</tr>
<tr>
<td>Female (%)</td>
<td>6 (55%)</td>
<td>5 (50%)</td>
<td>6 (55%)</td>
<td>5 (50%)</td>
<td></td>
</tr>
</tbody>
</table>

Age, height, weight and BMI (mean±standard deviation); sex (frequency); * p<0.05

Horizontal VOR Gain

The multivariate repeated measures ANOVA of the horizontal VOR gain showed a trending group x session (F_{3,31} = 2.53, p = .076) main effect in the pre- to post-training. Generally, all the groups, except controls (mean change = -.018), showed a decrease in the right VOR gain, with the greatest change occurring in the HHS (mean change = .077), followed by VHS (mean change = .049) and NHS (mean change = .023) (Fig. 3.10). However, when both vestibular groups were pooled together (HHS & VHS), a significant group x session effect (F_{2,32} = 3.57, p = .040) was found when compared to NHS and CTL groups separately. Specifically, this comparison showed that there was a difference
between the combined vestibular groups (HHS + VHS) and control group (0.06 vs -0.02; \( F_{1,23} = 8.33, p = .008 \)). There were no differences between the vestibular groups and NHS (0.06 vs 0.05; \( F_{1,25} = 0.15, p = .704 \)), and NHS and controls (0.05 vs -0.02; \( F_{1,16} = 2.96, p = .105 \)) (Fig. 3.11).

**Figure 3.10** VOR gain for the 4 groups. Lighter colors indicate session 2. * significant at 0.05

**Figure 3.11** Planned comparison of the vestibular groups against NHS and CTL. Purple = HHS + VHS, red = NHS, orange = CTL

**COP of Ramp Perturbations**

The first and average trials of the ramp perturbations was considered throughout the results section. The first trial represents participants’ first exposure to the assessment and
thus, no influence of learning effects, while the average trials represent participants’ ability to demonstrate that the effect of the assessment is retained. The COP ramp sway variables were computed from the ramp onset to the following 200 milliseconds of the trial. The four COP sway variables analyzed were: sway area, sway velocity standard deviation (sway velocity Std), medio-lateral Std sway (ML sway Std) and antero-posterior Std sway (AP Std).

There was a significant group x session main effects due to training in the sway velocity Std ($F_{3,37} = 4.35$, $p = .010$; average ramp up trials) as assessed by the ramp up trials (Table 3.4). The p-values of the changes in the trials are shown in Fig. 3.12.

Table 3.4 COP of Ramp up perturbation trials (P-values of session-by-group interactions)

<table>
<thead>
<tr>
<th>COP Variable</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sway area</td>
<td>0.280</td>
<td>0.466</td>
<td>0.039</td>
<td>0.063</td>
</tr>
<tr>
<td>Velocity Std</td>
<td>0.449</td>
<td>0.171</td>
<td>0.075</td>
<td>0.010*</td>
</tr>
<tr>
<td>ML Std</td>
<td>0.192</td>
<td>0.733</td>
<td>0.049</td>
<td>0.117</td>
</tr>
</tbody>
</table>

Std = standard deviation, significant values in bold and asterisks, trending values in bold only. Difference calculated by $S2 – S1$. $P < 0.017$ for individual trials, $p < 0.05$ for averaged trials.

Planned comparison of the sway velocity Std showed that the differences were found for HHS versus control ($0.038 \text{ cm/s vs } -0.123 \text{ cm/s}; F_{1,18} = 7.11, p = .016$), VHS versus NHS.
(0.100 cm/s vs -0.046 cm/s; $F_{1,19} = 4.66, p = .044$) and VHS versus control (0.100 cm/s vs -0.123 cm/s; $F_{1,17} = 6.95, p = .017$) (Fig. 3.13).

![Graph showing sway velocity comparisons](image)

Figure 3.13 Planned comparison of groups for COP sway velocity Std during ramp up trials. Green = HHS, blue = VHS, red = NHS, orange = CTL.

There was only one significant group x session main effect due to training in the sway area which survived Bonferroni correction ($F_{3,36} = 5.29, p = .004$) which occurred in the 2nd trial as assessed by the ramp down trials (Table 3.5). The p-values of the changes in the sway variables for the ramp down trials are shown in Fig. 3.14.

![Table showing COP variables](image)

Table 3.5 COP of Ramp down perturbation trials (P-values of session-by-group interactions)

<table>
<thead>
<tr>
<th>COP Variable</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sway area</td>
<td>0.187</td>
<td>0.004*</td>
<td>0.565</td>
<td>0.180</td>
</tr>
<tr>
<td>ML Std</td>
<td>0.156</td>
<td>0.055</td>
<td>0.538</td>
<td>0.450</td>
</tr>
</tbody>
</table>

Std = standard deviation, significant values in bold and asterisks, trending values in bold only. Difference calculated by S2 – S1. $p < 0.017$ for individual trials, $p < 0.05$ for averaged trials.

![Graph showing COP sway area](image)

Figure 3.14 COP Sway area of ramp down trials. Blue box = session 1, orange box = session 2, T = trial, x-mark = mean; * significant at 0.05.
Planned comparison of the sway area was found for HHS versus VHS (0.293 cm$^2$ vs -9.146 cm$^2$; $F_{1,18} = 9.00, p = .008$), VHS versus NHS (-9.146 cm$^2$ vs -1.781 cm$^2$; $F_{1,19} = 5.44, p = .031$) and VHS versus control (-9.146 cm$^2$ vs 0.015 cm$^2$; $F_{1,19} = 5.44, p = .031$) (Fig. 3.15).

![Sway area comparison](image)

**Figure 3.15** Planned comparison of groups for COP sway velocity Std ramp down trials. Green = HHS, blue = VHS, red = NHS, orange = CTL

The AP Std and sway velocity Std for the ramp up and down, respectively, did not yield any significant changes.

**COP Velocity of Automatic Postural Responses**

There was a significant group x session main effect due to training in the COP velocity for automatic postural responses (see Fig. 3.9, upper, from B to C) for the average ramp up trials ($F_{3,37} = 5.60, p = .003$) (Fig. 3.16). There was no significant group x session main effect in the ramp down trials.

Planned comparison showed that the change in velocity for the average ramp up trial was found for HHS versus VHS (0.205 vs -0.002; $F_{1,19} = 5.27, p = .033$), HHS versus NHS
Figure 3. 16 COP sway velocity (automatic postural response) for ramp up trials. Lighter colors indicate session 2. p < 0.05

(0.205 vs -0.065; $F_{1,20} = 9.16, p = .007$) and HHS versus control (0.205 vs -0.024; $F_{1,18} = 5.47, p = .031$) (Fig. 3.17).

Figure 3. 17 Planned comparison of groups for automatic postural response (ramp up trials). Green = HHS, blue = VHS, red = NHS, orange = CTL

**Peak Amplitudes and Reaction Times of Automatic Postural Responses**

The peak up and peak down amplitudes of the automatic responses (B to C), together with their respective timings and peak-to-peak vertical distances (i.e., vertical distance between peak up and peak down of the COP path trajectory) were analyzed. There was no significant group x session effect due to training in the peak amplitude, reaction time and vertical between peaks. However, there was a trending session x group significant effect ($F_{1,37} = 2.50, p = .075$) in the peak up reaction time of the averaged ramp up trials.
Head and Trunk Acceleration and Velocity during Ramp Perturbations

There were no significant group x session main effects in peak AP or ML head/trunk acceleration or in the average AP or ML heads/trunk velocity due to training. However, there was a trending group x session main effect in the average ML head velocity as assessed by 1st ramp down trial ($F_{3,36} = 2.920, p = .047$). The p-values of the changes in the trials are shown in Table 3.6.

<table>
<thead>
<tr>
<th>Kinematic</th>
<th>Trial</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak head acceleration in AP (ramp down)</td>
<td>0.387</td>
<td>0.672</td>
</tr>
<tr>
<td>Peak trunk acceleration in ML (ramp up)</td>
<td>0.957</td>
<td>0.080</td>
</tr>
<tr>
<td>Head velocity in ML (ramp down)</td>
<td>0.047</td>
<td>0.447</td>
</tr>
</tbody>
</table>

Std = standard deviation, trending values in bold only. Difference calculated by $S_2 - S_1$, $p < 0.017$ for individual trials, $p < 0.05$ for averaged trials.

Muscle Activation during SOT

The muscle activity changes due to training as tested during SOT pre- and post-assessment showed a significant main group x session effect in only the right medial gastrocnemius ($F_{3,34} = 3.27, p = .033$) (Fig. 3.18). Planned comparison showed group x session effects for HHS versus control ($F_{1,18} = 4.84, p = .041$) and VHS versus control ($F_{1,17} = 4.87, p = .041$). The pre- and post-changes in muscle activities for the condition 4 were: HHS = 15.9 millivolts (mv), VHS = 16.7 mv and control = -26.9 mv; condition 5 were: HHS = 11.1 mv, VHS = 16.0 mv and control = -5.7 mv; and condition 6 were: HHS = 9.5 mv, VHS = 10.4 mv and control = -1.3 mv. The positive amplitudes connote reduced
muscle activity, while the negative amplitudes connote increased muscle activity due to training.

The other muscles did not show any significant main effects in the surface, visual, surface x vision (as typically found in SOT equilibrium scores) except the right rectus femoris and left and right tibialis anterior. Also, the left tibialis anterior showed a trending surface x visual x group x session effect ($F_{6,46} = 1.97, p = .089$) (Table 3.7).

Table 3. 7 Muscle activity during SOT for other muscles

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Effect</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rt Medial gastrocnemius</td>
<td>Session x group</td>
<td>0.033*</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td></td>
<td>Vision; EO vs SRs ($F_{1,34} = 9.762, p = .004$)</td>
<td>0.016*</td>
</tr>
<tr>
<td></td>
<td>Surface x vision</td>
<td>0.378</td>
</tr>
<tr>
<td>Rt Rectus femoris</td>
<td>Session x group</td>
<td>0.216</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td>0.006*</td>
</tr>
<tr>
<td></td>
<td>Vision; EO vs SRs ($F_{1,34} = 5.833, p = .021$)</td>
<td>0.041*</td>
</tr>
<tr>
<td></td>
<td>Surface x vision</td>
<td>0.032*</td>
</tr>
<tr>
<td>Rt Tibialis anterior</td>
<td>Session x group</td>
<td>0.849</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td>0.001*</td>
</tr>
<tr>
<td></td>
<td>Vision; EO vs SRs ($F_{1,34} = 12.923, p = .001$)</td>
<td>0.004*</td>
</tr>
<tr>
<td></td>
<td>Surface x vision; EC vs SRs ($F_{1,34} = 16.195, p &lt; .001$)</td>
<td>0.002*</td>
</tr>
<tr>
<td>Lt Tibialis anterior</td>
<td>Session x group</td>
<td>0.124</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td>0.001*</td>
</tr>
<tr>
<td></td>
<td>Vision; EO vs SRs ($F_{1,23} = 15.008, p = .001$)</td>
<td>0.003*</td>
</tr>
<tr>
<td></td>
<td>Surface x vision; EO vs SRs ($F_{1,23} = 9.551, p = .005$)</td>
<td>0.022*</td>
</tr>
<tr>
<td></td>
<td>Surface x vision x session x group</td>
<td>0.089</td>
</tr>
</tbody>
</table>

EO = eyes open, EC = eyes closed, SRs = sway-referenced surface, significant values in bold and asterisks. p < 0.05
Figure 3. 18 Muscle activity of medial gastrocnemius during SOT. Blue = session 1, orange = session 2

**Muscle Activation during Ramp Perturbations (Ramp Trial Trajectory)**

The mean EMG amplitude during ramp perturbation trials (from ramp onset to the next 200 ms) did not show a significant group x session main effect due to training. However, the right tibialis anterior showed trending group x session effects in the 1st ($F_{3,36} = 2.37, p = .086$) and averaged ($F_{3,36} = 2.40, p = .084$) ramp down trials (Table 3.8).

<table>
<thead>
<tr>
<th>Muscle (ramp direction)</th>
<th>HHS</th>
<th>VHS</th>
<th>NHS</th>
<th>CTL</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rt Tibialis anterior (1st ramp down trial)</td>
<td>3.2±15.4</td>
<td>54.2±44.5</td>
<td>112.4±101.7</td>
<td>-352.4±236.0</td>
<td>0.086</td>
</tr>
<tr>
<td>Rt Tibialis anterior (avg ramp down trial)</td>
<td>-0.73±10.1</td>
<td>30.5±26.1</td>
<td>41.4±34.3</td>
<td>-203.1±138.0</td>
<td>0.084</td>
</tr>
</tbody>
</table>

Positive values indicate reduced muscle activity due to training, trending values in bold.
Difference calculated by S2 − S1. p < 0.05

**Muscle Activation during Ramp Perturbations (Peak Amplitude and Time Onset)**

In the ramp up perturbation trials, there was a significant *group x session* main effects due to training in the 1st trial of the time onset for the left cervical erector spinae ($F_{3,25} = 4.34, p = .0014$) (Table 3.9).
Table 3. 9 Muscle activation: ramp up perturbation trials (P-values of session-by-group interactions)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Muscle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time onset</td>
<td>Lt Cervical erector spinae</td>
<td>0.014*</td>
<td>0.460</td>
<td>0.686</td>
<td>0.158</td>
</tr>
<tr>
<td>Peak time</td>
<td>Lt Cervical erector spinae</td>
<td>0.049</td>
<td>0.236</td>
<td>0.264</td>
<td>0.127</td>
</tr>
<tr>
<td>Onset amplitude</td>
<td>Lt Rectus femoris</td>
<td>0.713</td>
<td>0.387</td>
<td>0.204</td>
<td>0.098</td>
</tr>
<tr>
<td></td>
<td>Lt Cervical erector spinae</td>
<td>0.037</td>
<td>0.660</td>
<td>0.158</td>
<td>0.184</td>
</tr>
<tr>
<td></td>
<td>Rt Medial gastrocnemius</td>
<td>0.659</td>
<td>0.212</td>
<td></td>
<td>0.025</td>
</tr>
</tbody>
</table>

Significant values in bold, italics and asterisks; trending values in bold only. \( p < 0.017 \) for individual trials, \( p < 0.05 \) for averaged trials.

Planned comparison showed the change in time onset for the left cervical erector spinae was for HHS versus NHS (100.6 milliseconds [ms] vs 717.6 ms; \( F_{1,13} = 7.25, p = .018 \)), VHS versus NHS (-152.2 ms vs 7171.6 ms; \( F_{1,12} = 6.33, p = .027 \)) and NHS versus CTL (717.6 ms vs -18.0 ms; \( F_{1,8} = 5.39, p = .049 \)) (Fig. 3.19).

![Image](EMG_time_onset.png)

Figure 3. 19 Planned comparison of groups for EMG onset time for left cervical erector spinae during ramp up trials. Green = HHS, blue = VHS, red = NHS, orange = CTL

There were also trending group x session main effects in the 1st ramp up trials of the peak time (\( F_{3,26} = 3.02, p = .049 \)) and time onset amplitude (\( F_{3,26} = 3.29, p = .037 \)) for the left cervical erector spinae (Table 3.10). In addition, the time onset amplitude showed trending
group x session main effects for the left rectus femoris \( (F_{3,29} = 2.30, \ p = .098) \) and right medial gastrocnemius \( (F_{3,36} = 3.29, \ p = .091) \) for the averaged ramp up trials (Table 3.10).

In the ramp down perturbation trials, the EMG time onset amplitude for the left rectus femoris showed a significant *group x session* main effect due to training in the 1\textsuperscript{st} trial \( (F_{3,22} = 4.00, \ p = .020) \) (Table 3.10).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Muscle</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time onset</td>
<td>Lt Rectus femoris</td>
<td>0.606</td>
<td>0.406</td>
<td>0.064</td>
<td>0.094</td>
</tr>
<tr>
<td></td>
<td>Rt Rectus femoris</td>
<td>0.076</td>
<td>0.717</td>
<td>0.151</td>
<td>0.086</td>
</tr>
<tr>
<td>Peak</td>
<td>Lt Rectus femoris</td>
<td>0.020*</td>
<td>0.084</td>
<td>0.359</td>
<td>0.237</td>
</tr>
<tr>
<td>amplitude</td>
<td>Rt Tibialis anterior</td>
<td>0.037</td>
<td>0.587</td>
<td>0.330</td>
<td>0.237</td>
</tr>
</tbody>
</table>

Significant values in bold, italics and asterisks; trending values in bold only. \( p < 0.017 \) for individual trials, \( p < 0.05 \) for averaged trials.

Planned comparison showed the change in time onset amplitude was found for HHS versus control (-12.0 mv vs 0.3 mv; \( F_{1,13} = 7.21, \ p = .019 \)) and HHS versus VHS (-12.0 mv vs 2.8 mv; \( F_{1,10} = 5.95, \ p = .035 \)) (Fig. 3.20).

There were trending group x session main effects in the 1\textsuperscript{st} ramp down trials of the peak amplitude \( (F_{3,36} = 2.50, \ p = .076) \) for the right rectus femoris and also of the time onset amplitude \( (F_{3,36} = 3.14, \ p = .037) \) for the right tibialis anterior (Table 3.11). In addition, the time onset showed trending group x session main effects for the left rectus femoris \( (F_{3,24} = 2.39, \ p = .094) \) while the peak amplitude showed trending group x session main effects.
Figure 3. Planned comparison of groups for EMG onset amplitude for left rectus femoris during ramp down trials. Green = HHS, blue = VHS, red = NHS, orange = CTL for the right rectus femoris ($F_{3,36} = 2.38$, $p = .086$) for the averaged ramp down trials (Table 3.11).

**Eye Movement Outcomes during Ramp Perturbations**

The eye movement outcomes measures showed significant *group x session* main effects following training in the horizontal eye movement variability (ML Std) for the averaged ramp down trial ($F_{3,30} = 3.65$, $p = .024$) (Table 3.11).

Table 3.11 Eye movement variables for ramp down trials (1st – 200 ms after ramp onset; P-values of session-by-group interactions)

<table>
<thead>
<tr>
<th>EOG Variable</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM velocity</td>
<td>0.802</td>
<td>0.036</td>
<td>0.610</td>
<td>0.826</td>
</tr>
<tr>
<td>EM ML Std</td>
<td>0.413</td>
<td>0.081</td>
<td>0.153</td>
<td>0.024</td>
</tr>
</tbody>
</table>

EM = eye movement, ML = mediolateral, Std = standard deviation, Significant values in bold, italics and asterisks; trending values in bold only. $p < 0.017$ for individual trials, $p < 0.05$ for averaged trials

Planned comparison showed the change was found for HHS versus VHS (-0.375 deg vs 0.413 deg; $F_{1,17} = 9.00$, $p = .008$) and HHS versus control (-0.375 deg vs 0.103 deg; $F_{1,18} = 4.57$, $p = .046$) (Fig. 3.21).
The ramp up trials did not show any significant group x session changes.

**Power Spectral density during Ramp Perturbations**

There was no significant group x session main effect due to training in the power spectral density as assessed by the ramp trials except for a trending effect in the 3rd ramp up trial for the left sternocleidomastoid ($F_{3,36} = 2.63, p = .065$).

**VVOR, VCR and VSR Gains during Ramp Perturbations**

There was no significant group x session main effect due to training in the reflex gains, except for a trending effect in the 3rd ramp down trial of the VSR gain ($F_{3,34} = 3.32, p = .031$).

**Falls during Ramp Perturbations**

Generally, ramp up trials resulted in more falls, with the first trials resulting in the greatest number of falls. NHS had the biggest reduction in falls following training (8 falls), followed by HHS (2 falls), and the least VHS and control (1 fall each). However, VHS recorded
higher total falls (i.e., both ramp up and ramp down) during the post-assessment because only four of its participants contributed to a total of 9 falls (i.e., 2, 2, 2 and 3 falls for each participant) while NHS had four participants recording one fall each. Repeated measures ANOVA did not show a significant group x session change ($F_{3,38} = 0.99, p = .406$) in the total number of falls (Table 3.12).

Table 3. 12 Number of falls during ramp trials

<table>
<thead>
<tr>
<th>Ramp falls</th>
<th>HHS (n = 11)</th>
<th>VHS (n = 10)</th>
<th>NHS (n = 11)</th>
<th>CTL (n = 10)</th>
<th>Total (n = 42)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1  S2 Diff</td>
<td>S1  S2 Diff</td>
<td>S1  S2 Diff</td>
<td>S1  S2 Diff</td>
<td></td>
</tr>
<tr>
<td>RU</td>
<td>9  8 1</td>
<td>11 13 -2</td>
<td>12 4 8 5</td>
<td>4 1</td>
<td>37</td>
</tr>
<tr>
<td>RD</td>
<td>2 1 1</td>
<td>3 0 3</td>
<td>0 0 0</td>
<td>0 0</td>
<td>29</td>
</tr>
<tr>
<td>Total</td>
<td>11 9 2</td>
<td>14 13 1</td>
<td>12 4 8</td>
<td>5 4 1</td>
<td>12</td>
</tr>
</tbody>
</table>

RU = ramp up, RD = ramp down, S = Session, Diff = difference

**VAS Symptoms during Exercise Training**

Five (46%) of the HHS participants expressed symptoms of dizziness or headache before and after training, while three (30%) VHS participants reported similar symptoms. Only one participant in the HHS group reported a pre-training symptom of 1 and 2 scores. No other participants had pre-training symptoms. Dizziness and headache change scores (due to training) were 11 and 2 for HHS, respectively. Similarly, dizziness and headache change scores were 6 and 1 for VHS, respectively.

**Discussion**

Our study examined the influence of vestibular activation on vestibular reflexes and sensory reweighting of postural control. Rhythmic headshake activity coupled with weight shift training showed significant changes in several of the outcome measures in the vestibular groups couple with no-headshake and control groups. The following changes
due to vestibular training were found: (1) decreased horizontal VOR gain, (2) faster automatic postural response, (3) improved postural flexibility, (4) decreased muscle activation and (5) decreased eye movement variability. The findings indicate that horizontal headshake activity alters VOR gain while vertical headshake activity alters VCR and VSR functions, all of which influence postural function. These findings are discussed in detail below.

**Vestibular Activation through Headshake Activities Alters VOR Gain**

The horizontal VOR gain was hypothesized to significantly change in the vestibular groups following headshake activity. All three-training groups showed a potential decrease in VOR gain compared to the no-training group (control). Although the main results showed a trending difference between and within the four groups, the HHS group showed the largest downweighting in the VOR gain, followed by VHS. This downweighting in the VOR gain, which is within the normal range of 0.8 and 1.70, suggests the underlying mechanism is vestibular habituation due to training. The repeated, rhythmic headshake activity activates the semicircular canals (SCCs) and transmits impulses through the vestibulocochlear nerve to the vestibular nerve at the lateral pontomedullary junction. Through mediating pathways including the abducens nucleus, medial longitudinal fasciculus and oculomotor nuclei, specific extraocular muscles are driven to produce compensatory eye movements leading to gaze stabilization for postural stability 11,92. When the vestibular system is trained through habituation, challenging postural conditions such as the sway-referenced vision or surface from the sensory organization test (SOT) and the ramp perturbations during reassessments has lesser effects on the postural system. That is, the repeated exposure of the vestibular system to a seemingly
provocative stimuli during the headshake activity leads to a reduced amplitude of the excitatory postsynaptic potential (EPSP) transmitted by the provocative stimuli and consequently reduced synaptic connections between neurons. The long-term neuroplastic changes along the neuronal pathways suppress the impact of the provocative stimuli such as dizziness that would otherwise destabilize the postural system \(^{53,58,61,90}\).

The vestibular habituation was confirmed by the secondary analysis where the vestibular groups (i.e., HHS and VHS) when pooled together showed significant differences between the vestibular groups vs. NHS, and the vestibular groups versus control. The difference in the vestibular groups could be as a result of our vHIT system, which only tests horizontal VOR, hence detecting a larger significant change in HHS. More expectedly, the difference could be due to actual VOR training/habituation in the HHS direction producing a larger gain change than in the VHS. Vertical VOR gain and nystagmus in the vertical plane have been found to be lesser and weaker than horizontal VOR gain and horizontal nystagmus in monkeys and cats \(^{110,111}\). Generally, large head yaw movements regularly occur during our daily activities when we look around and/or navigate the environment. Thus, horizontal VOR may be more adaptable or susceptible to habituation.

The unexpected decrease of the VOR gain in the NHS condition may be explained by the fact that visual feedback was necessary during WST. Maintaining gaze fixation on the visual targets may have driven oculomotor learning/adaptation, which could affect horizontal VOR gain \(^{59,112}\). That is, the WST was accompanied by smooth eye pursuits and gaze movements as the participant’s center of mass (COM) moved from one target
to the other. Since the performance of the WST got better from exercise day 1 to 5, it shows that the mechanisms of retinal slip and VOR allowed the lite target to remain in focus and aided the participant to subsequently shift the body’s COM into the required target. In other words, the motion of the randomly changing targets from the screen across the surface of the retina and the activation of the VOR as head movements occur during COM shift led to visual and vestibular adaptations.

**Vestibular Training Improves Postural Flexibility and Automatic Postural Response**

The ramp up trials resulted in significant difference in the averaged COP sway velocity Std compared to the ramp down trials which did not show any significant change in the either of the first or averaged trials. Similar to our findings, Chen and colleagues \(^{74}\) found ramp up perturbations to induce larger and faster medio-lateral COM than ramp down perturbation. Vestibular participants compared to age-matched controls have also demonstrated greater instability in trunk roll (i.e., ML variability) compared to pitch movements \(^{113}\). The results of our study support the evidence that vestibular training (using our protocol) can be evaluated by employing sway variables during ramp up perturbation trials.

Compared to the other groups (i.e., NHS and control), the vestibular groups (i.e., HHS and VHS), particularly the VHS group showed an increased sway velocity variability in postural control. More variability could indicate more flexibility and larger limits of stability for balance control. For instance, participants with Parkinson’s disease may exhibit lower variability compared to age-matched healthy participants, but that does not correlate into
better postural control. The lower variability in the Parkinson’s participants may be due to rigidity and inflexibility making the patients prone to falls. The important factor is not variability per se, but the sway measure being within the optimal range. Since the vestibular groups have demonstrated better postural control in SOT somatosensory downweighting and VOR assessments it connotes that the variability in the above sway variables are optimal leading to more flexibility. Additionally, since the velocity variability for NHS and control decreased after training, this may be suggestive of postural inflexibility thus lowering postural stability.

Automatic postural response showed a difference in postural control following training between the vestibular groups. This outcome measure as expressed by the sway velocity increased for HHS, indicating a faster automatic (reflex) response. Meanwhile, the sway velocity in the VHS and control did not change and participants in the NHS responded slower. These findings suggest that horizontal headshake produces a vestibular habituation and/or adaptation effect resulting in a faster reflex response.

**Vestibular Habituation Promotes Postural Stability through Decreased Muscle Activation**

**Muscle Activation during SOT**

During the SOT assessment, the medial gastrocnemius was the only muscle to demonstrate significant changes in muscle activity due to training. In accordance with our hypothesis, this change was a reduction in the muscle activation after vestibular training. This indicates that the medial gastrocnemius is responsible for the prevention of anterior falls. The training effect of the medial gastrocnemius was mainly found in VHS, followed
by HHS in conditions 4, 5 and 6 as seen in the reduced muscle activity. These conditions are dependent on visual, vestibular and visual-vestibular reweighting. The finding also suggests that the vertical headshake activity performed during training in the VHS activates the VSR to elicit vestibular responses to the medial gastrocnemius. Additionally, since the change in muscular activity was significantly greater in the headshake groups (particularly in VHS) but not in NHS, it supports the evidence that the change in muscle activity was influenced by the vestibular training. This finding is further supported by the significant somatosensory downweighting found in the headshake groups compared to the NHS and control groups (see Results of Chapter 2). During the performance of a task, the ability of the postural system to reweight its contributory sensory channels to maintain postural control is essential, and thus shows the effectiveness of our training protocol in the headshake groups. The sensory reweighting, together with the vestibular responses and then multi-sensory integration produced the appropriate motor output to the medial gastrocnemius for postural balance.

**EMG Peak Amplitude and Time Onset**

Cervical erector spinae showed a significant change in time onset for the ramp up perturbation. Ramp up rotations have been shown to activate neck extensors for postural correction. The decrease in cervical erector spinae onset after training in the current study was predominantly found in VHS, suggesting that the evidence of vestibular habituation and/or adaptation of VCR. During ramp up rotation, lower limb muscles contract to move the body forwards against the mechanical effect of the ramp up surface. Neck extensors then respond quickly to maintain head-on-body stability. The decrease in
cervical erector spinae onset in our study indicates its faster response via VCR to counterbalance the forward head movement translated from the lower limb muscles.

During the ramp down perturbation, the rectus femoris showed a decreased muscle activity at the onset time due to training in the HHS group. This finding indicates that activating the horizontal SCCs induces VSR habituation, which decreased the onset muscle activity. During ramp down rotation, the knee joint goes into slight flexion. Habituation of the VSR produces an optimal muscle output to the rectus femoris to counterbalance the effect of the flexion for postural correction.

*Horizontal Vestibular Activation May Promote Gaze Stabilization by Decreasing Eye Movement Variability*

The horizontal headshake activity (in the HHS group) clearly showed a habituation for horizontal eye movement variability during the ramp down perturbation, which can be attributable to vestibular training. Specifically, changes in the VOR was found in decreased horizontal eye movements due to the training. The decreased horizontal eye movement variability in the HHS indicates a well-controlled eye movement with a concomitant decrease in variability leading to a more efficient VOR for better fixation and gaze stabilization. During eyes open upright standing tasks and other ADLs such as walking in a busy environment, gaze stabilization helps to maintain postural stability. On the contrary, the VHS showed increased horizontal eye movement variability after training, suggesting the occurrence of vestibular adaptation. Here, the EOG test could be used to differentiate the effects of vestibular training on ocular movements between HHS and VHS. This finding
also supports that for extra ocular activities, it is more efficient to train horizontal VOR by utilizing horizontal headshake activities.

**Limitations**

The limitation of the VOR measured by the vHIT did not allow for the measurement of both horizontal and vertical VOR gains from the same device to easily differentiate the VOR gain changes due to HHS versus VHS. However, our study showed that the EOG potentially provided insight into the eye movement variability that was able to separate the VOR gains between the two groups. Furthermore, a group calibration conversion factor was used for the EOG analysis. Ideally, the conversion factor of individual participants should have been applied. However, the intra-rater reliability of the group calibration was significantly high (0.76 and 0.94) and therefore adequate to be applied to the group. In addition, the power analysis was not performed for individual measuring tools. Hence, the study could be underpowered by the effect size. Probably an effect size of 0.2 would have been sufficient to result into large significant changes of the outcome measures.

**Conclusion**

Combined vestibular activation and weight shift training modifies vestibular-dependent responses after a short training intervention as evidenced in VOR gain, eye movement variability, muscle activation, postural flexibility and automatic postural response. These changes after headshake training may be predominantly due to vestibular habituation and partly, adaptation of VOR, VCR and VSR which induced sensory reweighting. This novel vestibular-postural training protocol provides evidence for modifying three important vestibular reflexes (i.e., VOR, VCR and VSR) that can contribute to effective postural
control. The variables that showed significant changes can be used as determinants of assessing vestibular changes after vestibular activation training. In addition, the findings of the training protocol can be used as a basis to develop a vestibular training intervention for people with vestibular impairments or sensory integration challenges.
CHAPTER 4
CORRELATION OF POSTURAL VARIABILITY WITH MUSCLE ACTIVITY
AFTER VESTIBULAR TRAINING AMONG HEALTHY YOUNG ADULTS

Introduction

Postural stability is fundamental to performing many activities of daily living, including managing external and self-generated perturbations while a executing a task. Balancing requires the central integration of the somatosensory, visual and vestibular inputs to produce a context-specific motor output through gaze stabilization and appropriate activation of postural muscles\textsuperscript{18,19,115}. The postural system prioritizes the somatosensory and visual systems for balance control, particularly during static balance\textsuperscript{21}. However, when there is reduced, inaccurate or unavailable information from these systems the central nervous system (CNS) will depend on the information provided by the vestibular input\textsuperscript{20}.

The vestibular system plays an important role in postural control, as can be observed when this system is compromised; this often leads to postural dysfunction. The vestibular system, in part, helps maintain postural balance by ensuring visual fixation on an object during head and body movements using the activation of the vestibulo-ocular reflex (VOR)\textsuperscript{18,19}. The VOR further coordinates with the vestibulo-colic reflex (VCR) and vestibulo-spinal reflex (VSR) to coordinate ocular-motor responses with head, neck, and body muscle responses for postural maintenance\textsuperscript{26–28}. The measurement of these vestibular reflexes is important as it may provide insight into specific parts of the vestibular system that are affected by vestibular training.
Several methods have been used to assess vestibular-motor responses during postural control and vestibular rehabilitation studies. These methods include: the sensory organization test (SOT), electro-oculography (EOG), electromyography (EMG), video head impulse test (vHIT) and accelerometry. The SOT is an objective gold standard tool used for assessing postural stability during quiet stance by systematically disrupting the postural sensory selection process to analyze relative sensory weighting. The EOG has been shown to measure all types of eye movements with precise measurements accuracy, including coordinated smooth pursuits and VOR which occurs when fixating on a static visual or head sway-referenced moving target during upright postural control. The EMG method can be used to assess muscle latency responses and synergies and power spectral densities during postural activities. The vHIT system is used to test the function of the semicircular canals (SCCs) by measuring the ratio of the compensatory eye movement velocity to a head movement velocity during a rapid head rotation performed passively along the planes of the specific canal. The output of the ratio is recorded as the VOR gain. Accelerometry has been used to measure the relative head-trunk and trunk-lower limbs movements during pitch and roll ramp perturbations, linking these motions to the influence of the vestibular system.

By analyzing changes in the eye movements and the VOR gain during balance tasks, one may understand the eye movement variability and specific SCC function, which may be influenced by vestibular postural training over time and potentially relate to effects of vestibular activation. Furthermore, changes in the EMG and accelerometry signals can
give insights into the EMG onset, peak amplitude, duration and average power frequency changes, and relative movement of body segments.

Many studies have employed several of the aforementioned posturography, bioelectrical and accelerometric kinetic and kinematic measurement tools to investigate postural behavior with respect to sensory reweighting across different populations. Horak and colleagues 75 used an SOT principle-based method, EMG and kinematic data to study the roles of somatosensory and vestibular information in the coordination of postural responses between bilateral vestibular loss patients and normal controls during surface translation displacements. Also, Horak & Hlavacka 76 used force plate technology, galvanic vestibular stimulation and kinematics to show that when the somatosensory system is impaired or somatosensory information is disrupted it leads to an increase in vestibulospinal sensitivity. Another study conducted by Amiridis et al. 77 employed force plate instrumentation, EMG and two-dimensional kinematic data to explore how young and older adults respond to increased postural demands (i.e., bipedal, Romberg-sharpened and one-legged stances) during quiet stance. Furthermore, Gauchard et al. 78 investigated the effects of physical activities on VSR and ocular movements of visual and vestibular origins in the elderly using various vestibulo-ocular and vestibulo-motor tests and EMG analyses.

Other studies with direct clinical focus have been conducted to assess the vestibular changes that occur following vestibular rehabilitation. In assessing the effects of specific vestibular exercises on central compensation in acute/subacute unilateral vestibular lesion patients, Strupp et al. 79 used laser ophthalmoscope (for testing ocular torsion), subjective
visual vertical test (for perception) and force plate technology (for total sway path). Furthermore, using a motion analysis kinematic technique, Patten et al. \cite{81} investigated the effects of a 16-week protocol of vestibular rehabilitation on head and body coordination during unconstrained, paced and in-place gait between vestibulopathic individuals and their age-matched healthy counterparts.

The above studies employ multiple tools to examine postural reactions and provide insights into postural sensory systems, with or without vestibular intervention. However, some of the studies use only posturography via COP measures. While this method does not directly measure vestibular changes, changes in the COP have been attributed to recalibration of the vestibular system \cite{76}. The studies which used several measurement tools \cite{75,77} do not provide any statistical correlation between the measures. Computing such information to show possible correlations between measures can assist clinicians to identify related outcome measures which can be used as predictors during the assessment of vestibular dysfunction, and also serve as monitoring tools for vestibular rehabilitation protocols. That is, the assessment of one outcome measure, e.g., the EMG amplitude, can be used to predict another, e.g., COP sway velocity. It is only the Gauchard and colleagues’ study \cite{78} that correlated the vestibulo-ocular and vestibulo-motor tests and EMG outcome measures used in its investigation. However, the participants in the active group did not engage in any specific vestibular training, but either one or two sporting activities such as yoga, soft gymnastics, jogging or swimming. Moreover, at the moment, no study has investigated the correlation between postural balance variability and vestibular-ocular and motor responses after vestibular training by using a rhythmic headshaking intervention.
Investigating the correlations of the bioelectrical signals and posturography after vestibular training can be a valuable method to predict the outcome of a vestibular protocol and also can provide substantive evidence for its efficacy. For instance, in this current study, if the COP or EMG amplitude during ramp perturbation assessments are lower after training in the headshake groups, it could suggest a lower acceleration in the relative head-to-trunk movement (due to controlled postural control). Moreover, the use of several assessment methods to identify vestibular changes in this current study can enhance the clinician’s ability to make proper diagnosis and monitor the effects and progress of a vestibular training program. Furthermore, the correlations can show which of the outcome measures will be more sensitive in determining vestibular changes after vestibular training, and thus, guide clinicians in making decisions for a better assessment tool.

The current study was conducted to assess the correlations between postural measures and vestibular responses following vestibular training in healthy young adults as measured by the SOT, vHIT, EOG, EMG and body segment acceleration. The vestibular responses VOR, VCR and VSR (all from the EMG), together with the eye movement variability (from the EOG), were elicited during ramp perturbation rotation trials. We hypothesized that COP variability measures would be positively correlated with EMG peak amplitude and onset time (VCR and VSR), and also VOR gain post-training in the headshake groups. Similarly, we hypothesized that the COP variability measures would be positively correlated with peak horizontal and vertical eye movement variability, eye movement area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation post-training in the headshake groups. Furthermore, COP multiscale entropy velocity and SOT
vestibular ratio would correlate negatively with eye movement variability post-training in the headshake groups.

**Methods**

As an exploratory aim, Pearson’s correlational analysis was performed to examine associations between vestibular and postural measures following a four group pre- and post-intervention study on healthy young participants.

**Participants, Instrumentation and Assessment Procedures**

Forty-two healthy young individuals from Temple University were randomized into four groups. Eligibility, participants' groups, instrumentation and assessment procedures were the same as described in the methods sections of Chapters 2 and 3.

**Data Management/Statistical Analysis**

Data management was the same as described in the Methods sections of Chapters 2 and 3. The outcome measures obtained and processed included the pre- and post-assessments of SOT equilibrium and composite scores, SOT sensory ratios, COP sway measures from the SOT time-series data of each equilibrium score and horizontal VOR gain. Others included COP sway measures, linear and angular head and trunk trajectories, eye movement variability and power spectral density during ramp up and down perturbation trials. The rest included muscle activity measures during SOT and ramp up and down perturbation trials, and vertical VOR, VCR and VSR gains during ramp up and down perturbation trials. Apart from these separate pre- and post-measures, the
differences between the pre- and post-measures (i.e., Session 1 – Session 2) were computed to obtain change scores of each measure.

Pearson product-moment correlational analysis was used to evaluate the associations between:

(1) SOT equilibrium and composite scores vs EMG peak amplitude and power spectral density
(2) SOT-COP sway area, sway velocity standard deviation, antero-posterior sway standard deviation (AP Std), medio-lateral sway standard deviation (ML Std) and multiscale entropy (MSE) sway velocity vs EMG peak amplitude and power spectral density
(3) SOT equilibrium and composite scores vs horizontal and vertical eye movement, eye movement area and eye movement velocity
(4) Sensory ratios vs horizontal and vertical eye movement, eye movement area and eye movement velocity
(5) SOT-COP sway area, sway velocity Std, AP Std, ML Std and MSE sway velocity vs horizontal and vertical eye movement, eye movement area and eye movement velocity
(6) SOT equilibrium and composite scores and sensory ratios vs VOR, VCR and VSR gains
(7) SOT-COP sway area, sway velocity Std, AP Std, ML Std and MSE sway velocity vs VOR, VCR and VSR gains

These correlations were performed on the pre- and post-training changed scores of all participants. For assessments which were performed in multiple trials, averages were
used in the analysis. Significant correlation coefficients ($r$) of 0.40 – 0.69 were considered as moderate, while 0.70 – 1.00 as strong association. Additionally, where at least a significant moderate correlation was found for a pair of measures, post-hoc pre-training correlation was performed to obtain baseline correlations. Moderate correlation was considered from 0.40 because all $r$-values of 0.40 and above resulted in significant values that are equal to or less than 0.01. Strong correlations of change scores indicated high associations between measures to differentiate the effects of combined vestibular and postural training (WST) and the effects of WST on the participants. That is, since we hypothesized that the biggest change in outcome measures occurs in the headshake groups, we further hypothesize that these correlations will be attributed to the combined vestibular and WST. All statistical analysis was conducted using SPSS software (version 25.0; IBM Corporation, Armonk, NY) and significance level set at alpha equal to 0.05.

**Results**

All the forty-two young participants (20 males; 22 females; 23.0±3.9 years [18-35 years]; 1.6±0.1 meters) completed most of the pre- and post-assessments. The demographics of the participants are the same as from Chapter 3 (Table 3.3). Correlations were performed on the pre- and post-training change scores of all participants. The results of the correlation have been reported below.
**SOT Equilibrium Change Scores vs EMG Peak Amplitude Change Values during SOT**

There were no significant negative associations between the change scores pre- to post-training of SOT equilibrium scores and EMG peak amplitude of muscles contrary to what we hypothesized.

**COP Sway Variables Change Scores vs EMG Peak Amplitude Change Values during SOT**

There were significant moderate positive and negative associations between the change scores pre- to post-training of COP sway variables of SOT and EMG peak amplitude for three muscles (Table 4.1). The highest positive association was found between COP sway area and EMG peak amplitude of rectus femoris in C6 ($r = 0.498; p = <.0001$), followed by COP sway area and EMG peak amplitude of tibialis anterior in C5 ($r = 0.445; p = .003$).

| Table 4.1 Correlation of SOT-COP sway variables vs EMG peak amplitude with r-values (p-value) |
|----------------------------------|-----------------|-----------------|-----------------|
| SOT-COP                          | ES              | RF              | TA              |
| C3 ML                            | -0.047          | -0.413*         | 0.331*          |
|                                  | (0.769)         | (0.007)         | (0.032)         |
| C5 SA                            | -0.098          | 0.157           | 0.445*          |
|                                  | (0.536)         | (0.322)         | (0.003)         |
| C6 Vel                           | 0.317*          | 0.439*          | 0.276           |
|                                  | (0.041)         | (0.004)         | (0.077)         |
| C6 SA                            | 0.435*          | 0.498*          | 0.390*          |
|                                  | (0.004)         | (<0.0001)       | (0.011)         |
| C6 MSE Vel                       | 0.381*          | 0.444*          | 0.082           |
|                                  | (0.013)         | (0.003)         | (0.606)         |

C = SOT condition, ES = cervical erector spinae, RF = rectus femoris, TA = tibialis anterior, ML = COP mediolateral sway, Vel = COP sway velocity, SA = COP sway area, MSE Vel = COP multiscale entropy sway velocity, significant moderate correlations and above in bold and asterisks, significant weak correlations in asterisks only.

Additionally, C6 showed associations between COP sway area and EMG peak amplitude of cervical erector spinae ($r = 0.435; p = 0.004$), COP velocity Std and rectus femoris ($r =$...
0.439; \( p = .004 \) and then COP MSE sway velocity and rectus femoris \( (r = 0.444; p < .003) \). COP ML Std did not show a positive association with rectus femoris in C3 as hypothesized.

**SOT Change Scores vs Eye Movement Variability of Ramp Trials Change Scores**

There were significant moderate positive and negative associations between the change scores pre- to post-training of SOT scores and eye movement variability during ramp perturbations with the highest association occurring between C2 and horizontal eye movement velocity during ramp trial \( (r = -0.521; p = .001) \), followed by C6 and eye movement area of excursion during down \( (r = -0.509; p = .002) \) (Table 4.2).

<table>
<thead>
<tr>
<th>SOT scores</th>
<th>Horizontal EM Vel (RU)</th>
<th>Horizontal EM Vel (RD)</th>
<th>EM Vel Std (RD)</th>
<th>EM area (RD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>0.065 ( (0.705) )</td>
<td>(-0.521^*) ( (0.001) )</td>
<td>0.003 ( (0.988) )</td>
<td>0.199 ( (0.244) )</td>
</tr>
<tr>
<td>C5</td>
<td>0.190 ( (0.268) )</td>
<td>(-0.351^*) ( (0.036) )</td>
<td>(-0.348^*) ( (0.038) )</td>
<td>(-0.485^*) ( (0.003) )</td>
</tr>
<tr>
<td>C6</td>
<td>0.351* ( (0.036) )</td>
<td>(-0.072) ( (0.676) )</td>
<td>(-0.411^*) ( (0.013) )</td>
<td>(-0.509^*) ( (0.002) )</td>
</tr>
<tr>
<td>Composite</td>
<td>(0.451^*) ( (0.006) )</td>
<td>(-0.063) ( (0.716) )</td>
<td>(-0.307) ( (0.069) )</td>
<td>(-0.404^*) ( (0.015) )</td>
</tr>
</tbody>
</table>

C = SOT condition, EM = eye movement, RD = ramp down trial, RU = ramp up trial, Vel = velocity, significant moderate correlations and above in bold and asterisks, significant weak correlations in asterisks only.

Condition 5 was associated with eye movement area of excursion during ramp down trials \( (r = -0.485; p = .003) \), while the composite score was associated with eye movement area of excursion during ramp down trials \( (r = -0.404; p = .015) \). Composite score did not show a negative association with horizontal eye movement velocity as hypothesized.
**SOT and Sensory Ratios Change Scores vs VOR, VCR and VSR Gains Change**

**Scores**

There were significant moderate positive and negative associations between the change scores pre- to post-training for the two VOR gains versus SOT scores and sensory ratios. The highest association was found between vertical VOR (VVOR) gain during ramp trial and SOT C4 (r = -0.553; p = < .0001). The visual ratio showed a negative moderate association with VVOR during ramp trial (r = -0.545; p = < .0001), while somatosensory ratio showed a negative moderate association with horizontal VOR (HVOR) as measured by the vHIT (r = -0.527; p = .002). There was no association between vestibular ratio or SOT C5 and any of the reflex gains (Table 4.3).

<table>
<thead>
<tr>
<th>Reflex gain</th>
<th>C2</th>
<th>C4</th>
<th>Composite</th>
<th>SOM</th>
<th>VIS</th>
<th>PREF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVOR (vHIT)</td>
<td>-0.460*</td>
<td>0.077</td>
<td>0.165</td>
<td>-0.527*</td>
<td>0.059</td>
<td>0.423*</td>
</tr>
<tr>
<td></td>
<td>(0.008)</td>
<td>(0.675)</td>
<td>(0.368)</td>
<td>(0.002)</td>
<td>(0.750)</td>
<td>(0.016)</td>
</tr>
<tr>
<td>VVOR</td>
<td>-0.094</td>
<td>-0.553*</td>
<td>-0.462*</td>
<td>-0.064</td>
<td>-0.545*</td>
<td>-0.380*</td>
</tr>
<tr>
<td></td>
<td>(0.559)</td>
<td>(&lt; 0.0001)</td>
<td>(0.002)</td>
<td>(0.691)</td>
<td>(&lt; 0.0001)</td>
<td>(0.014)</td>
</tr>
</tbody>
</table>

C = SOT condition, SOM = somatosensory ratio, VIS = visual ratio, PREF = preference ratio, HVOR = horizontal vestibulo-ocular reflex, VVOR = vertical VOR, vHIT = video head impulse test recording, significant moderate correlations and above in bold and asterisks, significant weak correlations in asterisks only

**SOT-COP Sway Variables Change Scores vs VOR, VCR and VSR Gains Change**

**Scores**

There were no significant positive associations between the change scores pre- to post-training of vestibular reflexes and COP sway variables of SOT as hypothesized.
Additional Exploratory Comparisons

**COP Sway of Ramp Trials Change Scores vs EMG Peak Amplitude of Ramp Trials**

**Change Scores**

There were significant moderate positive associations between the pre- and post-training change scores of COP sway measures and the EMG peak amplitudes of rectus femoris and biceps femoris ($r = 0.472 - 0.540; p = < .0001 - .003$) during ramp trials. The highest association was between COP sway area and biceps femoris during ramp up trials ($r = 0.540; p = < 0.0001$), followed by COP sway area and rectus femoris during ramp up trials ($r = 0.520; p = 0.001$) and then COP velocity Std and biceps femoris ($r = 0.510; p = 0.001$) (Table 4.4).

<table>
<thead>
<tr>
<th>COP</th>
<th>RF</th>
<th>BF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML (RU)</td>
<td>0.493*</td>
<td>0.472*</td>
</tr>
<tr>
<td></td>
<td>(0.002)</td>
<td>(0.003)</td>
</tr>
<tr>
<td>AP (RU)</td>
<td>0.195</td>
<td>0.374*</td>
</tr>
<tr>
<td></td>
<td>(0.228)</td>
<td>(0.019)</td>
</tr>
<tr>
<td>SA (RU)</td>
<td>0.520*</td>
<td>0.540*</td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td>(&lt; 0.0001)</td>
</tr>
<tr>
<td>SA (RD)</td>
<td>0.324*</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td>(0.047)</td>
<td>(0.855)</td>
</tr>
<tr>
<td>Vel (RU)</td>
<td>0.368*</td>
<td>0.510*</td>
</tr>
<tr>
<td></td>
<td>(0.019)</td>
<td>(0.001)</td>
</tr>
</tbody>
</table>

RF = rectus femoris, BF = biceps femoris, ML = COP mediolateral sway, AP = COP anteroposterior sway, SA = COP sway area, Vel = COP sway velocity, significant moderate correlations and above in bold and asterisks, significant weak correlations in asterisks only

**COP Sway of Ramp Trials Change Scores vs Eye Movement Variability of Ramp Trials Change Scores**

There was no association greater than 0.4 between the change scores pre- to post-training of postural and eye movement variability during ramp trials. The significant associations
below 0.4 were between COP sway area and vertical eye movement velocity ($r = 0.342; p = .041$) and between COP ML Std and vertical eye movement velocity in 200 ms ($r = 0.341; p = .048$).

**COP Sway of Ramp Trials Change Scores vs VOR, VCR and VSR Gains Change Score**

There were no significant positive associations between the change scores pre- to post-training of COP sway variables and vestibular reflexes during ramp trials.

**EMG Peak Amplitude of Ramp Trials Change Scores vs Eye Movement Variability of Ramp Trials Change Scores**

There was a moderate positive association between the change scores pre- to post-training of horizontal eye movement velocity and biceps femoris during ramp trial ($r = 0.467; p = .007$).

**Eye Movement Variability of Ramp Trials Change Scores vs VOR, VCR and VSR Gains Change Score**

There was a moderate positive association between the change score pre- to post-training of vertical eye movement velocity in 200 ms and VVOR gain during ramp trials ($r = 0.443; p = .009$).

**Discussion**

This exploratory aim examined the correlations between changes in postural sway measures, muscle activations, eye movement variability and vestibular reflex gains after
different exposure levels of vestibular activation and weight shift training. Generally, it was hypothesized that since the biggest changes in many of the outcome measures were prevalent in the headshake groups following training as seen in Chapters 2 and 3, the significant correlations are attributable to the combined vestibular activation and weight shift training (WST). The training revealed moderate associations ($r = 0.40 – 0.69$) between the various outcome measures. The following correlations were found: (1) negative correlations between horizontal and vertical VOR gains versus postural sway measures, (2) negative correlations between eye movement variability versus postural sway measures and (3) positive correlations between EMG peak amplitudes versus postural sway measures and eye movement variability. The theoretical and clinical relevance of these correlations are discussed below.

**Vestibular Habituation Decreases VOR Gain and Improves Postural Stability**

Vestibulo-ocular reflex (VOR) gain was hypothesized to result in negative associations with SOT equilibrium, composite scores and sensory ratios. These hypotheses were supported by the findings in our study. Vestibular habituation through vestibular training has been shown to decrease VOR gain $^{59}$ and improve postural stability $^{13,50}$. The changes due to vestibular habituation likely occur in the vestibular nuclei, which have ascending and descending pathways and reciprocal connectivity to the cerebellum $^{116–118}$. When VOR gain is decreased through vestibular activation, the vestibular signal drives oculomotor control to produce eye-in-head coordination and gaze stabilization. Meanwhile, the habituated vestibular signal also produces the vestibular inputs that maintains head-on-neck and trunk stability by driving the vestibulo-colic reflex (VCR) and vestibulo-spinal reflex (VSR) responses. Afferent input from the vestibular end organ to the medial, superior and inferior vestibular nuclei project to the cerebellum via the inferior cerebellar
These pathways innervate the flocculonodular node which modulate and coordinate postural adjustments and gaze.

The change in vertical VOR (VVOR) gain following training seemed to be associated with more SOT measures than that of horizontal VOR (HVOR) gain. Specifically, VVOR gain was negatively associated with changes in SOT visual ratio (i.e., condition 4) and composite score, while HVOR was negatively associated with SOT somatosensory ratio (i.e., condition 2). The VVOR gain was calculated as the ratio of the vertical eye velocity in pitch to the head angular velocity in pitch during ramp perturbation, while HVOR gain was calculated as the ratio of horizontal eye velocity to horizontal head velocity using the vHIT system. The two vestibular reflex gains in individual terms provide findings that support each other. SOT condition 4 is dependent on visual processing, which was supported by VVOR also being associated with SOT visual ratio. While, SOT condition 2 depends on somatosensory processing with HVOR also being associated with SOT somatosensory ratio. While the visual processes allow for optokinetic adaptation to move the eyes and track moving large-field visual stimuli, somatosensory processing from the soles of the feet and proprioception from ankle joints contribute to maintain postural control. In addition, the association between VOR gains and the SOT scores, suggest that VOR gain provides some predictive value for somatosensory and visual processing.

The difference in sensory reweighting patterns between VVOR and HVOR is inconsistent with the literature. Assessing the VVOR along the sagittal plane primarily stimulates the otolith organs which activates VSR to drive lower limbs muscles. As lower limb muscles are activated to maintain postural control, the bottom-up signals from the somatosensory
channel and spinal reflexes also contribute to modulate postural behavior. Assessing HVOR along the horizontal plane stimulates lateral semicircular canals which drives oculomotor control to maintain gaze stabilization. Instead, our study found VVOR to be associated with visual reweighting and HVOR with somatosensory reweighting. Further studies should investigate the basis behind these inconsistent findings.

**Eye Movement Measures May Indicate Specific Postural Sensory Processing**

Our findings corroborated our hypothesis that eye movement measures will be negatively associated with SOT equilibrium and composite scores. In other words, as eye movement variability decreases, postural stability increases. Several studies have demonstrated that decrease in eye movement variability have a direct influence on improved postural control. Although vision is not necessary for normal balance — since it is possible to perform static balance in the dark — there is evidence that vision improves postural control. We showed a decrease in horizontal eye movement variability after vestibular activation exercises in Chapter 3. The decreased eye movement variability may be due to two sources of oculomotor control: decreased VOR or less spontaneous saccadic activity. Regardless of the source, the result is better gaze stabilization and visual fixation, which contributes to better postural control. Visual fixation assists in maintaining well-controlled eye-in-head position and consequently head-over-torso position.

The change in eye movement area was the measure that showed significant correlations with the most SOT scores (i.e., conditions 5, 6 and composite score). Since eye movements affect postural control and based on our findings above, eye movement area appears to be a good predictor of postural control, particularly for vestibular (condition
5) and visual-vestibular (condition 6) processing components. The vestibular and visual-vestibular components suggest that our training protocol was effective in altering the vestibular and/or visual contributions to posture. The smaller eye movement area suggests less eye movement variability and greater gaze stabilization which led to better postural control. In addition, the association between eye movement area and SOT composite score, which is an overall postural assessment outcome measure, provides some basis to compare the eye movement measure to postural control. This further suggests that during a postural assessment, particularly involving the vestibular system, the eye movement area may be indicative of the individual’s postural control.

**Vestibular Habituation Decreases Muscle Activation and Improves Postural Stability**

Our findings were in agreement with our hypotheses that peak muscle activation following combined vestibular-postural training was positively associated with postural sway measures. Both outcome measures were reduced in amplitude following the training (see Results of Chapter 3). It has been previously shown that a multisensory balance training program can affect compensatory postural responses after training by optimizing muscle activations \(^{121}\). The optimal effect in the muscles were found in decreased onset latency of neck flexors and a trend toward decreasing the response frequency of antagonist muscles. The decrease in the onset latency and response frequency following training could be attributed to sensory reweighting and integration mainly between the vestibular and somatosensory systems. In addition, vestibular-postural training has been shown to improve postural control by decreasing the center of pressure distribution area and sway velocity in people with central vestibular disorders \(^{122}\).
The associations found in the current study following training were between cervical erector spinae, rectus femoris and tibialis anterior versus SOT conditions 5 and 6. SOT conditions 5 and 6 rely on vestibular and visual-vestibular processing for balance control, suggesting that our combined vestibular-postural training could be modifying activation of underlying processes in a targeted manner. VCR and VSR drive neck and lower limb muscles, respectively. The headshaking activities, which activate vestibular processes during the WST balance activities, may be specifically recalibrating VCR and VSR gains such that eye-in-head, head-on-trunk, and trunk-on-lower limb control are being optimized. Because the training is specifically targeting oculomotor and vestibulo-postural processes, the changes in neck and lower limb activity were most evidence in the two conditions most dependent on vestibular and visual-vestibular processing (condition 5 and 6). The ramp perturbation assessments showed positive associations between COP ML Std, COP sway area and COP velocity Std versus rectus femoris and biceps femoris following training. Similar to the SOT, these associations showed a concomitant decrease in postural variability with muscle activations, suggesting a possible habituation of VSR after vestibular activation.

**Vestibular Activation Influences Eye Movement Variability, Muscle Activation and Postural Control**

The findings of the associations for the visuo-motor, muscular activity and postural sway measures following our combined vestibular activation and weight shift training indicate that the novel training protocol influences the efficiency of the postural system. Habituation and/or adaptation of the vestibular reflexes (i.e., VOR, VCR and VSR) decreases
vestibular gains to transmit optimal impulses to extra-ocular muscles for efficient control of eye movements. Control of eye movements is mediated by gaze stabilization and image fixation on the retina, which ensure controlled eye-in-head position, clearer vision and suppression of vection. Simultaneously, the habituated VCR and VSR drive neck and lower limb muscles to maintain head-on-torso and trunk stability. The modulation of vestibular responses as a result of the headshake activities and WST may drive compensatory reweighting of the somatosensory and/or visual channels. These processes lead to less postural variability and thus, more efficient postural responses.

**Limitations**

Strong correlations were not obtained in this study probably because of a number of limiting factors. These include the relatively small sample size for a correlational analysis combined with loss of data in some of the SOT and ramp perturbation trials (i.e., EMG and EOG signals). Furthermore, large changes in vestibular gains may have been limited by the short duration of training coupled with the fact that we were training healthy young adults with healthy vestibular systems. However, the correlations of outcome measures of this novel training protocol provide some neurological basis for designing and assessing vestibular rehabilitation. In addition, the limitation of our vHIT device did not allow for measurement of both horizontal and vertical VOR gains from the same device. These limitations should be addressed in future studies.

**Conclusion**

Concurrent vestibular activation and postural training via weight shift training shows moderate associations between postural measures and vestibular responses in vestibular
reflex gains, eye movement variability and muscle activations. The associations between measures confirm the influence of rhythmic headshake activity coupled with postural training on postural control processing. These associations provide insight into the underlying mechanisms of the neural structures, pathways and processes that drive the effectiveness of our combined vestibular and postural training. These findings can be used as novel preliminary data to predict postural changes through vestibular habituation and also provide insight into the behavior of eye movements and muscle activations following vestibular training. Ultimately, the associations obtained from this current training protocol can inform researchers and clinicians to design vestibular rehabilitation interventions for people with vestibular disorders or sensory integration problems. 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.
CHAPTER 5
DISCUSSION

Review of Specific Aims

Rehabilitation of vestibular dysfunction has become a vital area in the management of balance problems. Vestibular dysfunction alone can cause severe postural imbalance leading to prolonged decrease in activities of daily living and productivity, increase in risk of exposure to further injuries, and huge economic cost. In the US, 69 million adults aged 40 years and older experience vestibular problems. Several studies have found vestibular disorders in different populations over the world and across all ages, from children to the elderly. Due to the wide range of the affected populations, the total annual mean economic burden of both unilateral and bilateral vestibular deficiency in the US per patient in 2012 was $16,550.

A cardinal outcome to consider during vestibular rehabilitation is to ultimately achieve an efficient postural control. Postural control is maintained by the central 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 using the activation of VOR which coordinates with VCR and VSR, and it also integrates with the visual and somatosensory systems to maintain postural stability. Vestibular rehabilitation research studies have shown evidence that it can be effective in improving primary and secondary vestibular symptoms. However, a review study showed that some groups of patients may not show improvement, probably due to the type of vestibular rehabilitation employed. Also, the use of sensory reweighting to explain the benefits of training protocols in improving the vestibular system has been established.
17, however, there remain open questions regarding the neural structures, pathways and processes that drive the effectiveness of sensory reweighting mechanisms specific to improving vestibular impairment through vestibular activation and postural rehabilitation. The focus of this dissertation was to identify the specific underlying postural mechanisms mainly along the vestibular pathways following our vestibular activation and weight shift training (WST) intervention. In addition, the correlations between postural, eye movement and vestibular response measures following the intervention were explored.

This novel combined vestibular activation and WST protocol was designed to positively influence the underlying physiological processes and to determine whether the protocol may cause changes in vestibular response and balance. At the moment, no study has either used our concurrent vestibular activation and WST protocol in any rehabilitation setting or investigated the vestibular changes associated with our training protocol, coupled with using horizontal and vertical headshake activities in the same cohort groups. Our protocol design could help increase patients’ compliance to rehabilitation schedules as two different exercise activities are performed simultaneously to achieve more gains in shorter training time.

The main purpose of this study was to assess sensory reweighting of postural control processing after combined vestibular activation with voluntary WST in healthy young adults. We employed four groups which were involved in the following: (i) visual feedback WST coupled with active sinusoidal horizontal headshake (HHS), (ii) the same WST with vertical headshake (VHS) activity, (iii) WST with no HS (NHS) and (iv) no training (control). The main outcome measures included: (i) postural measures using the SOT and ramp
perturbation trials, (ii) muscle activations during SOT and ramp perturbation trials, (iii) eye movement variability measures during ramp perturbation trials and (iv) horizontal VOR (HVOR). In addition, head and trunk accelerations during ramp trials were obtained, and vertical VOR (VVOR), VCR and VSR gains were computed.

To achieve the purpose of the study, the following specific aims and hypotheses were tested:

**Specific Aim 1:** Assess the effect of a vestibular training protocol on sensory weighting during postural control among young healthy adults.

**Hypothesis 1.1:** SOT equilibrium and composite scores will significantly increase in the headshake groups post-training compared to the other two groups.

**Hypothesis 1.2:** Sensory weighting will change significantly in the headshake groups by changing the ratios of visual, somatosensory and vestibular dependence post-training.

**Hypothesis 1.3:** Postural stability will improve (i.e. COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will decrease but MSE velocity will increase) in the headshake groups post-training.

**Specific Aim 2:** Assess changes in vestibular-motor responses after vestibular training of postural balance control.

**Hypothesis 2.1:** VOR, VCR and VSR gain responses during platform ramp rotations will significantly decrease in the headshake groups post-training (as recorded as EOG and EMG onset, duration and peak amplitudes).
**Hypothesis 2.2:** EMG peak amplitude, onset and duration and EMG power spectral density (PSD) in muscles will significantly change in the headshake groups post-training.

**Hypothesis 2.3:** Head and trunk accelerations during platform ramp rotations will significantly decrease in the vertical headshake group post-training.

**Hypothesis 2.4:** Horizontal and vertical eye movement variability, eye movement area, velocity and anterior-posterior and medio-lateral variability during platform ramp rotations will significantly decrease post-training in the headshake groups, respectively.

**Hypothesis 2.5:** Postural stability will improve (i.e. COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will decrease) during platform ramp rotations in the vestibular groups post-training.

**Specific Aim 3:** Perform an exploratory analysis between change scores of postural balance variables, eye movement measures, muscle activations and vestibular responses.

**Hypothesis 3.1:** Change scores in SOT equilibrium and composite scores will be negatively correlated with change scores in EMG peak amplitude, onset and duration, and EMG PSD post-training in the headshake groups.

**Hypothesis 3.2:** Change scores in COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will be positively correlated with change scores in EMG peak amplitude, onset and duration, and EMG PSD post-training in the headshake groups.
**Hypothesis 3.3:** Change scores in SOT equilibrium and composite scores will be negatively correlated with change scores in horizontal and vertical eye movement variability, eye movement area and velocity post-training in the headshake groups.

**Hypothesis 3.4:** Change score in vestibular ratio will be negatively correlated with change scores in horizontal and vertical eye movement variability, eye movement area and velocity post-training in the headshake groups.

**Hypothesis 3.5:** Change scores in COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will be positively correlated with change scores in horizontal and vertical eye movement variability, eye movement area and velocity post-training in the headshake groups.

**Hypothesis 3.6:** Change scores in SOT equilibrium, composite scores and vestibular ratio will be negatively correlated with change scores in VOR, VCR and VSR gains post-training in the headshake groups.

**Hypothesis 3.7:** Change scores in COP sway area, velocity, anterior-posterior standard deviation and medio-lateral standard deviation will be positively correlated with change scores in VOR, VCR and VSR gains post-training in the headshake groups.

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**Summary of Results**

Forty-two healthy young adults aged 18 to 35 years (mean age, $23.0\pm3.9$ years; 20 males) participated in the study. Our concurrent vestibular activation and postural training showed evidence of sensory reweighting in the headshake groups compared to without headshake (WST only) and the control group. Additionally, our training protocol found a decrease in VOR, muscle activation and eye movement variability, and also a faster automatic postural
response and improved postural flexibility in the headshake groups relative to the other
groups. The exploratory analysis found moderate negative associations between VOR
gain and eye movement variability versus postural sway measures. Also, moderate
positive associations were found between EMG peak amplitudes versus postural sway
measures and eye movement variability.

**Aim 1**

The findings that our concurrent vestibular activation (via headshake activities) and
postural training protocol showed evidence of improving postural control is consistent with
the literature. Many studies, including systematic reviews, have shown that there is
moderate to strong evidence supporting the effectiveness of WST 36,123,124 or vestibular
rehabilitation 12,13,51,59,125–127 in the improvement of postural control. The Melo et al. study
125 reviewed articles on children aged up to 12 years old and found evidence that vestibular
rehabilitation can improve postural control, balance and gait. The other vestibular
rehabilitation studies that employed young and older adults, and vestibular impaired
populations focused on other outcome measures (such as dizziness, target following,
gaze stabilization and dynamic visual acuity) apart from postural sway which directly uses
computerized dynamic posturography (CDP) assessment. To the best of our knowledge,
the current study is the first vestibular rehabilitation study that uses CDP sensory ratios to
assess postural changes through sensory weighting in healthy young adults, and any adult
category for that matter. Posturography assessment such as the use of SOT sensory
ratios allows one to directly obtain data on the multisensory systems (i.e., somatosensory,
visual and vestibular) for specific postural analysis, compared to other aforementioned
measures that would infer some sensory changes such as visual-vestibular 128.
Our study is the first to use concurrent headshake activities and WST to improve postural control through the underlying mechanism of sensory weighting. This finding provides evidence for the advantages of using our novel training protocol, which includes gaze stabilization, smooth pursuit, somatosensory inputs, optimized vestibular responses, faster automatic responses and improved postural flexibility (see results of Chapters 2 and 3). The training protocol provides a neurological basis to habituate and/or adapt the multisensory systems through reweighting and integration for efficient postural control. The rhythmic headshake activity causes habituation and adaptation of the vestibular system by suppressing possible vestibular symptoms such as dizziness or improving the VOR gain. Subsequently, the headshake motions also cause adaptation of the visual system to produce eye-in-head coordination and gaze stabilization. The WST on different surfaces (i.e., flat, foam and rocker board) recalibrates somatosensory channel and spinal reflexes from the soles of the feet and lower limb joints with the vestibular and visual systems.

The findings in the current study showed a downweighting in the somatosensory system in the headshake groups. This was contrary to the findings we obtained in a similar study, which found an upweighting in the somatosensory system. Possible explanations could be attributable to the difference in maximum headshake activity during the training protocol in the current study (i.e. 120 versus 100 beats/minute). This study also had an overnight break between the last training session and the final outcome measures assessment. Questions regarding the length of retention of any training effects require further investigation.
Since there are no studies which have investigated sensory reweighting using a concurrent vestibular activation and WST, the findings of our current study will be discussed in the light of headshake activities and WST separately. The sensory reweighting findings support our main aim that concurrent vestibular and postural training protocol showed evidence of altering dependence on somatosensory input to compensate for the changes in vestibular and/or visual dependence to maintain posture. However, as explained earlier the direction of somatosensory reweighting obtained was contrary to our hypothesis. On one hand, postural training has been shown to improve postural balance. A systematic review \(^{124}\) showed strong evidence for the effectiveness of balanced training, of which WST is an example. The evidence was demonstrated in 14 out of 16 of the studies. The authors of this review suggest that even for healthy individuals balance training can improve static balance on stable and unstable surfaces, and also improve dynamic balance. The type of training modalities included wobble board, ankle disc, foam pad, balance trampoline, tilting platform and trunk motion. The outcome measures included center of pressure excursion, oscillation area and velocity, balance time, stability index, degrees of sway and surface pressure level. Postural training has also proven to be effective in a diseased population. WST was found to be beneficial for training postural control in chronic hemiparetic stroke individuals by improving balance measures such as trunk control and proprioception \(^{36}\). The WST involved long or normal sitting on surfaces which included a balance pad and a dynamic ball cushion under their buttocks on an exercise mat or on the edge of a testing table. Training on these surfaces over time modifies somatosensory inputs and transmits bottom-up signals which integrate with the visual and vestibular systems to improve postural control. Although the above studies did
not directly assess the sensory channels, the improved postural outcomes suggest
evidence of postural control processing, through sensory reweighting.

On the other hand, a 6-week study aimed to compare the effects of gaze stabilization and
habituation exercises on vestibular function showed improvements in dizziness, motion
sensitivity and dynamic visual acuity in a unilateral vestibular hypofunction population 59.
These measures were assessed by the Dizziness Handicap Inventory (DHI), motion
sensitivity quotient (MSQ) and dynamic visual acuity (DVA) test. It suggests that the
improvement in the outcome measures consequently improved the postural balance of
the study participants. The gaze stabilization exercises included progressive horizontal
and vertical VOR exercises in sitting and standing. The habituation exercises involved
participants performing rapid horizontal and vertical cervical rotations in large amplitudes
in sitting and standing postures. In addition to these habituation exercises, participants
performed seated trunk flexion-extension exercises and standing pivots. Both gaze
stabilization and habituation exercises involve headshake activities with gaze stabilization
exercises utilizing target fixation to induce the benefits of retinal slip (i.e., VOR adaptation)
and habituation exercises which does not necessarily involve target fixation.
Improvements in the outcome measures following training suggest that the significant
changes were due to a common factor, the headshake activities. The headshake protocol
in the above study 59 is similar to that of the current study. This is because in the current
study, during the concurrent headshake activities and WST, habituation occurs as a result
of the rhythmic headshake, while gaze stabilization is likely to occur as the participant
fixates on the target that is providing visual feedback for the participants to voluntarily shift
their COM. However, it is dissimilar from the current study because it is unlikely that the
headshake activities, the seated trunk flexion-extension and standing pivots used in the Clendaniel study\textsuperscript{59} were performed concurrently.

Also, compared to our protocol, the seated trunk flexion-extension movements may not stimulate the somatosensory system enough to contribute to the bottom-up mechanism that would drive the sensory reweighting and integration processes. Although the Clendaniel study (Clendaniel, 2010) lends support to the benefits of headshake activities, it is limited by the small sample size of seven and there was no control group. Hence, generalization of the findings should be done with caution. In addition, two other studies\textsuperscript{130,131} have demonstrated improvements in measures of ataxia and postural stability\textsuperscript{131} and standing balance performance and VOR gain\textsuperscript{130} in individuals with vestibular dysfunction following vestibular rehabilitation. However, the improved balance performance was not based on sensory reweighting to directly explain the underlying mechanisms of adaptation and habituation. Lastly, our study is novel and robust because it uses the combined benefits of vestibular adaptation and habituation to improve posture.

\textit{Aim 2}

One of the main benefits of vestibular rehabilitation is the improvement in gaze stabilization through VOR habituation and/or adaption following VOR headshake exercises\textsuperscript{59}. In accordance to our hypothesis, horizontal VOR (HVOR) gain was reduced in the headshake (HS) groups following training compared to the control group. Mitsutake and colleagues\textsuperscript{39} showed that vestibular adaptation and balance exercises improved VOR and gait performance of individuals with poststroke hemiparesis. VOR and gait performance were assessed using the gaze stabilization test (GST), dynamic gait index
(DGI), 10-meter walking test (10MWT) and timed-up-and-go (TUG) test. The experimental group significantly improved in GST and DGI after three weeks of rehabilitation compared to controls. Improvements in the GST indicate a change in VOR and improvements in DGI indicate a better dynamic balance function. Improvements in both functions indicate that vestibular rehabilitation coupled with the WST positively influences the sensory reweighting mechanism by facilitating the reflex mechanism related to vestibular function.

The Mitsutake and colleagues study\textsuperscript{39} is similar to the current study in that it incorporates both vestibular rehabilitation using eye-head coordination exercises (i.e., VOR X 1 and VOR X 2) and balance exercises. VOR X 1 involves continuous head rotation while keeping the eyes on a stationary target, while VOR X 2 is performed by the same head rotation but with moving the target to the opposite directions to the head simultaneously. For the balance training, participants rotated their neck and trunk to the left and right and also performed forward-backward and side-to-side weight shift. However, it does not appear that the neck and trunk rotations were performed at a similar fast frequency of 80 – 120 beats/second to activate the vestibular system at the same level. Also, the gaze stabilization and balance exercises were not performed simultaneously to obtain the real time benefits of actively stimulating the multisensory systems for optimal integration to produce an appropriate postural response. Further studies should be conducted to ascertain whether our concurrent headshake activities and WST yields superior benefits than performing two exercises in succession. In addition, a non-vestibular population group was used, although persons with stroke may exhibit an increase in postural perturbation due to inadequate ability to utilize vestibular information and thus could benefit from vestibular rehabilitation and postural training\textsuperscript{132–134}. 

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Contrary to our hypothesis, there was a significant increase in the average COP sway velocity during ramp trials in the headshake groups following our protocol. This suggests a faster and greater postural variability in the headshake groups. However, the faster sway velocity may not necessarily be tantamount to greater postural instability. Thus, from another interpretation, the faster sway velocity following vestibular training is suggestive of better postural flexibility and larger limits of stability. For instance, participants with Parkinson’s disease may exhibit lower variability compared to age-matched healthy participants, however, lower variability may be due to rigidity and inflexibility making the Parkinson’s patients prone to falls. The important factor is not variability per se, but the sway measure being within the optimal range. Since the vestibular training groups in our study demonstrated better postural control in SOT somatosensory downweighting and HVOR gain assessments, this may suggest that variability in the sway velocity is optimal leading to more flexibility. Additionally, since the velocity variability for NHS and control decreased after training, this may be suggestive of postural inflexibility thus lowering postural stability. The postural flexibility was also reflected in the faster automatic response shown by the HHS group.

In support to our hypothesis, eye movement variability in the medio-lateral direction decreased in the HHS group following training, which suggests an evidence of vestibular habituation. During the ramp perturbations, decreased eye movement variability is essential for gaze stabilization leading to greater postural stability. The horizontal headshake activities coupled with the WST resulted in a decreased HVOR gain, thereby ensuring a well-controlled eye-in-head position and consequently head-over-torso position. Decrease in eye movement variability has been found to have an influence on
improved postural control by the suppression of nystagmus in a population with unilateral vestibular neuritis. In the VHS group, the training protocol did not have the same effect, but rather showed an increase in eye movement variability. This could be explained by the underlying mechanism of the head activity along the sagittal plane during training. Vertical headshake activities stimulate the anterior and posterior SCCs (i.e., vertical SCCs) and the saccular otolith organs which mainly activate the VSR to produce a motor out to postural muscles beneath the neck region, rather than causing major changes in VOR. In addition, unlike the horizontal HS activity that was performed approximately along the planes of the horizontal SCCs (i.e., 30° neck flexion), the vertical HS activity was performed off the planes of the vertical SCCs. To effectively activate the vertical SCC, the head movements should match the right anterior left posterior (RALP) and the left anterior right posterior (LARP) planes; that is, by rotating the head 45° to the right or left from the sagittal plane. The vertical HS activity performed by the VHS group during training in the current study was along the mid sagittal plane. Therefore, the vertical HS activity probably did not have as much influence on VOR compared to the horizontal HS activity.

**Aim 3**

The postural control system encompasses various subsystems including multisensory reweighting and integration which produce an appropriate motor output. The effects of the motor output are typically exerted on the ocular, cervical, trunk and lower limbs muscles. The vestibular system plays a major role in the postural control system in that it senses the body’s current orientation and if the body is in a state of disequilibrium, transmits the appropriate motor responses to these muscles for efficient postural balance. Actively training the vestibular system, together with other multisensory systems through weight
shift training, can enhance the postural system \cite{12,13,51,59,125–127}. Since the postural system is multifaceted, such form of training can reveal some associations of the components which can provide valuable insights into predicting the outcomes of the training.

In this aim we investigated associations between postural measures, vestibulo-ocular and vestibulo-motor following our novel concurrent vestibular activation and WST. A comparable study was conducted by Gauchard et al. \cite{78} to assess the effects of physical activities on vestibulospinal reflex and ocular movements of visual and vestibular origins in elderly people. Twenty-six healthy older adults (mean age, 72 years) were divided into a sports training and non-sporting groups and gaze control and posture stabilization measures were assessed. Specifically, the assessments involved dynamic posturographic test with electromyography, as well as electronystagmography with caloric and rotational vestibular tests, ocular saccades, smooth pursuit and optokinetic tests. The sports group practiced one or two physical activities such as yoga, soft gymnastics, jogging or swimming, while the non-sporting group were sedentary individuals and their lifestyle was not due to any pathology. The authors concluded that the gaze stabilization and postural control performance was improved in the sports group by showing improvements in the vestibulospinal, vestibulo-ocular and visuo-ocular reflexes. The study shows positive effects of physical activities on the above measures to improve gaze and postural control in the elderly. However, it does not incorporate any particular vestibular training as used in our study. An addition of a vestibular activation training to the postural training (i.e., WST) in the current study showed associations between postural measures and vestibular responses in vestibular reflex gains, eye movement variability and muscle activations.
In tandem to our hypothesis, the current study revealed a negative association between SOT composite and VOR gain following training. A habituated VOR gain following vestibular activation drives oculomotor control to produce eyes-in-head coordination and gaze stabilization, which consequently leads to head-on-trunk control and postural stability. VOR function has shown to be associated with postural control, including gait function. Gaze stabilization (a function of VOR), as measured by the gaze stability test (GST), was associated with measures of gait performance. The authors used 12 elderly participants (mean age, 71) with vestibular hypofunction and 20 aged-matched controls who identified a visual optotype (letter E) during controlled vertical and horizontal head movements using the GST. All participants performed the DGI and TUG test prior to performing the GST. The significant association between gaze stabilization and gait performance was found in the vestibular participants but not in the controls, indicating that persons with vestibular disorders exhibit poorer performance in gait with lower gaze stabilization performance. These findings provide insight into how the underlying mechanisms of VOR gain can affect dynamic postural control.

The finding on the role of eye movement on postural control was supported by our hypothesis showing that as eye movement variability decreases, postural control increases. The effect of reduced eye movement variability on improved postural control has been established in the literature. Glasauer et al. demonstrated in 15 healthy women (aged 22 to 45 years) that slow eye movements, performed by the eyes alone or by combined eye–head movements, can result in significant body sway. During smooth pursuits or eye-head movements, postural sway was significantly affected compared to when participants fixated a stationary target. Comparatively, smooth pursuits and eye-head movements will increase eye movement variability, negatively affecting gaze and
consequently inducing posture instability. Jahn et al. 96 also showed an association between the suppression of spontaneous nystagmus and improvement of postural control in persons with vestibular neuritis.

Apart from reducing eye movement variability, producing the appropriate motor response to postural muscles is necessary to maintain an effective postural control. Our findings showed that the peak muscle activation following the concurrent vestibular-postural training was associated with postural sway measures. Since the peak muscle activation was decreased after training and showed an association with increased postural control, it suggests that our vestibular-postural training induced an optimal muscle activity through sensory reweighting and integration. Hu & Woollacot 121 have shown that a multisensory balance training program can affect compensatory postural responses after training by optimizing muscle activations. They found in decreased onset latency of neck flexors and a trend toward decreasing the response frequency of antagonist muscles. Such changes following training could be attributed to sensory reweighting and integration mainly between the vestibular and somatosensory systems.

**Summary on Sensory Reweighting Framework of Study Findings**

Based on the findings of the study our initial sensory reweighting framework (Fig. 1.2) was modified (Fig. 5.1). The concurrent vestibular activation and WST induces vestibular response (i.e., HVOR) following the rhythmic headshake activities to produce decreased eye movement variability and gaze stabilization through the underlying mechanisms of vestibular habituation and adaptation. The gaze stabilization in turn leads to a well-controlled head-over-torso position. The continuous somatosensory stimulation during
WST performed on different surfaces causes the postural system to downweight the somatosensory system. Simultaneously, the habituated vestibular responses from VCR and VSR through recalibrations drive neck and lower limb muscles to maintain head-on-torso and trunk stability. This process is mediated by an up-ward signal of the somatosensory channel which centrally integrates with the vestibular and visual inputs. As a result, a faster automatic postural response is produced, together with optimal flexibility which leads to an improved postural control.

Figure 5.1 Sensory reweighting mechanisms after concurrent vestibular activation and WST. WST = weight shift training, HVOR = horizontal vestibulo-ocular reflex, HHS = horizontal headshake group, VHS = vertical headshake group, M-L = medio-lateral, MG = medial gastrocnemius, Std = standard deviation

Figure 5.2 shows a schematic diagram of the associations between postural sway measures, muscle activations, eye movement variability and vestibular reflex gains following the vestibular activation and WST. Generally, there were positive associations between improved postural sway and decreased muscle activations, and between
decreased muscle activations and decreased eye movement variability. Furthermore, as eye movement variability decreased, postural sway improved, signifying a negative association. HVOR and VVOR were negatively associated with improved postural sway, indicating an enhanced vestibular function.

![Diagram of associations between postural and vestibulo-ocular and motor response.](image)

**Figure 5.2** A schematic diagram of associations between postural and vestibulo-ocular and motor response. HVOR = horizontal vestibulo-ocular reflex, VVOR = vertical vestibulo-ocular reflex, COP = center of pressure, SOT = sensory organization test, positive sign (+) = positive association, negative sign (−) = negative association

**Limitations**

There are several limitations in this study that should be considered for future investigations. The absence of vestibular impairment in the sample made it difficult to induce large changes in otherwise functional behavior. Also, the 20 minutes of training/day for only five sessions was relatively short to induced large vestibular changes, but despite this we were able to detect vestibular changes. Future studies should be conducted for a minimum of six to eight weeks and also with follow-up reassessments to ascertain the duration of retention.
In addition, the trunk EMGs were not analyzed in this study to investigate the effect of vestibular training/responses on trunk postural behavior due to EKG contamination. However, the neck and lower limb muscles were adequate to show changes due to our concurrent vestibular activation and postural training. A group calibration conversion factor was used for the EOG analysis. Ideally, the conversion factor of individual participants should have been applied. However, the intra-rater reliability of the group calibration was significantly high (0.76 and 0.94) and we felt it was adequate to be applied to the group.

Conclusion
The concurrent vestibular activation and weight shift training modifies vestibular-dependent responses after the training intervention as evidenced in somatosensory downweighting, decreased VOR gain, decreased eye movement variability and better postural flexibility and faster automatic postural response. The findings suggest this is predominantly due to vestibular habituation and adaptation of VOR, VCR and VSR which induced sensory reweighting. The study also found moderate associations between postural measures and vestibular responses in vestibular reflex gains, eye movement variability and muscle activations. These findings may help predict postural changes through vestibular habituation and also provide insight into the behavior of eye movements and muscle activations following vestibular training.

Implications for Future Research
This is the first study to use a concurrent vestibular activation and weight shift training protocol to induce changes in vestibulo-ocular and vestibulo-motor responses in healthy young adults. The changes show that the postural system can be enhanced by targeting
sensory reweighting mechanisms via the activation of the vestibular system. Future research is warranted to explore this novel training protocol to rehabilitate persons with vestibular impairments or sensory integration problems.

The somatosensory downweighting was found in all three training groups. Future studies should investigate the effect of rhythmic headshake activities with no weight shift training on sensory reweighting in order to establish the proportion of contribution from the headshake activities only. This will inform us about the appropriate dosage of headshake activities to include when redesigning the protocol. Furthermore, future studies should be designed to include larger sample size in the training groups with increase training dosage of eight weeks to detect larger differences in the vestibular changes. The training should have follow-up assessments to ascertain the amount and duration of retention of the changes.

Replicating the study in populations with vestibular impairments or sensory integration challenges will be valuable for assessing improvements in impaired populations. Populations which could benefit from our training protocol would include persons with vestibular dysfunction, stroke or concussion. The use of customized, progressive activities would be beneficial in treating the impairments associated with sensory weighting and integration. Ultimately, the training protocol may be modified for home-based training with virtual reality goggles or using smart-phone solutions, which will increase portability, accessibility and affordability.
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APPENDIX A

CLINICAL MUSCULOSKELETAL EXAMINATION FORM

Vestibular Training History Questionnaire

GUID:  
ID #:  

Participant Birth Name (first, middle, last):  
DOB (M/D/Y): ________ Sex at birth: M F  
Race: ________ Ht: ________ Wt: ________  
City of birth: ________ Country of birth: ________  
Today’s Date: ________ Year in school: ________  

School:  

<table>
<thead>
<tr>
<th>Concussion History?</th>
<th>Headache History?</th>
<th>History of vestibular issues?</th>
<th>History of ocular issues?</th>
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</thead>
<tbody>
<tr>
<td>Y __ Dx __ N __</td>
<td>Y __ Dx __ N __</td>
<td>Y __ Dx __ N __</td>
<td>Y __ Dx __ N __</td>
</tr>
<tr>
<td>Data of recent concussion?</td>
<td>Prior Treatment for Headache (list):</td>
<td>Prior Treatment for vestibular issues (list):</td>
<td>Prior Treatment for ocular issues (list):</td>
</tr>
<tr>
<td>Family History of concussion List:</td>
<td>Family History of migraine headache List:</td>
<td>Family History of vestibular issues List:</td>
<td>Family History of ocular issues List:</td>
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NB: Dx=Diagnosis

Short Clinical Musculoskeletal Examination

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<tr>
<th>Spine:</th>
<th>Pelvis:</th>
<th>Leg Length Measurement:</th>
<th>VAS:</th>
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<tbody>
<tr>
<td>Lordosis Y __ Dx __ N __</td>
<td>Ant-Post Tilt Y __ Dx __ N __</td>
<td>Right leg length (cm):</td>
<td>0-1-2-3-4-5-6-7-8-9-10</td>
</tr>
<tr>
<td>Scoliosis Y __ Dx __ N __</td>
<td>Lat. Tilt Y __ Dx __ N __</td>
<td>Left leg length (cm):</td>
<td>0 - No pain</td>
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<tr>
<td>Kyphosis Y __ Dx __ N __</td>
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<td>Difference (cm):</td>
<td>10 - Worst pain ever</td>
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<th>Symptoms Visual Analog Scale Score</th>
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<tr>
<td>Session 1</td>
</tr>
<tr>
<td>Headache:</td>
</tr>
<tr>
<td>Dizziness:</td>
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<td>Nausea:</td>
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**PHYSICAL ACTIVITY AND HEALTH HISTORY**

Do you have any general health problems or illnesses (i.e. diabetes, respiratory disease)?  
- If so, please list them: ____________________________________________________________

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Do you drink alcohol?  
- If yes, how often? ____________________________  
- When did you last drink? ____________________________

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Do you have any cognitive disorders?  
(i.e. memory loss, concentration abnormalities)

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Please list any medications you take regularly: ____________________________________________________________

Approximately how many hours per week would you say you are physically active?  
(i.e. running, lifting weights, recreational sports, etc.)

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Please list all physical activities that you are currently engaged in. For each activity, please indicate how much time you spend each week in this activity, the intensity of the activity (i.e. competitive or recreational) and for how long you have been regularly participating in the activity.

<table>
<thead>
<tr>
<th>Activity</th>
<th>#Days/week</th>
<th>#Minutes/Day</th>
<th>Intensity</th>
<th>Activity Began When?</th>
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What time of day do you generally engage in the above activities?

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Please list other conditions / concerns that you feel we should be aware of: ____________________________

<p>| |</p>
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***Investigator Comments:__________________________________________

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APPENDIX B

SYNCING NEUROCOM® TO EOG BLUE GAIN BOX

The sync pulse was an external trigger electrical unit built on an Arduino board and connected to NeuroCom® sync output. This pulse sent electrical activity from NeuroCom® to the BlueGain device, which is represented on the EOG output file as non-zero numbers to signify the beginning and end of a trial. Without the sync pulse, the “marker column” of the EOG output file is typically filled with zeros (Fig. 3.5). The NeuroCom® IR LED sync pulse has a delay start time of 500 milliseconds and a delay end time of 1000 milliseconds.

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<tr>
<th>Time</th>
<th>Marker</th>
<th>Channel 1</th>
<th>Channel 2</th>
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<td>318256</td>
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</tbody>
</table>

EOG output file, showing trigger from NeuroCom®, beginning and end of trial