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Comparison of Computerized Dynamic Posturography (CDP) results with subjective visual vertical (SVV) test in patients with and without vestibular dysfunction: effects of horizontal headshaking

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COMPARISON OF COMPUTERIZED DYNAMIC POSTUROGRAPHY (CDP) RESULTS WITH SUBJECTIVE VISUAL VERTICAL (SVV) TEST IN PATIENTS WITH AND WITHOUT VESTIBULAR DYSFUNCTION: EFFECTS OF HORIZONTAL HEADSHAKING

By

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Abstract: The goal of the present study is to identify what effect headshaking in the horizontal plane has on Computerized Dynamic Posturography results in normals and patients with unilateral vestibular dysfunction. Additionally, we will compare these results to results of the dynamic subjective visual vertical test.

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TABLE OF CONTENTS

LIST OF TABLES

ABBREVIATONS

ADT	Adaptation test
AP	Anterior-posterior sway
BPPV	Benign Paroxysmal Positional Vertigo
CDP	Computerized Dynamic Posturography
CNS	Central Nervous System
COG	Center of Gravity
ENG	Electronystagmography
GIA	Gravito-Inertial Acceleration
HS-SOT	Head Shake Sensory Organization Test
IUD	Interutricular Distance
MCT	Motor Control Test
OCR	Ocular Counter Roll
SCC	Semicircular Canal
SOT	Sensory Organization Test
SVV	Subjective Visual Vertical
UC	Unilateral Centrifugation
VEMP	Vestibular Evoked Myogenic Potentials
VOG	Video-oculography
VOR	Vestibulo Ocular Reflex

Introduction and Review of the Literature

Human postural control is governed by vestibular, visual, and proprioceptive inputs and their central processing (Basta, et al., 2005). The vestibular system is located in the inner ear, in a structure referred to as the labyrinth. The vestibular portion of the labyrinth includes five separate sensory end organs. These include the otolith organs called the saccule and utricle, located in the vestibule, and the three semicircular canals (SCC). The semicircular canals are sensitive to angular acceleration and do not provide information about the static position of the head, and are therefore influenced by rotational movement of the head. The three semicircular canals in each inner ear are positioned in orthogonal pairs and are named according to their relative positions in the upright head: superior, posterior, and lateral (horizontal) semicircular canals. The superior and posterior canals are oriented vertically, and the lateral canal is oriented in approximately a horizontal plane. At the end of each of these semicircular canals is an ampulla, which houses the sensory receptor organ (Wright and Schwade, 2000; Yates et al, 1998). Gravity, position, and orientation are registered by tiny grains called otoconia moving in two fluid-filled sacs in the inner ear in response to any change in position or orientation. These two fluid-filled sacs are the utricle and saccule, and their motion is detected by sensory hairs. Rotation is also detected by sensory hairs through the inertial lag of fluid in the semicircular canals. The otolith organs (saccule and utricle) are sensitive to linear acceleration, and provide information relating to linear motion and head position. The saccule detects linear acceleration in the vertical plane, while the utricle detects linear acceleration in the horizontal plane. Both the utricle and saccule also provide information relative to the static position of the head in space, more specifically information about the head's position with respect to the rest of the body. These organs provide inputs for balance regarding the movement of the head in three ways: left-right (yaw), up-down (pitch), and side to side (roll). Not only is the vestibular system important for maintaining movements of the head and balance, but clear vision is also an important characteristic of maintaining balance. Each labyrinth actually influences the muscles that pull the eyes in a direction opposite to the direction of head rotation. This response is known as the vestibulo-ocular reflex (VOR) (Redfern et al, 2001). Lastly, proprioception is the human ability to perceive stimuli relating to position, posture, equilibrium, or internal condition. The nerve endings in skeletal muscles and on tendons provide constant information or feedback relating to limb position and muscle action for the coordination of limb movements. The perception of gravity allows humans to be conscious of equilibrium changes. The central nervous system then integrates these signals in order for humans to perceive stimuli relating to position, posture, and overall balance (Britanica, 2007).

Given the complexity of the vestibular system, specific functional tests for the receptors in each of the organs are needed for a comprehensive vestibular examination. However, since all of the five vestibular organs work together in controlling and maintaining balance, while at the same time three of the five vestibular organs detect angular acceleration and two of the five organs detect linear acceleration, it is difficult to develop and utilize specific tests to evaluate each organ separately. Therefore, it becomes increasingly more difficult to devise tests that further evaluate the right vestibular system versus the left vestibular system and/or isolate one vestibular organ in one ear versus the same vestibular organ in the other ear. Despite this fact there are some tests that have been developed and utilized in the differential diagnosis of vestibular disorders; more are still needed.

The bithermal caloric irrigation test is the basis of all vestibular testing; it measures only the lateral SCC function and only at a low frequency of .003Hz (Halmagyi, 2004). There are also ocular-motor tests that evaluate the function of the peripheral and central vestibular system, more specifically the ocular-motor pathways in the brainstem and cerebellum that are required for the function of the vestibulo-ocular-reflex. With pathologic conditions, specific head positions or changes in head position can induce abnormal eye movements called nystagmus. Because of certain fixed pathways between the eye muscles and the vestibular system, careful analysis of the nystagmus can give insight into the site of vestibular disturbance. Nystagmus present in static head postures or nystagmus induced by a new head position is called positional nystagmus, and nystagmus caused by head movement is termed positioning nystagmus. Thus, there are both positional and positioning tests that can be utilized to provide information about the site of vestibular lesion. With positional tests there are three classifications of nystagmus that can be observed. Type I nystagmus has been thought to be related to central pathology, the horizontal canal variant of Benign Paroxysmal Positional Vertigo (BPPV), or with barbiturates, salicylates, or alcohol intoxication. Type II nystagmus can be seen with either central or peripheral etiologies, where the peripheral etiologies are usually those disorders that cause a significant loss of unilateral vestibular function. Type III nystagmus usually indicates the classic posterior canal BPPV. In contrast, positioning testing also evaluates nystagmus but rather evaluates the latency, duration, direction, and fatigability of the nystagmus observed (Goebel, 2001). The Dix-Hallpike Maneuver, one of the most common positioning tests, is used in the diagnosis of BPPV. This test evaluates the semicircular canals where the posterior canal is most often the affected canal (Goebel, 2001). All of these tests are utilized together in a major test battery called Video-Oculography (VOG) and are collaboratively interpreted in order to diagnose a specific vestibular lesion. Lastly, vestibular evoked myogenic potentials (VEMPs) are also now being used to find a variety of peripheral and central vestibulopathies. VEMPs evoked by clicks are a robust, reproducible screening test of otolith function, more specifically saccule function (Colebatch et al., 1994 & Kingma, 2006). There are two main reasons why VEMP arises from stimulation of the saccule. First, the saccule is the most sound-sensitive of the vestibular end-organs and second, because not only do click-sensitive neurons in the vestibular nerve respond to tilts, most originate in the saccular macula (Halmagyi, 1999).

To assist in determination of the site of the lesion or to help expand the VOG evaluation, both rotational chair testing and Computerized Dynamic Posturography (CDP) are utilized. Rotational chair testing has been used to expand the evaluation of the peripheral vestibular system. Since the peripheral vestibular system functions across a range of intensity (acceleration) and frequency, the ability to evaluate the range using VOG is limited. The use of caloric irrigations in the VOG test battery stimulates the system in a manner equivalent to a frequency between .002 and .004 Hz and accelerations of less than 10 degrees/s^2. These values are well below the level within which the Vestibulo-Ocular Reflex (VOR) generally functions; therefore rotary chair testing has been utilized due to the fact that it can assess greater frequencies and accelerations (Goebel, 2001). There are two main protocols used for rotary chair testing: sinusoidal rotation and the step test. In both tests, the VOR is assessed through the evaluation of gain, phase, and asymmetry. In the past it was understood that the rotational chair was not a tool that could be used to isolate one peripheral system from the other because each stimulus affects both sides simultaneously. Therefore, a more refined method was necessary to test each otolith system separately. As stated previously, the VEMP test was developed by

Colebatch et al. in 1994, which represented a new unilateral test for the saccule. Unilateral utricular stimulation technique, based on eccentric rotation, was developed by Yegorov et al., Wetzig et al. and further employed by Clarke et al. in the 1990s (Wuyts et al., 2003). This test is termed the Subjective Visual Vertical test (SVV), and is based on the evaluation of ocular counter rolling.

During the SVV test, a subject is rotated at 300^0/s in the normal upright position in a vertical axis rotational chair. After the initial acceleration, the rotation is maintained at a constant velocity to extinguish lateral canal stimulation in order to assess only the utricle. The subject is then laterally displaced along an interaural axis so that one utricle becomes aligned with the axis of rotation and the other utricle alone is exposed to the radial acceleration component generated by the centripetal force. When the axis of rotation crosses precisely through one utricle, only the opposite utricle will be stimulated (Nowe et al., 2003). This type of rotation is called eccentric rotation. In order to achieve eccentric rotation where the axis of rotation passes precisely through one utricle, the interutricular distance has to be known. Nowe et al. (2003) studied the interutricular distance as determined from external landmarks and Magnetic Resonance Imaging in 50 adults. They concluded that the mean distance between the medial margins of the vestibules Interutricular Distance (IUD) was 7.22 cm. This implies that the lateral displacement along the interaural axis so that one utricle becomes aligned with the axis of rotation should be approximately 4 cm. Thus, when utilizing the eccentric rotation in SVV testing, the patient should be displaced to the left and to the right 4 cm in order to test each utricle separately. This technique exploits the eccentric location of the labyrinths in the head and can be termed unilateral centrifugation (UC).

When the chair is translated to the right during ongoing rotation at 300^0/s, the left utricle becomes aligned with the axis of rotation and the right utricle is exposed to a centrifugal acceleration and vice versa. When added to the gravity vector, this stimulus results in a GIA (gravito-inertial acceleration) tilt. A positive GIA tilt corresponds to a right ear down tilt, while a negative GIA tilt corresponds to a left ear down tilt. The GIA detected by the utricle generates an ocular counterroll (OCR) of the eyes (Wuyts et al., 2003). Ocular counterroll is of primary importance for testing utricular function.

In order to assess ocular counterroll in patients either highly expensive contact lenses or a light bar is utilized. The subjects can be fitted with scleral search coils, which are specialized contact lenses that allow effortless recording of saccades, smooth pursuit, vestibular and optokinetic eye movements, and also miniature eye movements such as tremor, drift, and microsaccades. The induction coil is embedded in a flexible ring of silicone rubber which adheres to the limbus of the eye concentric with the cornea. In addition to this coil, which is wound in the frontal plane, a second coil is wound in the sagittal plane. This combination coil simultaneously measures horizontal, vertical, and torsional eye position. This torsional eye position can also be referred to as ocular counterroll and can be measured and calculated for the SVV testing (Scleral Search Coil Systems, 2007). The second approach is to use a luminous line or light bar that subjects can manipulate with a turn dial to a vertical position. During on-axis rotation and eccentric rotation, the subject is asked to set the light bar to what he or she perceives to be vertical. Normal subjects are able to set the light bar with great accuracy close to the true vertical during on-axis rotation (Tribukait et al., 1998). But, due to the event of ocular counterrolling during unilateral centrifugation, the normal subject will set the light bar toward the utricle or side that is aligned with the axis of rotation. In contrast, subjects with a compensated unilateral deficit show a significant tilt of the light bar toward the side with the lesion during on-axis rotation. During unilateral centrifugation, they show good accuracy in setting the light bar close to the true vertical.

According to Bohmer and Mast (1999b), in all instances, the SVV for subjects with a unilateral deficit was shifted with the upper pole of the light bar toward the lesioned side. They later stated that this was due to all of the subjects being in the acute stage of unilateral vestibular deafferentation. As proposed by Helling et al. (2006), the Subjective Visual Vertical (SVV) estimation during on-axis rotation provides an efficient screening test of utricle function during the acute stage of unilateral vestibular loss. The subjective visual vertical (SVV) during on-axis rotation deviates significantly from true vertical toward the affected ear in the acute stage of unilateral vestibular loss, but recovers during following weeks. According to Curthoys (2000), perceptual judgments of visual horizontal and vertical are affected in peripheral vestibular loss, and this visual bias appears to be caused by the loss of otolithic input affecting the ocular torsion position and thus perception of the orientation of visual stimuli. Immediately after unilateral vestibular deafferentation, humans show large ocular torsional position toward the affected side and a corresponding change in their perceptual judgments. But, both of these symptoms decrease over time, showing that a partial recovery of otolithic static symptoms does occur but there is a small permanent deficit. Because this deviation of the SVV is compensated during the following months, patients with chronic unilateral vestibular loss no longer differ from normal subjects (Bohmer & Mast, 1999a). Clarke et al. in 2003 have shown that this response of ocular counter rolling proves to be highly symmetrical and conjugate in normal subjects during UC stimulation. In patients with unilateral deafferentation, stimulation of the healthy utricle or labyrinth elicited a clear response, while stimulation of the lesioned utricle or labyrinth elicited little or no response. Simply stated, with the use of eccentric rotation and unilateral centrifugation or SVV, compensated subjects can be identified through the evaluation of ocular counterrolling utilizing either goggles or through the manipulation of a light bar.

After the VOG test battery and the rotational chair battery, one last test can be utilized in the diagnosis of vestibular disorders. Computerized Dynamic Posturography (CDP) determines the cause underlying functional limitations by measuring impairments to the sensory input and automatic motor response systems necessary for normal balance (Goebel, 2001). CDP is comprised of a Sensory Organization Test (SOT), Motor Control Test (MCT), and an Adaptation Test (ADT). The individual protocols of each of these tests quantify organization of vestibular, somatosensory, and visual inputs to balance, coordination of automatic motor and voluntary motor responses and strategies, and the center of gravity alignment. Thus, CDP analyzes the subject's ability to maintain or regain postural control under a variety of sensory conditions and challenges. It is also an important test to monitor improvement in postural stability during vestibular rehabilitation (NeuroCom Int., 2000).

During testing, subjects stand on a force platform (dual forceplate). The platform can either remain stable, tilt, or translate in the anterior/posterior direction. The subject's field of view is obstructed by an enclosure or visual surround that can also tilt. During the SOT, both the support surface and visual surround can tilt in response to patient sway. During the MCT, the visual surround is fixed and the dual forceplate moves horizontally from center to back or center to front (translations). During the ADT, the visual surround is fixed and the dual forceplate tilts (rotates) in either toes-up or toes-down position, independent of patient sway. The computer then receives force measurements from the dual forceplate, analyzes the information, and generates a printed report (NeuroCom Int., 2000).

Depending upon the equipment used, the SOT involves three trials of six sensory conditions, lasting 20 seconds each, that examine postural control under various combinations of support surface and visual surround motion. Although there are slight variations in how the six conditions are accomplished, they follow a standard pattern of progressively reducing or distorting information used for the maintenance of balance. As the conditions become progressively more difficult, the subject is forced to rely more on visual, somatosensory, or vestibular inputs individually. Condition one consists of a stable platform with eyes open in a stable visual environment. In this condition the subject has full use of all information: visual, vestibular, and somatosensory. Condition two consists of a stable platform with the subject's eyes closed. In this condition the subject must rely on vestibular and somatosensory information only. Condition three consists of a stable platform with a moving visual surround. Thus, the subject must suppress a false sense of visually induced movement and rely on vestibular and somatosensory inputs. Condition four includes an unstable platform with the subject's eyes open and a stable visual environment. In this condition the subject must rely on vestibular and visual inputs only. Condition five consists of an unstable platform and the subject's eyes are closed. Thus, the subject must rely primarily on vestibular input since the somatosensory and visual inputs have been eliminated. Lastly, condition six involves an unstable platform and unstable visual surround. In this condition the subject must rely primarily on vestibular input alone and suppress a false sense of visually induced movement (Desmond, 2004).

Optimal performance on the SOT requires accurate visual, vestibular, and somatosensory inputs, appropriate sensory integration and an intact musculoskeletal system. A vestibular dysfunction pattern is referred to as a "5, 6" pattern. This means that the patient was unable to maintain postural control in conditions 5 and 6 of the SOT where both the visual and somatosensory cues are absent or distorted and the subject must rely only on vestibular information to maintain balance. Thus, if the subject's vestibular input is compromised, the subject has insufficient information to maintain balance. As the subject undergoes central compensation, the likelihood of displaying a "5, 6" pattern deceases (Fetter et al., 1991). A "visual preference" (3, 6) pattern indicates that the subject makes use of three senses but relies on false visual information and loses balance in the sway-referenced conditions. This pattern does not suggest vestibular dysfunction, but rather is suggestive of abnormal central processing of vestibular and visual information (Nashner, 1993). A "surface dependence" pattern has been suggested when the subject is unable to maintain balance when somatosensory information is distorted (conditions 4, 5 and 6). A "visual dependence" pattern suggests that the subject may be overly reliant on visual information for maintaining balance. When visual information is either removed or distorted, the subject loses balance (conditions 2, 3, 5, and 6). And lastly, an "aphysiologic" pattern suggests that the subject demonstrates better balance on the more difficult conditions than on easier conditions (Desmond, 2004). Additionally, the SOT report includes a comprehensive report that provides the subject's equilibrium score, Sensory Organization Test

Center of Alignment (COG) trace report, COG alignment, strategy analysis, and strategy score. These are all also collectively analyzed to determine a subject's pattern or diagnosis.

The MCT examines reflex actions following unexpected platform translation or rotation. The extent of translations are directly related to the subject's height. The MCT involves recording the subject's response to small, medium, and large brief movements of the support surface. Measurements of response latency and symmetry are compared with established norms. Subjects with vestibular dysfunction typically have responses within the normal range. Prolonged or abnormal latencies or symmetry imply dysfunction in either the sensory or motor portion of the reflex loop and are suggestive of CNS disorders that affect the long-loop pathways from the lower extremities (DiFabio, 1995).

The ADT evaluates the subject's ability to balance on irregular surfaces by suppressing automatic reactions to surface perturbations when they are disruptive to stability. The subject completes five sequences of toes-up movements and five sequences of toes-down movements in different rotations. The role of the ADT is similar to that of the sway-referenced visual surround component of the SOT, in that they both assess the ability to suppress reactions to visual and somatosensory stimuli tending to disrupt balance (Goebel, 2001). Measurements taken during the ADT indicate the adaptation of the motor system, more specifically, adaptation to repeated stimuli (NeuroCom Int., 2000).

The SOT is relatively insensitive in the detection of abnormalities in subjects with vestibular disorders who are well compensated, such as individuals with a unilateral vestibular deafferentation (Nashner, 1998). These individuals, as stated previously, compensate within weeks or months and appear to exhibit scores within normal range. Thus, the Head Shake-Sensory Organization Test (HS-SOT) technique has been developed to try to identify individuals who are symptomatic, but perform within the normal range on the standard SOT. The HS-SOT is an enhancement of the SOT and may be a useful outcome tool for individuals who would otherwise be considered "well compensated", or able to score within functional limits on tests of sensory organization and functional balance. Shaking the head during the SOT increases the sensitivity of the CDP for the specific population of well compensated unilateral patients.

Because the HS-SOT is a relatively new enhancement of traditional sensory organization testing, its use as an outcomes measure has thus far not been documented (Roma, 2004). During the HS-SOT the clinician is able to assess conditions 2 and 5 with the subject conducting horizontal head movement (yaw axis). The subjects stand on the same forceplate platform as the SOT and are asked to close their eyes and rotate their head through an arc of approximately 30 degrees to the right and to the left (shaking their head “no”). Head motion occurs at approximately 1 cycle per second. This procedure is performed for both conditions 2 and 5 of the standard SOT. The HS modification on SOT conditions 2 and 5 can measure postural control in subjects whose head movements provoke symptoms and disrupt balance during stance and ambulation (Roma, 2004). The HS-SOT analysis provides reports in four formats: the numeric report, the comprehensive report, COG trace report, and the SOT raw data report. The two main values that are assessed in all of these reports are the subject's equilibrium score and the subject's COG position. Thus far, the main score assessed or used in preliminary research is the subject's equilibrium score (NeuroCom Int., 2000).

The equilibrium score reflects how much the subject swayed during each trial. The equilibrium score compares the subject's maximum anteriorposterior (AP) sway during each trial to a theoretical sway stability limit of 12.5 degrees. A subject swaying to the limits of stability will receive a very low score and a subject with the highest possible score of 100% indicates that the subject did not sway at all. A score of 0% is automatically assigned to all trials marked as falls. The HS-SOT is more difficult than the standard SOT, and the equilibrium scores of normal subjects are slightly lower. Subjects who perform abnormally on the HS-SOT do so because of two main reasons. First, their stability is reduced under one or both of the two conditions. Second, they maintain stability, bit do so only by moving the head more slowly than the required minimum velocity (NeuroCom Int., 2005).

Certain head movements challenge the subject's system by generating a vestibular stimulus in addition to that generated by the subject's sway. In order for the subject to maintain balance in the absence of alternative visual and somatosensory inputs while moving the head, the brain must differentiate the sway of head-shake stimuli. Degradations in the sensitivity and accuracy of the vestibular receptors can interfere with the process of the signal differentiation and reduce balance during head shaking. Due to the vestibular system being composed of multiple, direction specific sense organs, these degradations may also be axis specific, creating imbalance only when head movements occur about the involved axis (NeuroCom Int., 2005). Thus, if a subject was to shake his or her head horizontally (yaw axis), it would be assumed that the utricle would be of primary stimulation.

Preliminary research which aided the development of the HS-SOT was performed using an 'enhanced' SOT to determine both sensitivity and advantages of a modified protocol for sensory organization testing for individuals who appear to be "well compensated" (Roma, 2004). Shepard et al. (1998), compared the sensitivity of the HS-SOT for horizontal head movement (yaw axis) to the standard SOT for 27 subjects with known vestibular disorders who scored within normal limits on the SOT. Subjects were then compared to 51 normal subjects. Condition 5 scores were significantly different for the vestibular disorders group and the normal subject group when the trials were associated with HS but not when the head was fixed (Shepard et al., 1998). Based on Shepard's work and her own work, Roma in 2004 has suggested that the HS-SOT may identify a vestibular abnormality which previously may have been overlooked. She also stresses how no other studies to date have examined this test as an outcome measure for rehabilitation interventions, and that further testing is needed to validate this test or instrument.

These last two tests described (SVV and HS-SOT) will be used in the current study in order to possibly evaluate utricle function, because there are many tests to evaluate both the SCC and the saccule, but not many that either directly evaluate the utricle or have been validated for clinical use. In the current study the authors hope to further advance the research that has already been gathered with HS-SOT in order to hopefully validate the testing of unilateral utricular dysfunction with the HS-SOT. The investigators believe that the sensitivity and specificity of HS-SOT for detection of instability secondary to vestibular dysfunction will be enhanced by headshaking in the horizontal plane either prior to or during performance of the test due to the introduction of a vestibular stimulus which negatively affects central compensation. With this testing, the authors expect to observe significantly decreased equilibrium scores for subjects with unilateral vestibular deficits as compared to the normal subjects when head shaking either before or during each trial is introduced. It is proposed that by adding the headshaking component to the test it will decompensate the subject's vestibular system and bring out the underlying unilateral vestibular deficit. Also, the investigators believe that the Subjective Visual Vertical (SVV) test results for both groups will parallel HS-SOT results for the detection of patients with vestibular dysfunction. The same relationship will hold true between SVV and routine (best effort) SOT 2 and 5 with no active headshaking.

Methods

Control subjects included a group of 14 Caucasian adults with no prior history of imbalance (12 female, 2 male; age range 22-51 years; mean age 33 years). The experimental group consisted of 2 Caucasian adults with documented unilateral vestibular dysfunction as defined by historical, exam, and laboratory methods (1 female, 1 male; age range 60-67 years; mean age 63 years). One of the unilateral vestibular dysfunction subjects has a diagnosed left sided vestibulopathy, which is most likely vestibular neuritis with post-neuritic benign positional vertigo. The second unilateral vestibular dysfunction subject has a left sided vestibulopathy, which is most likely viral labyrinthitis on top of cervical vertigo. The authors made a substantial effort to recruit a greater number of subjects with unilateral vestibular dysfunction, but were only able to recruit two individuals with a unilateral vestibular dysfunction. Inclusion criteria for the normal subjects were: 1) willingness to undergo repeated CDP trails and rotational studies, 2) no evidence of cognitive dysfunction, 3) no significant musculoskeletal abnormalities, and 4) no motion intolerance. Inclusion criteria for the patients with unilateral vestibular dysfunction included all of the previously stated four inclusion criteria for the normal subjects, and also included written documentation of unilateral loss of vestibular function as documented on physical examination and video-oculography (or VOG). More specifically, the subjects that presented with greater than 50% asymmetry or reduced vestibular response with caloric stimulation during the VOG were considered to be excellent candidates for the unilateral vestibular dysfunction group and were invited to take part in the study. There was one exception to the study in that any subject weighing over 200 pounds was not able to complete the SVV section of the study due to weight limit constraints for the rotational chair. Subjects with unilateral dysfunction were recruited from the patient population seen by the principal investigator of the study, who is employed by a well-established medical institution. Normal subjects were recruited from the surrounding community by word of mouth. The subjects were scheduled in a blinded fashion into the test sessions to avoid bias by the examiner.

Each session consisted of multiple balance trials using Computerized Dynamic Posturography (CDP) and rotational trials using the Subjective Visual Vertical test (SVV). CDP trials were performed in a (NeuroCom International) mechanized platform while wearing a safety harness. Twenty second trials were performed with either Condition 2 (platform stable and eyes closed) or Condition 5 (platform moving in concert with sway of subject and eyes closed) of the Sensory Organizational Test (SOT). These two different conditions were performed with and without active headshaking in the horizontal plane (yaw axis). Thus, the subjects were required to either shake their head, 20 seconds before the trial, shake their head, during the 20 second trial, or not shake their head, at all before or during the trial. The six different CDP trials that were performed in a random order were as follows: 1) Condition 2 with eyes closed and no headshaking, 2) Condition 2 with eyes closed and 20 second headshaking in the horizontal plane before the trial, 3) Condition 2 with eyes closed and headshaking in the horizontal plane during the trial, 4) Condition 5 with eyes closed and no headshaking, 5) Condition 5 with eyes closed and 20 second headshaking in the horizontal plane before the trial, 6) Condition 5 with eyes closed and headshaking in the horizontal plane during the trial. Head motion occurred at approximately 1 cycle per second and each of the six conditions was performed three times in a random fashion. The conditions were performed in a random fashion for each subject due to the documented learning effect that is associated with CDP testing. In CDP testing, there is a very overwhelming learning effect as the subject completes each trial. Basically, the subjects will perform better with each subsequent condition due to their ability to almost predict what is coming and essentially prepare themselves for the condition. In order to account for this learning effect and try to reduce these effects in the results, there was a randomized presentation of each condition for each subject.

Second, the Subjective Visual Vertical test was performed with a vertical axis rotational chair (Micromedical Inc.). The subjects were secured in place with safety straps and headrest and rotated in complete enclosed darkness. The chair was accelerated for 30 seconds up to 300^{0}/s constant velocity centric rotation and maintained for 60 seconds to ensure that the lateral semicircular canal response had ceased (2 trials). Next, the chair was translated 4 cm to the left and was accelerated for 30 seconds up to 300^{0}/s eccentric rotation and maintained for 60 seconds to ensure that the semicircular canal response had ceased (2 trials). Since the chair is being translated to the left in this trial, this implies that the right utricle becomes aligned with the axis of rotation and the left utricle is exposed to a centrifugal acceleration. Thus, for this trial the left ear is considered the test ear. Finally, the chair was translated 4 cm to the right and was accelerated for 30 seconds up to 300^0/s eccentric rotation and maintained for 60 seconds to ensure that the semicircular canal response had ceased (2 trials). In this trial the chair is being translated to the right which implies that the left utricle becomes aligned with the axis of rotation and the right utricle is exposed to a centrifugal acceleration. Thus, for this trial the right ear is considered the test ear. During each of the above trials, the subject was asked to align a light bar placed in front of him or her in the upright position using a joystick to maneuver the bar, once from the bar starting all the way to the right and once from the bar starting all the way to the left. Static and dynamic measures were taken for each trial where the subject was able to position the light bar in the static position and then again during constant rotation. Static measurements were taken when the patient was not moving. This measurement was evaluated prior to each dynamic measurement that was taken during the 300^0/s constant velocity measurement. The difference between each static and dynamic measurement for each trial was considered the "change in tilt" for that trial.

Two measurements were taken for the CDP trials. The first measurement taken was the peak-to peak anterior-posterior sway amplitude during each 20 second trial. The second was the Fourier analysis of sway frequency data from each trial. Therefore, the resulting score from these measures that is obtained is the equilibrium score. For the SVV trials, two basic measurements were taken for each trial and then repeated with the light bar starting from the opposite direction of the previous measures for that trial. The first two were a static and a dynamic measurement of degree tilt or vertical alignment during centric rotation. The second two were a static and a dynamic measurement of degree tilt or vertical alignment during eccentric rotation where the left utricle was off axis. The third and final two measurements were a static and dynamic measurement of degree tilt or vertical alignment during eccentric rotation where the right utricle was off axis. These two measures (static and dynamic) obtained for each trial where then added together to obtain a final score or degree tilt for that trial.

The investigators have proposed two expected outcomes from these methods. The first is that the peak-to-peak sway amplitude and/or sway frequency will be increased with headshaking either before or during CDP trials. Thus, the subject's equilibrium score should decrease with the introduction of headshaking. The second outcome the authors hope to gain from this study is that the sensitivity of horizontal headshake CDP tests will be similar to SVV for detection of unilateral dysfunction.

Results

It is important to note that, due to the inability to recruit more than two individuals for the experimental group (unilateral vestibular deficit group), the authors were unable to complete any statistical tests that warrant any statistically significant results between the control and experimental groups. The authors did however, examine and report the results obtained for both groups in a descriptive manner using mean scores and percentage of falls per each trial or condition. In addition, the authors provide case studies along with the testing results for the two unilateral vestibular deficit individuals to better analyze their results according to the hypotheses.

The two subjects that were documented to have unilateral vestibular dysfunction were labeled as AB and CD. Subject AB is a 67 year old female that first presented with occasional tinnitus, severe vertigo, nausea, vomiting, and a high frequency moderate to severe hearing loss bilaterally. Her physical examination revealed a blood pressure of 164/90. Cranial nerves, upon examination were found to be symmetric and intact. No spontaneous, gaze, positional, or Hallpike-induced nystagmus was noted and the cerebellar and Romberg testing was within normal limits. However, she did have a very prominent right beating post-headshake nystagmus and a left headthrust sign, implying a left labyrinthine horizontal canal dysfunction. An MRI was found to be negative. Her CDP results were essentially within normal limits; however, her VOG results revealed a 100% left reduced vestibular response, absence of response to ice water stimulation in the left ear, and 3 deg/s rightward beating spontaneous nystagmus (without fixation) that increased to 6 deg/s with post-headshake. Her rotation chair testing revealed decreased low frequency VOR gain with phase lead and decreased time constants. All of the test results combined suggest significant asymmetry in the peripheral labyrinthine input with the left side being weaker than the right. She was evaluated by two separate physicians and one of the physicians attributed her symptoms and test results to be from viral labyrinthitis on top of cervical vertigo, while the other physician’s impression was broader, possibly indicative of a partially compensated left-sided vestibulopathy. It was recommended she receive rehabilitation therapy to improve her instability and, Meclizine was prescribed for her dizziness. She has stated that her symptoms have decreased, but she is still "desperate for a cure".

Subject CD is a 60 year old male that first presented with nausea and vomiting, but no vertigo. However, severe spinning started the next day and lasted for three to four days. He noticed no change in his hearing, tinnitus, or ear pressure. Now, he is left with some imbalance and difficulty in dynamic environments, such as in a car or in a boat, and he also has some dizziness whenever he moves his head to the left. He also complains of rolling over in bed to the left because this makes him dizzy. His audiologic evaluation revealed a mild to moderate high frequency hearing loss bilaterally. Upon physical exam, his blood pressure was 142/88, his Weber and Rinne tuning fork tests were within normal limits, and his cranial nerve exam was symmetric, except for cranial nerve VIII as previously stated. He did, however, demonstrate a clear left headthrust sign and right beating post-headshake nystagmus. Based on these findings he was thought to have clear evidence of a left-sided vestibulopathy that is most likely vestibular neuritis. Further testing revealed a borderline reduced SOT 2 and isolated fall on SOT 6 and prolonged latencies during Motor Control Testing with both forward and backward translations for the CDP test battery. His rotational chair testing showed decreased gain and increased phase, decreased time constant, and a leftward asymmetry, all consistent with left-sided peripheral vestibular loss. His VOG showed a 64% left reduced vestibular response, a total eye speed of 28 deg/s, and a torsional 15 deg/s rightward beating and 17 deg/s upward beating positioning nystagmus with head hanging left, consistent with BPPV emanating from the left side. Based on all of the test findings, he was diagnosed with left-sided vestibular neuritis and post-neuritic benign paroxysmal positional vertigo. Epley repositioning maneuver was performed and he also was advised to start a rehabilitation exercise program. After six months, he no longer has vertigo, but still has some occasional imbalance and continues in his rehabilitation program.

Figures 1 and 2 represent experimental group subjects' mean scores for each condition assessed in the CDP trials. The minimum and maximum scores that can be obtained on these conditions are 0%-100%, with 100% representing no sway. Subject AB was able to perform fairly well for the conditions where the platform is stable [SOT 2 (no headshake), SOT 2 (headshake prior), and SOT 2 (headshake during)]. When subject AB completed the conditions

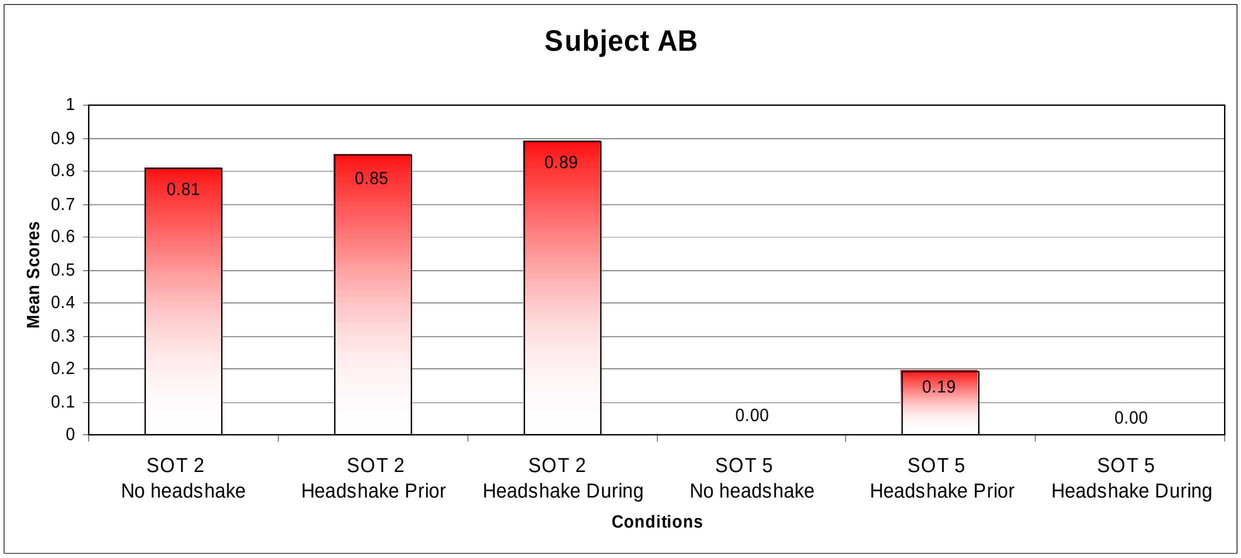

Figure 1 Subject AB's mean scores for each condition of CDP

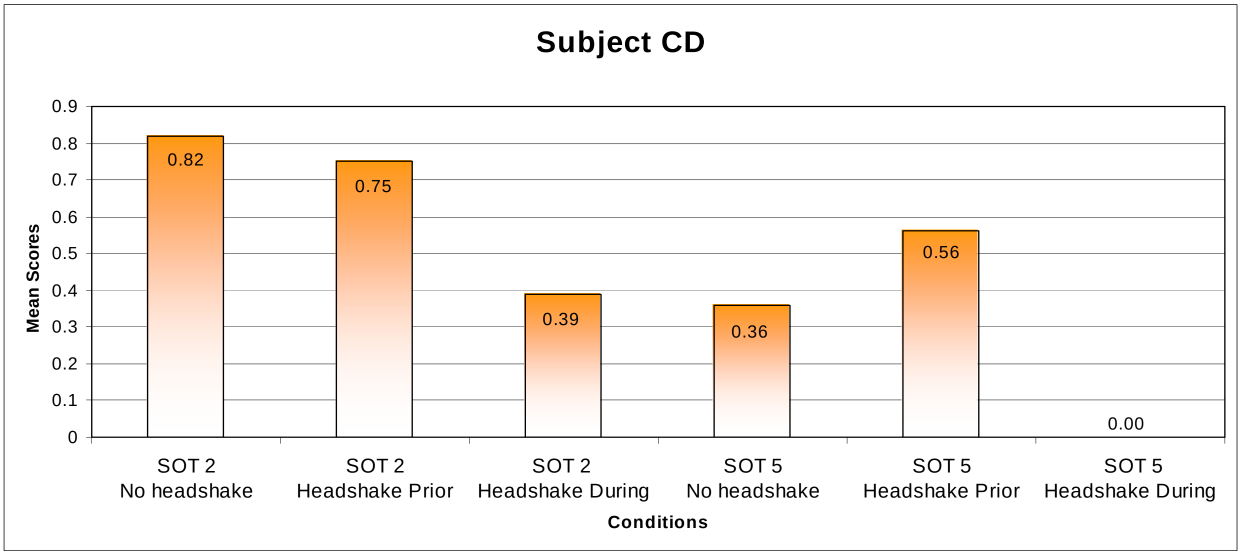

Figure 2 Subject CD's mean scores for each condition in CDP

where the platform was unstable, regardless of headshake, the subject experienced increased difficulty. In contrast, subject CD had increased difficulty when performing any condition that involved headshaking and also in one condition that had no headshaking. He performed fairly well for the SOT 2 (no headshake) condition and performed considerably poorer for all subsequent conditions. Figure 3 represents the side by side comparison of subject AB's and subject CD's mean scores for all conditions of the CDP. When looking at both subject's scores together, one may notice that the subjects performed similarly for only the SOT 2 (no headshake) condition and the SOT 2 (headshake prior) condition. All of their other scores for each condition were highly variable and inconsistent between the two.

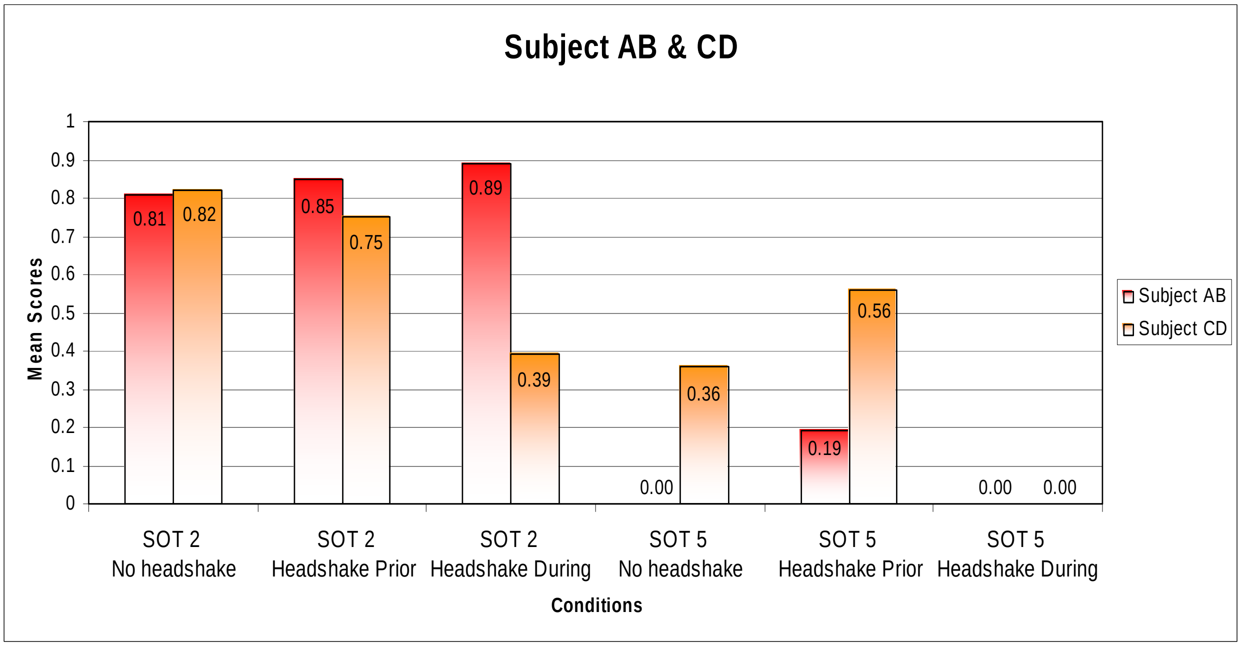

Figure 3 Subjects AB and CD's mean scores for each condition of CDP

Since the CDP test battery has shown a high correlation between increased performance and subsequent trials 1-3 within each condition, it is well established that there is a learning effect as the subject completes each trial within each condition. However, even though performance increases slightly within the trials of each condition due to the learning effect, the performance decreases between conditions as the conditions become more difficult. Thus, in order to eliminate or reduce this effect we included three trials for each condition in a highly randomized fashion for each subject. Since each subject completed three trials randomly for each condition, the authors derived a mean score for the three conditions that better evaluated the true score for that condition for that particular subject. Figures 4 through 9 illustrate each of

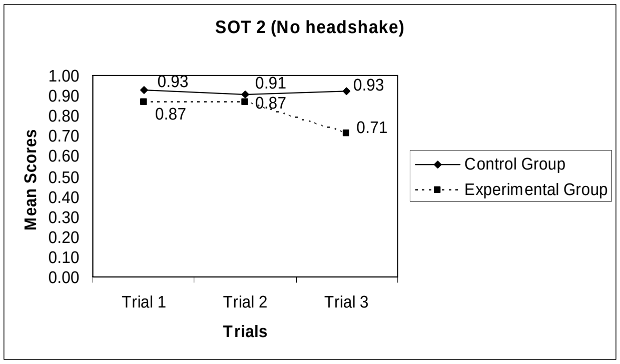

Figure 4 Mean Scores of SOT 2 (No Headshake) for three separate trials

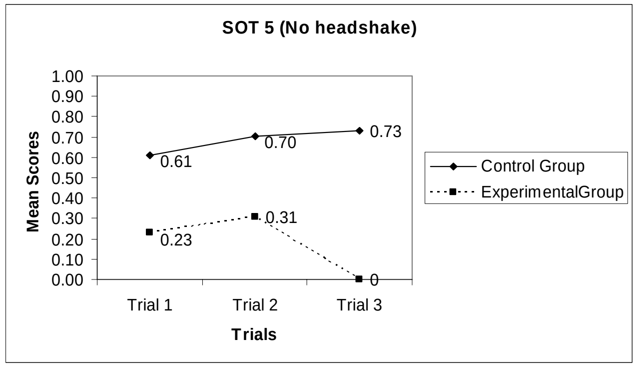

Figure 7 Mean Scores of SOT 5 (No Headshake) for three separate trials

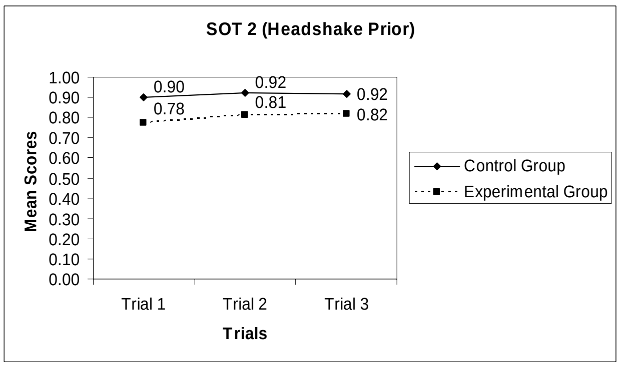

Figure 5 Mean Scores of SOT 2 (Headshake Prior) for three separate trials

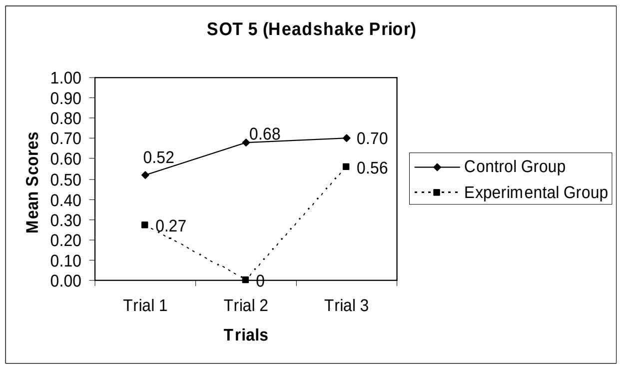

Figure 8 Mean Scores of SOT 5 (Headshake Prior) for three separate trials

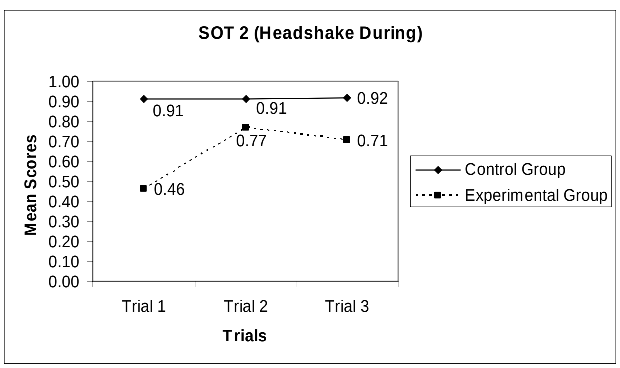

Figure 6 Mean Scores of SOT 2 (Headshake During) for three separate trials

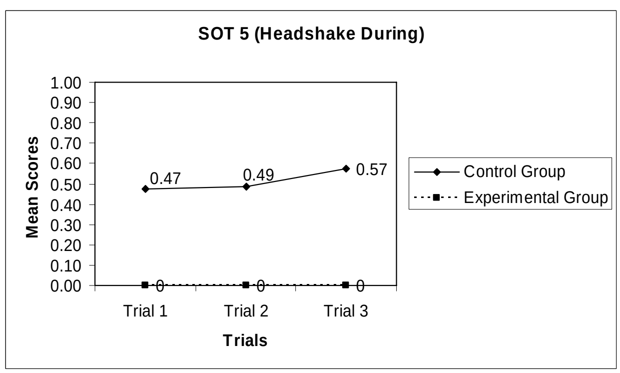

Figure 9 Mean Scores of SOT 5 (Headshake During) for three separate trials

three trials for the six conditions. The scores shown are a compilation of the mean scores for each group for that trial in that condition. In Figures 7 through 9 there are values of 0.00 which are due to falls in that trial or condition. Only the subjects in the experimental group obtained mean scores of 0.00 for certain trials, while the subjects in the control group did not obtain a mean score of 0.00 for any trial of any condition.

After the authors evaluated mean scores for each individual trial in each condition, they then averaged these to attain a total or combined mean score for each condition for each group. Figure 10 represents the combined mean scores for each condition for the control group. The minimum and maximum scores that can be obtained on these conditions are 0.0-1.0. The average mean scores for each condition for the control group varied between .92 and .35. The control group overall performed better than the experimental group (unilateral deficit group) on each condition. Figure 11 represents the combined mean scores for each condition for the experimental group. Again, the minimum and maximum scores that can be obtained on these conditions are 0.0-1.0. The average mean scores for each condition for the experimental group varied between .81 and 0.00. With further review, these figures show that the control group performed better than the experimental group in all of the conditions assessed. This can be clearly seen in Figure 12 which illustrates the side by side comparisons of the mean scores of each condition for both groups. The control group performed only slightly better than the experimental group for the SOT 2 (no headshake) condition and the SOT 2 (headshake prior) condition. The control group performed much better than the experimental group for the SOT 5 conditions (with or without headshaking). However, it should be re-stated that since there were only two subjects that made up the experimental group (unilateral deficit group), there were not enough subjects to demonstrate any statistically significant differences between the groups.

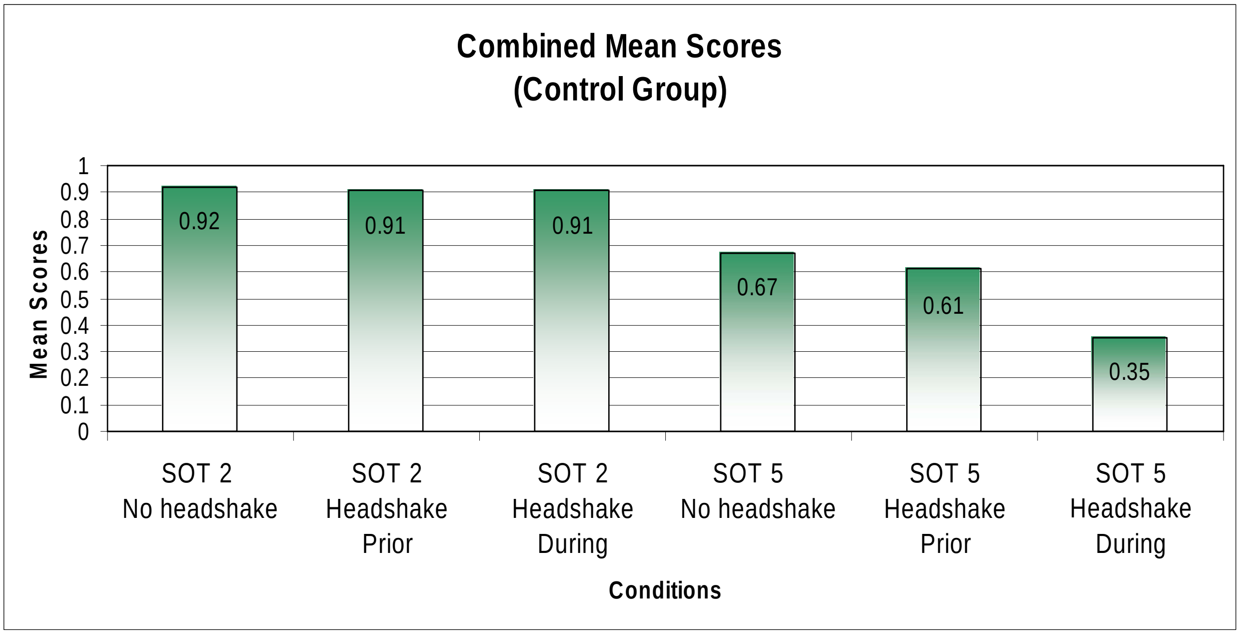

Figure 10 Combined Mean Scores for the Control Group for each condition (all three trials are included for each condition)

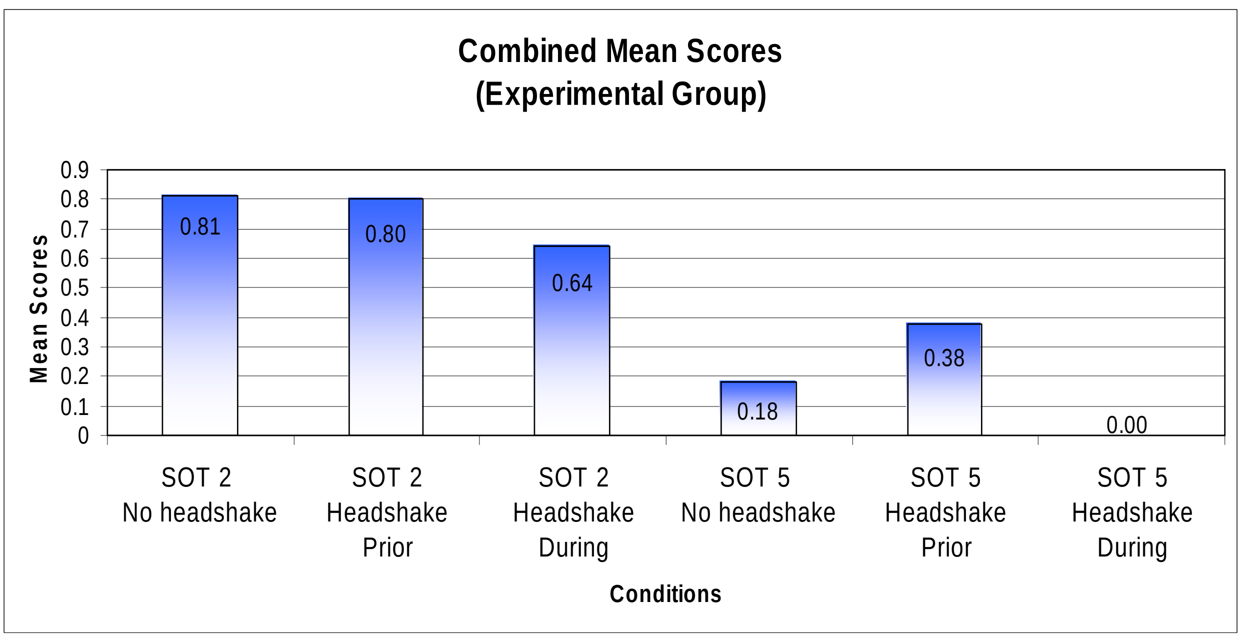

Figure 11 Combined Mean Scores for the Experimental Group for each condition (all three trials are included for each condition)

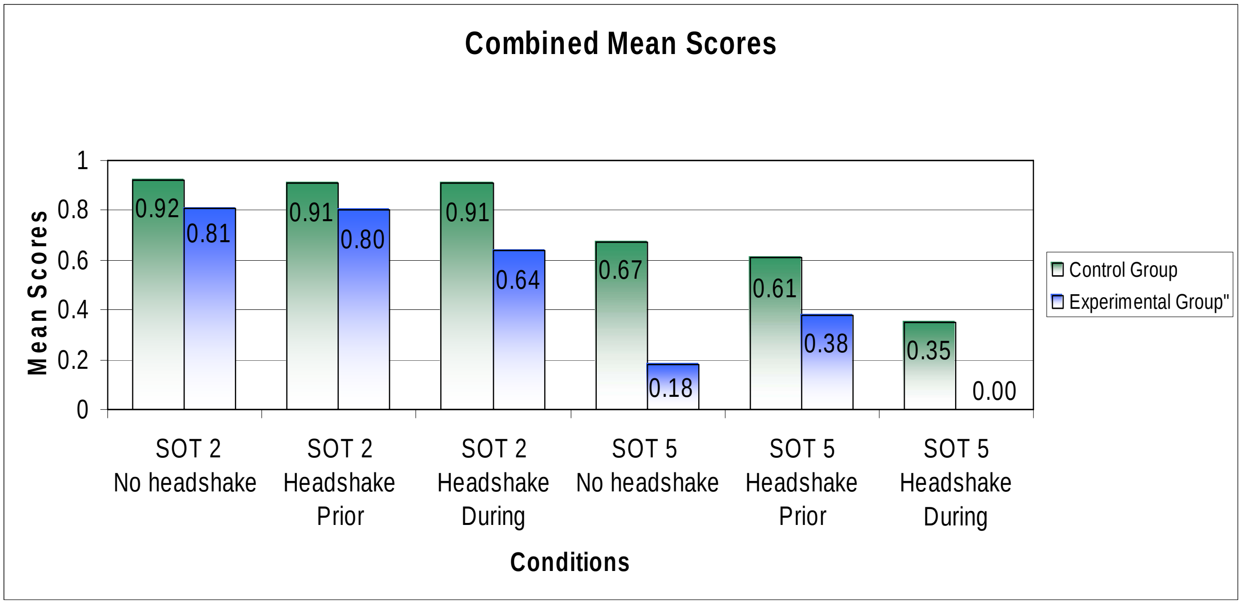

Figure 12 Combined Mean Scores for the control and experimental groups for each condition (all three trials are included for each condition)

Lastly, the investigators then evaluated the percentage of falls per each condition for each group. This calculation was made because there were an increased number of falls for the experimental group versus the control group. Figure 13 illustrates the percentage of falls per condition for the control group. A 0% indicates the subject fell 0% of the time, and a 100% indicates the subject fell 100% of the time in that certain condition. Not one subject in the control group fell on SOT 2 conditions, regardless of headshaking or non-headshaking. When the unstable platform was introduced, during all SOT 5 conditions, members of the control group did demonstrate some falls. It can be observed that the control group subjects fell an increased percent of the time as the conditions became increasingly more challenging.

It did not seem to be the same relationship for the experimental group (unilateral deficit group). Figure 14 illustrates the percentage of falls per condition for the experimental group. Again, a 0% indicates the subjects fell 0% of the time, and a 100% indicates the subjects fell

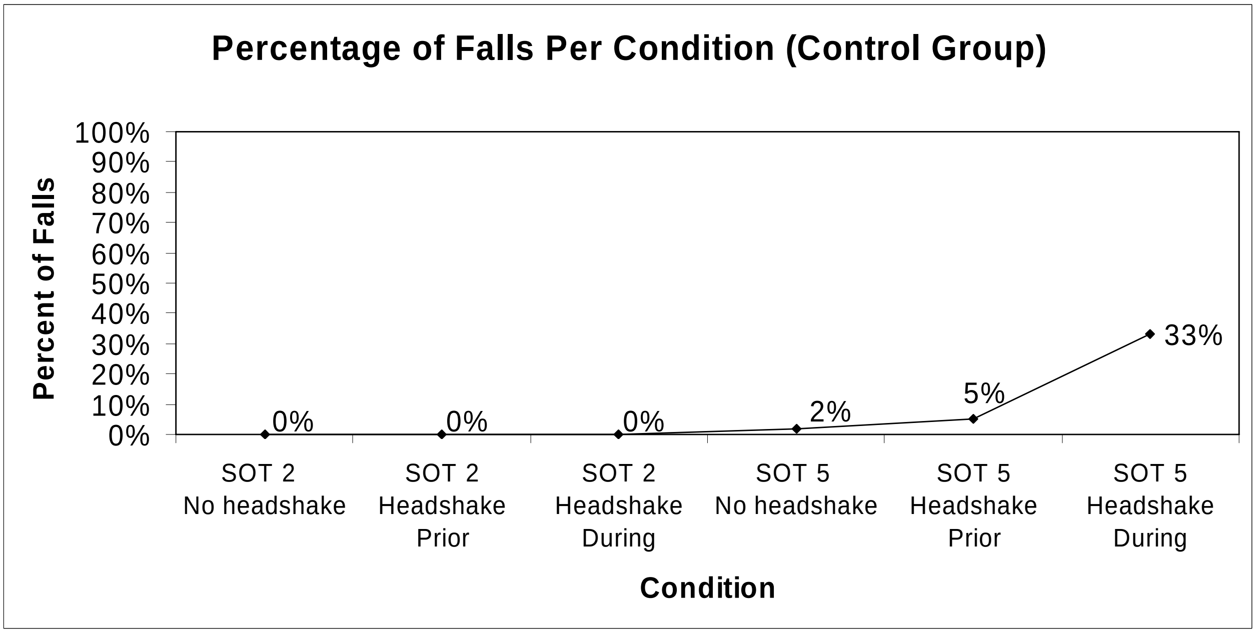

Figure 13 Percentage of falls for each condition for the control group

100% of the time in that certain condition. The two subjects in the experimental group did not fall on either the SOT 2 (no headshake) condition or the SOT 2 (headshake prior) condition. However, the experimental group fell more with the SOT 5 conditions, where the platform is unstable as opposed to the SOT 2 conditions where the platform is stable regardless of whether headshaking was introduced. One quite interesting observation was noticed with the experimental group, in that these subjects fell 100% of the time during the SOT 5 (headshake during) condition. The linear relationship that was shown for the control group, where the percentage of falls increased as the conditions became more challenging, was not evident with the experimental group. These comparisons between groups can be more easily identified when reviewing Figure 15, which illustrates the percentage of falls per condition for both the control and experimental groups.

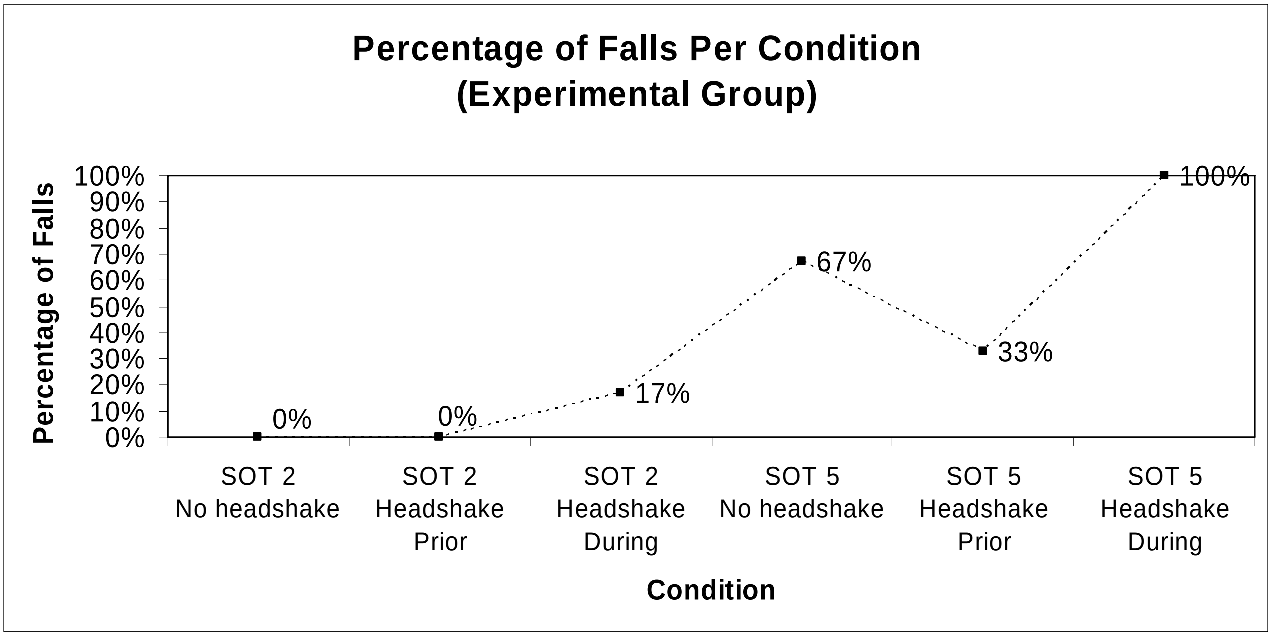

Figure 14 Percentage of falls for each condition for the experimental group

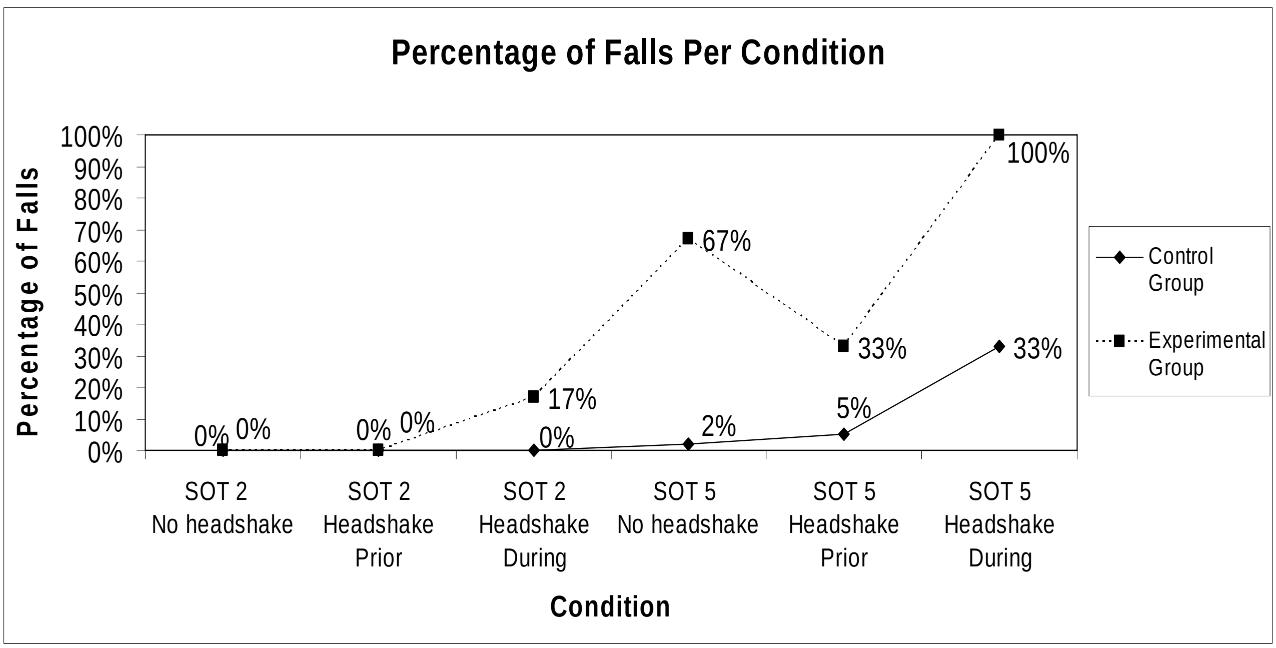

Figure 15 Percentage of falls for each condition for both the control and experimental groups

Finally, the SVV results could only be obtained for the control group and not for the experimental group (unilateral deficit group). It was not possible to complete the SVV testing with the two experimental group subjects due to weight constraints; thus the investigators were only able to obtain data regarding the SVV testing for the control group. After reviewing the data and results of the control group with SVV testing, it was concluded that the results were very highly variable and were not able to provide information regarding the usefulness of the degree of tilt for assessment of a unilateral vestibular deficit. This is most likely due to the axis of rotation not passing precisely through the utricle. This may occur since there are very different interutricular distances between subjects and the 4 cm is an average. Thus, in order to better utilize this promising tool for the identification of unilateral vestibular deficit individuals, a method to determine each individual's interutricular distance should be developed. Thus, the authors were unable to compare the data collected from the SVV testing with the data collected from the CDP (headshake) testing.

Discussion

In reviewing the data and examining the relationships between groups, it should be re-stated that there are no statistically significant differences between the groups due to a very small sample size for the experimental group (unilateral deficit group). However, there are still some very noticeable and distinctive differences between the two groups. Through examining the raw scores and mean scores, the most significant difference that was observed was the performance difference between the groups for all of the SOT 5 conditions. There were also other small differences between the groups and subjects that should be noted.

When viewing the performance of each subject in the experimental group, the pattern of increased difficulty can be seen as the conditions become more challenging. Their scores on the CDP conditions for this study appeared much poorer than their scores on the standard CDP conditions. This can be attributed to either the fact that the CDP conditions for this study were inherently more difficult than those conditions for the standard CDP, or because the addition of headshaking to the CDP conditions brought out the unilateral deficit that was otherwise compensated. This latter theory can not be accurately assessed, due to the small sample size that was studied for the experimental group. In addition, the control group also showed a pattern of decreased performance as the conditions became more challenging, but they consistently performed better than the experimental group in every condition assessed. Thus, the pattern does suggest that the authors' hypothesis could hold true, but it may be statistically significant and better demonstrated if the experimental group had a larger number of subjects.

When examining the separate trials for each condition, there is great variability between the trials for the same condition. This may be attributed to the learning effect that occurs when completing the CDP conditions as stated previously. It has been shown through these trials that the control group appears to perform better than the experimental group in every condition or separate trial. The difference between the performances of the two groups becomes larger as the conditions become more challenging, which appears to be a recurring theme or pattern in the study. Since the experimental group subjects performed essentially within normal limits on the standard CDP test battery, these subjects should be able to score very similar to the control subjects due to their compensation. But, as one can observe in the repeated trials for each condition, the experimental (unilateral deficit) subjects are not able to score similar to the control group during nine out of the nine trials for the SOT 5 conditions. This pattern may support the theory that the headshaking would cause the subjects to be de-compensated and score much differently than the control subjects.

Next, the mean scores for each condition for both the control group and the experimental group were examined. For both groups, the SOT 2 (no headshake) and the SOT 2 (headshake prior) conditions were performed with fairly good accuracy. But, for SOT 2 (headshake during), the control group was able to perform with fairly good accuracy, while the experimental group had slightly increased difficulty in performing this certain condition. For all of the SOT 5 conditions, both the control and experimental groups scored much more poorly than for the SOT 2 conditions, but there was still a large difference between the control group's and the experimental group's scores. The difference between scores on the SOT 5 conditions were much different in that the control group's scores were at least double that of the experimental group's scores in every SOT 5 condition. This would likely suggest that when the condition becomes more challenging with the introduction of headshaking, the subject who has a unilateral deficit would essentially no longer be compensated and have increased difficulty performing the conditions as compared to normal subjects.

When comparing the two groups and the mean scores on the different conditions, the most observable difference is for condition SOT 5 (headshake during). Every time either of the two unilateral deficit subjects attempted to complete this condition, they were unable to maintain stability and fell. In addition, some of the control group subjects were also unable to maintain balance for this condition, but not as consistently as the unilateral deficit subjects (experimental group). It is also interesting that neither of the two unilateral deficit subjects scored 0.00 for the standard SOT 5 condition for CDP. When headshaking was introduced to the SOT 5 condition however, both unilateral deficit subjects fell every time. This is a very important piece of data in that this could be attributed to the idea that the headshaking is essentially de-compensating the vestibular system. But, this can not be accurately deemed the cause, due to the small sample size that was obtained for the experimental group (unilateral deficit group).

Lastly, the authors reviewed the data regarding the percentage of falls per each condition. The control group managed to not fall for any of the SOT 2 conditions and obtained very small percentages of falling for the SOT 5 (no headshake) condition and the SOT 5 (headshake prior) condition. However, the control group did obtain a percentage of falling on the SOT 5 (headshake during) condition of 33%. This may be considered as minimal falls for this condition for this group, but it is a fairly larger percentage than any of the other conditions' percentages. In contrast, the experimental group's percentages of falls per each condition were considerably larger than the control group. The experimental group did, however obtain exactly the same percentage of falls as the control group for the SOT 2 (no headshake) condition and the SOT 2 (headshake prior) condition. The experimental group did not fall on either of these two conditions. But, the experimental group's percentage of falls for the SOT 2 (headshake during), SOT 5 (no headshake), SOT 5 (headshake prior), and SOT 5 (headshake during) conditions were observably larger than the control group's percentages and were considerably large percentages. The unilateral deficit subjects (experimental group) fell 100% of the time for condition SOT 5 (headshake during), as compared to the normal subjects falling only 33% of the time for the same condition. Another interesting piece of data is that the experimental group fell less with shaking their heads prior to the condition SOT 5 than with no headshake for the same SOT 5 condition.

Conclusion

When looking at the considerably different mean scores and percentages of falls between the two groups for all conditions assessed, one could propose that the theory of the introduction of headshaking to the CDP protocol could bring out an otherwise compensated unilateral vestibular loss. In addition, the differences between the standard CDP results and the CDP with headshaking results for the unilateral deficit subjects were very different. But, we can not attribute these results to the introduction of headshaking to the test battery alone. There was not an adequate sample size for the experimental group; thus, none of the results can be statistically significant, but rather only viewed as very consistent patterns.

It was suggested that the introduction of headshake in the horizontal plane to the CDP conditions 2 and 5 would de-compensate the subject's system in order to bring out an underlying compensated unilateral vestibular loss. It is believed that the current study was able to show strong patterns and data regarding the addition of headshake to the CDP as a viable option to try to identify individuals with compensated vestibular systems. However, it is recommended that the research in this area be elaborated upon. The investigators recommend more studies like this one, with an adequate sample size in order to determine if this addition really is statistically significant. Secondly, the authors recommend that the SVV testing be further investigated and studied in order to try to develop norms for this test battery for better identification of individuals with unilateral vestibular loss. Lastly, this study would support further investigation of the usefulness of headshaking during CDP to quantify impairment and assess the efficacy of vestibular rehabilitation. This would be the ultimate goal.

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