Home-based Computer Gaming in Vestibular Rehabilitation: Effects on Gaze and Balance Impairment

by

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ABSTRACT:

When vestibular sense organs suffer damage functional problems arise such as imbalance and falls as well as difficulty with gaze control, resulting in blurred vision, dizziness and feelings of disorientation. A novel computer-based rehabilitation program has been developed. Using the Gyration ™ motion-sense mouse, attached to a headband, to control computer applications and games, the participants were able to interact with targets in computer games through head motion, allowing different gaze exercises to be carried out. Balance exercises can be incorporated simultaneously and progressively into the rehabilitation program. The main findings of this study revealed that using head rotation to interact with computer games coupled with demanding balance conditions resulted in substantial improvements in gaze control, standing balance and walking performance. These observations provide support that a low-cost home computer-gaming rehabilitation program is well suited to train gaze control through active and passive head motion and to concomitantly train standing balance.

GLOSSARY of TERMS

AP	anterior-posterior
CL	closed loop (with respect to head)
CM (cm)	centimeters
CNS	central nervous system
COD	coefficient of determination
COP	centre of foot pressure
CVA	cerebral vascular accident
DGI	Dynamic Gait Index
DHI	Dizziness Handicap Inventory
DVA	Dynamic Visual Acuity
EC	eyes closed
ENG	electronystagmography
EO	eyes open
F	fixed surface
FFT	Fast Fourier Transform
FSA	force sensor array
HF	high frequency
HP	home program
HZ (Hz)	hertz
LF	low frequency
mCTSIB	modified Clinical Test of Sensory Interaction in Balance
ML	medial-lateral
OKN	Opto-Kinetic Nystagmus
OKR	Opto-Kinetic Reflex
OL	open loop (with respect to head)
PF	primary frequency
PSD	power spectrum density
PVD	peripheral vestibular disorder
RMS	root mean square
S	sponge surface
SCC	Semi Circular Canals
SEM	standard error mean
TPL	total path length
VOR	Vestibulo-Ocular Reflex
VR	vestibular Rehabilitation
W	treadmill walking

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DEDICATION:

I dedicate this manuscript to those who suffer the symptoms of vestibular disorders and have sought help from medical professionals who understand and continue to seek new and innovative ways to help you adapt. Thank you to those who participated in this study.

To the physical therapists that are and will be treating those with vestibular disorders, I hope this manuscript will impart some level of excitement and wonder and encourage you to think outside the box.

To those who assisted in my education: my advisor, my advisory committee, my fellow graduate students and past and present instructors. Thank you each of you for your encouragement and the times of teaching, especially MatLab and SPSS.

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1. INTRODUCTION:

Accounts of dizziness and vertigo can be traced back to ancient Greece and Egypt. Prior to the 1800's, dizziness and vertigo were typically grouped together with epileptic seizures and strokes into a class of disorders called "apoplectiform cerebral congestion". Treatment consisted of bleeding, leeching, cupping and purging. Prosper Meniere, in 1861, recognized the association between hearing loss and vertigo and the inner ear was recognized as the source of the symptom. This opened the door to research.

The incidence of vestibular disorders is difficult to determine as symptoms mimic those of other disorders/diseases therefore data collection is based on physician reports of symptoms of dizziness or falling and not diagnosis of peripheral vestibular disorder.

Reports by national funders and tracking agencies (i.e. Center for Disease Control) are disease-based and not symptom-based, thus research into the economic impact of health conditions is often based on specific diseases rather than symptoms. However, research does show that dizziness and vertigo are two of the most common complaints seen in the primary care setting. [107]

Looking at the economic impact of vertigo and chronic imbalance, the statistics in the United States are immense. Statistics from 2001 to 2004 estimated that 69 million

Americans (35.4%) aged 40 and older suffered from a vestibular dysfunction using vertigo and imbalance as criteria.[71] In a report from the National Institute on Deafness and Other Communication Disorders (2006 – 2008), the annual cost for medical assistance for those with balance disorders exceeded $1 billion in the USA.[108] While these statistics are concerning, it is hypothesized they may be underestimates due to the fact dizziness and vertigo are symptoms and not diseases.

2. ANATOMY and PHYSIOLOGY:

The vestibular system in humans has three important functions:

1. Gaze control - eye-head coordination to maintain image stability or prevent visual blurring.
2. Perception of body movement and orientation relative to gravity. (i.e. vertical)
3. Maintenance of posture and stability. (i.e. balance)

Spatial information provided by the vestibular sense organs, along with information from the visual and somatosensory systems, is integrated by the central nervous system (CNS) to ensure adequate function for gaze, orientation and balance.

Peripheral Vestibular Apparatus:

*For a detailed description of the peripheral vestibular apparatus see "Principles of Neural Science" 4th Ed., Kandel ER, Schwartz, JH, Jessell, TM; McGraw-Hill, New York, 2000; 782-852.[69] The following is a summary of this material.

The peripheral vestibular apparatus lies within the petrous portion of the temporal bone (bony labyrinth). The membranous labyrinth lies within the bony labyrinth and contains the cochlea (hearing) and the vestibular sense organs (equilibrium). The membranous labyrinth is filled with endolymph and it is surrounded by perilymph.

The vestibular sense organs are comprised of a set of three semicircular canals (SCC) – anterior, posterior and horizontal – and two otoliths – the utricle and saccule. Each of these are specialized sensors that detect:

1. angular (SCC) and linear (otoliths) acceleration, which are essential for eye-head coordination, gaze stability and self-motion.
2. location of gravity (utricle) - thus providing absolute vertical reference (with respect to gravity) and body orientation in space

The SCC are transducers of angular acceleration and detect head rotation in three planes. The utricles and saccules are transducers of linear acceleration, detecting linear head motion and head orientation with respect to gravity. Injury to this important system produces a range of symptoms that include imbalance and postural instability, difficulty with gaze control due to nystagmus and problems with eye-head coordination, as well as dizziness, vertigo, oscillopsia, nausea and motion sensitivity. [41, 145]

Within each sense organ is a cluster of hair cells that convert mechanical stimuli into receptor potentials. Mechanical stimuli consists of movement of the endolymph against the hair cells, such as occurs with head rotation, head tilt, body rotation, or locomotion. The deflection of the cluster of hair cells toward the kinocilium (or largest hair cell) results in depolarization and release of neurotransmitters. Deflection away from the kinocilium results in hyperpolarization of the hair cell and a reduction in release of neurotransmitters.

The clusters of hair cells within the utricle and saccule are attached to the macule, an area of dense calcified otolithic membrane, and respond to linear acceleration and gravity. At the top to the hair cell clusters is a gelatinous layer called the otolithic membrane that has minute calcium carbonate crystals imbedded in it called otoconia. When linear head movement occurs, this otolithic membrane lags behind due to the otoconia within it, thus causing the hair cell clusters to bend. The mechanical stimulus releases a neurotransmitter and information is relayed to the vestibular nuclei in the pons and medulla where it is integrated with information from the somatosensory system, cerebellum and visual system. This information is then projected to many higher cortical areas such as ocular motor nuclei, motor cortex, vestibular region of the cerebellum and the thalamus. Some hair cells are more sensitive to vertical acceleration or head position relative to gravity. These specialized motion receptors give an absolute frame of reference with respect to gravity and provide important information for orientation of the head and body to vertical.

Similar to the utricle and saccule, the SCC also detect acceleration due to relative movement of the endolymph. The SCC are oriented at right angles to each other, creating a three-axis system and each detect head angular acceleration about its own axis of rotation. The SCC work in pairs based on the axis of rotation – left anterior and right posterior; left posterior and right anterior; and horizontal canals. The SCC are an enclosed tube however at the bottom of each tube is a gelatinous diaphragm called the cupula that extends across the canal at the widest region (ampulla). There is an area of the cupula not firmly anchored to the canal and it is here that bundles of hair cells protrude into the cupula. Angular acceleration of the head causes relative movement of the endolymph within each canal in the direction opposite to that of the head movement. This causes a deflection of the cupula, bending the hair cells and results in neuronal firing. Similar to the utricle and saccule, the magnitude of hyper- or depolarization depends upon the amplitude of the mechanostimulation.

The axon terminals of the peripheral afferent nerve fibres (Scarpa's Ganglia), which synapse on the hair cells, comprise the vestibular component of CN VIII. The vestibular portion of CN VIII has two divisions;

1. Superior division, which innervates the cristae of the anterior and horizontal semicircular canals, the macule of the utricle and the antero-superior part of the macule of the saccule.
2. Inferior division, which innervates the crista of the posterior semicircular canal and the majority of the macule of the saccule.

Central Vestibular Pathways:

The vestibular nerve enters the brainstem at the medulla and synapses with vestibular nuclei (VN). Additionally, some central terminals of ganglion cells directly synapse on cells in the cerebellum. There are four vestibular nuclei.

1. Superior VN receives input mainly from the SCC and some from the otoliths. Fibers from the SVN project to the ocular motoneurons and are involved in VOR and eye-head motor coordination.
2. Medial VN (MVN) also receives most of its input from the SCC and some from the otolith organs. It also projects to the ocular motoneurons.

3. Lateral VN (also referred to as Deiter's Nucleus) receives mainly otolith and some SCC input. Its main efferent projection is to the lateral vestibulospinal tract for control of upper and lower limb muscles.
4. Inferior VN (descending nucleus) receives input from both otoliths and SCC and its output is to the medial vestibulospinal tract for control of neck and axial muscles.

The cells of the VN are both relay cells and processing cells. As processing cells, they receive convergent input from the visual system (specifically the superior colliculus), cerebellum and branches of the ascending somatosensory dorsal column tract.

Through the cells of the vestibular nuclei, the SCC, utricle and the saccule have neurological connections to three pairs of ocular eye muscles.

1. superior and inferior rectus
2. medial and lateral rectus
3. superior and inferior oblique.

The anterior SCC excitatory neurons project to the ipsilateral superior rectus and contralateral inferior oblique muscles. The inhibitory neurons of the anterior SCC project to the contralateral superior oblique and ipsilateral inferior rectus muscles. The posterior

SCC vestibular neurons project to the opposite muscles. The horizontal SCC neurons project to the medial and lateral rectus muscles.

2.1 Gaze Control:

*For a detailed description of the peripheral vestibular apparatus see: 1. *Walsh and Hoyt's Clinical Neuro-Ophthalmology* 4th Ed. Vol 2, Williams & Wilkings, Baltimore, 1985; 608-651.[162] 2. *Principles of Neural Science* 4th Ed., Kandel ER, Schwartz, JH, Jessell, TM; McGraw-Hill, New York, 2000; 782-852.[68] The following is a summary of this material.

Vision is a complex system that relays tremendous amounts of information regarding images in our environment and guides our visual attention. Normal visual processing requires that the primary visual target of interest be fixated on the fovea of the retina; a small area encompassing only 1% of the retina by volume, but occupying 50% of the visual cortex and is responsible for high visual acuity. Gaze control (or gaze stability) refers the coordination of eye and head movement to maintain the primary visual target on the fovea of the retina (foveation) and the means to prevent excessive retinal image slip – or movement of the image off the fovea - during head/body movement, visual target movement or visual background motion. Gaze stability is critical for clear vision as excessive retinal image slip results in blurred vision and dizziness. Foveation is achieved (and maintained) by a combination of:

1. Two voluntary processes - saccadic eye movement and smooth pursuit systems
2. Two reflex mechanisms -Vestibular-Ocular Reflex (VOR) and Optokinetic Reflex (OKR).

Saccades are very rapid, voluntary eye movements (up to 900°/second) that reposition the eye onto the target so the image is stabilized on the fovea and therefore brought into focus. Retinal image slip (during pursuit), sounds, tactile stimulation and verbal commands are capable of initiating saccadic eye movements.

Smooth pursuit eye movements are also voluntary and are independent of head movement. The smooth pursuit system assists in maintaining the image of a moving target on the fovea and is important in visual acuity. The maximum velocity for smooth pursuit is 100°/second (range: 10° - 100°/second). Smooth pursuit provides gaze stabilization at relatively slow rates of visual image motion.

In order to maintain a stable image on the fovea when the head moves, the eyes must move in the opposite direction to the movement of the head but at the same velocity. This is the responsibility of the VOR. The SCC sense information regarding head acceleration, relay this information along the vestibular nerve (section of CN VIII) to vestibular nuclei in the medulla and onward to ocular motor neurons in the brainstem where it is then relayed to the appropriate muscles of the eyes resulting in compensatory eye movements of equal velocity but in opposite direction to the head, thereby minimizing retinal image slip. Thus VOR is an exceedingly fast reflex (< 15 msec), is the predominant ocular motor system reflex and is responsible for maintaining gaze stability during rapid head movements.[82,141,145] The VOR can be translational (horizontal, vertical), rotational or counter-rolling although it is usually a combination of translation and rotation.

When eye velocity equals the velocity of the head, the ratio is referred to as the VOR gain and the value "must approximate unity"[145] or 1.0 and when referring to 'phase', the eyes are 180° out of phase with the head. If the VOR gain is greater than or less than 1.0, the image on the retina will not remain on the fovea (referred to as retinal image slip) and will be blurred. In response to this a saccade or a nystagmus fast phase is used to bring the fovea back toward the target. If the head is still, nystagmus is observed. If the head is moving and there is an imbalance in the VOR gain or phase, or excessive retinal image slip, clients will complain of blurred vision, dizziness or oscillopsia.[145] Retinal image slip occurs when the visual target moves off the fovea. In those with vestibular disorders, the use of retinal image slip as an error signal (i.e. imagined target paradigm) has been used in treatment to assist in adaptation to deficient angular VOR (aVOR).[140] The OKR is a complementary reflex to the VOR and stabilizes gaze at very slow velocities or during sustained velocities of head rotation. When a visual scene moves across the retina, whether by movement of the visual surround or by head rotation, full field retinal image motion occurs. Visual processing of this retinal image motion can be used to determine head rotation thus, as with the VOR, compensatory eye movement can be generated to compensate for the head rotation.[145]

Nystagmus is a rhythmic oscillation of the eyes that typically has two phases - slow phases consisting of eye movements in one direction alternating with fast eye movements (fast phase) in the opposite direction. There are two types of nystagmus; physiologic and pathologic. Physiologic nystagmus occurs during activation of the SCC (sometimes referred to a vestibular nystagmus) or during optokinetic stimulation (referred to as optokinetic nystagmus or OKN). Pathologic nystagmus is often seen in vestibular disorders of peripheral or central origin and is observed as horizontal, vertical and/or torsional in movement. Types of pathologic nystagmus include those that occur spontaneously (i.e. congenital), gaze- evoked nystagmus (i.e. triggered by eccentric eye movements), head-shaking nystagmus (i.e. observed after horizontally shaking the head for 15 seconds) and positional nystagmus due to changes in head position relative to gravity.

2.2 Orientation:

Fundamental to our perception of the world is our ability to orient ourselves to vertical. Orientation relies on multisensory integration of spatial information with internal and external frames of reference to correctly identify body position relative to vertical.[72, 82] Therefore, in addition to the vestibular system – an internal reference frame -, the visual and tactile somatosensory systems provide external reference frames for vertical or ground respectively, while proprioceptors (muscle spindles) provide knowledge of body position or placement.

The perception of vertical is obtained from the otoliths, which provide an absolute frame of reference to gravity, and vision, which provides a relative frame of reference (to gravity) for determining vertical. To determine if you or the environment around you is moving, the CNS must integrate information from the visual, vestibular and somatosensory systems. While vision can provide accurate spatial information regarding vertical (visual vertical), it is less effective in the dark or low light conditions. It is known that healthy individuals make perceptual errors within 2° of true physical vertical [150,157] and those with CNS or vestibular disorders can make visual vertical errors significantly higher (≥ 5°).[157]

Reliance on vision alone for orientation to vertical is problematic as visually derived motion cues can be illusionary. Some visual illusions include; a) Filehne illusion - During smooth pursuit: a stationary background is perceived as moving in the opposite direction as the eyes, b) Duncker illusion or Induced movement - during movement of a large background: a smaller, stationary target appears to move, c) Train illusion - movement of a large background produces a sensation of self motion.

Loss or reduction of vestibular function results in changes in "selection" of reference frames to vertical, thus perception of vertical may be altered. In a review by Borel *et al* (2008), comparing results of navigation tasks in normal subjects and those with a vestibular deficit, they determined that spatial orientation could be impaired even though vestibular input is not required for the task, as visual vertical is typically perceived as tilted toward the lesioned side.

Despite multisensory inputs for orientation and balance the CNS is adaptable and will rely on the intact senses for accurate orientation. For example, when standing near a moving train, the CNS of a normal healthy adult will disregard the visual motion input and rely on the intact input from the vestibular and somatosensory systems relaying that no physical motion is occurring. The result is that the person remains oriented to their surroundings. However, in a person with a unilateral vestibular loss, the reduced vestibular input in conjunction with the modified or reduced visual vertical reference may result in disorientation and possibly loss of balance.[148]

Movement of the environment across the full field of view creates an optokinetic stimulus Those with normal gaze control manage and tolerate this stimulus however, if a vestibular deficit is present and vestibular vertical and gaze stability are also deficient, then when exposed to OKS, the person will complain of dizziness, nausea, unsteadiness and if standing, will increase body sway.[47, 120]

Studies of vestibular deficient subjects in environments where visual vertical was absent or indistinguishable, confirm the influence of the vestibular system on orientation as the subject who has distorted or absent otolith input for absolute reference to gravity demonstrated deviations in walking direction toward the lesioned (involved) side. [17, 158]

Use of immersion virtual reality environments (i.e. projection-based CAVE Audio Visual Environment) enables researchers to investigate response to OKS. In 2009, Keshner and Kenyon studied healthy adults and the effect of OKS during standing and walking. When viewing an OKS background while standing the subjects displayed increased trunk and head motion. During a walking task while viewing an OKS background the subjects either: 1) walked with normal length steps but walked in the direction of movement of the OKS or 2) walked with short stamping steps and increased medial-lateral sway of the trunk and head.

Body spatial orientation relies on information from the otoliths for head alignment with respect to gravity in addition to the visual system providing information with respect to visual vertical. A study in 2001 by Borel et al revealed that those 1 week post unilateral peripheral vestibular neurotomy presented with head tilts and COP toward the lesioned side when vision was occluded or no visual vertical reference was available however, when a visual vertical reference was available the subjects tilted their heads and COP toward the intact side. Prior to the surgery, they found no difference in head position between normal controls and patients. These studies conclude the concomitant role of vestibular and visual reference frames for absolute vertical for body orientation.

2.3 Balance Control:

Balance is a functional term and its control is a subtle, multi-dimensional process. Balance refers to the ability to position and move the body centre of mass (COM) with respect to the base of support (BOS) and to manage unpredictable conditions common in our environments. Sensing the state or threat to balance and timely selection of appropriate corrective actions is dependent on both task demands and the environment, which can change substantially according to characteristics of the support surface (uneven, compliant), visual conditions, obstacles or crowds.[97,102,104,105,112,117,121]

All three primary sources of spatial information (vestibular, visual and somatosensory) are used to distinguish self-motion, visual background or visual target motion and support-base motion from each other. Each class of sensor provides the CNS with unique information about position and motion of the body or spatial information with respect to the environment and gravity thereby allowing simultaneous adaptation necessary for rapid balance adjustments to prevent falling. The otoliths and vision provide information with respect to gravity and vertical respectively however, body segment orientation, tactile sensation and motion are also critical in sensing the state of stability or threat to balance.

Different types of balance requirements include:

1. Maintain stability at rest, during voluntary movements (i.e. walking, running, jumping).
2. Maintain stability while base of support stationary or during predictable movement (i.e. escalator).
3. Restore total body stability or balance following an unpredictable/sudden disturbance or loss of balance.
4. Must accommodate for changes in characteristics of the support surface (i.e. slippery, uneven, compliant).

Though the vestibular, visual and somatosensory systems provide different types of orientation and motion information, there is some redundancy in the spatial information provided. Internal body frame of reference provided by proprioceptors in muscle spindles and joint afferents provides information regarding position and motion of one body segment relative to another. Additionally, vision can provide this same information. Exteroceptors (i.e. cutaneous sensory receptors) provide external reference frames such as defining vertical or location of the ground. For example, pressure (mechano) sensors in the feet provide information regarding position of the foot relative to the ground. Vision can provide reference frame regarding "earth vertical" (visual vertical) or horizontal. The otolith organs provide absolute reference to gravity.

Laboratory tests that have been developed to assess balance performance manipulate the various sources of sensory information (i.e. isolates the effects of vestibular signals versus visual and somatosensory signals). The most advanced laboratory and clinical test is the Sensory Organization Test (SOT)[83], which includes a moving platform and a visual surround. This device operates to distort or eliminate visual and somatosensory signals (sway-referenced) and thus vestibular signals are required to maintain balance. The SOT uses a composite score of the six conditions to estimate postural stability and comparisons are done pre and post treatment. The six conditions are:

1. Fixed surface, eyes open
2. Fixed surface, eyes closed
3. Fixed surface, visual surround sway referenced, eyes open
4. Support surface sway referenced, eyes open
5. Support surface sway referenced, eyes closed
6. Support surface and visual surround sway referenced, eyes open

The six conditions also assist in classifying patterns of sensory dysfunction. Conditions 1 and 2 are performance baselines that are used to determine changes in performance in the remaining 4 conditions. Changes in performance in conditions 1, 2 and 3 reflect influence of visual input and whether the subject can adjust to absent or suppress distorted visual input on conditions 2 and 3 respectively. Condition 4 reflects the effect of unstable support surface and altered somatosensory input. Conditions 5 and 6 reflect altered somatosensory and absent or distorted visual input (condition 5 and 6 respectively) and changes in stability performance, thus effectively altering all useful inputs except vestibular. Those with vestibular dysfunction demonstrate considerable difficulty or loose their balance under conditions 5 and 6.[120,131,132,161]

In those with vestibular dysfunction, the distortion of sensory cues during the SOT assist in providing evidence that:

1. Distortion or elimination of one sensory system (i.e. eyes closed, or moving surface – conditions 2 and 4 respectively) may result in postural swaying but no loss of balance.
2. Distortion or elimination of two sensory systems concurrently (i.e. conditions 5 and 6) results in increased postural swaying and often loss of balance.

Shumway-Cook and Horak[147] developed an inexpensive test for daily clinical practice based on the same principles as the SOT, known as the Clinical Test of Sensory Interaction and Balance (CTSIB). The CTSIB uses a compliant sponge as an unstable support surface to emulate the SOT in terms of somatosensory distortion, with an added advantage that it is not limited to the pitch plane therefore the disturbance could be multi-directional.[35] The use of a compliant surface modifies the ground reaction forces under the feet; i.e. the compliant surface cannot completely reciprocate the normal body forces beneath the feet as the centre of body mass moves.[36] This increases the magnitude and frequency of body sway, thus increasing balance demands. Unpredictable changes in support surface conditions require the subject to rely more heavily on visual and vestibular inputs.[36,131]

Elimination or distortion of one source of sensory information (i.e. vestibular, vision or somatosensory, such as distorted tactile information from the feet on a compliant sponge surface) does not result in significant balance deficits. However, when there is elimination or distortion of two sensory inputs such as using a sponge surface and eyes closed conditions of the CTSIB (condition 5 of the SOT), significant increases in body sway and loss of balance become evident.[21,33,36,147]

In a September 2010 study, Yu examined visual vigilance performance of nine subjects on a ship after nine days of rough seas. Examining postural activity, visual performance and stance width, they found that visual performance diminished and the crewmembers reported increased mental workload and increased postural activity when tested on an unpredictable moving surface (rough seas). They found that stance widths influenced postural activity regardless of land or sea and less predictable postural activity in both anterior-posterior and medial-lateral directions was noted during unpredictable moving surface conditions. Rough seas did increase the magnitude of motion by approximately three times that of motion observed on mild seas.

Developing a Dynamic Balance Assessment based on a modified CTSIB (mCTSIB) and including voluntary movements that cause the body's COM to be displaced, Desai *et al* (2010) investigated dynamic balance and functional performance in community-dwelling elderly people receiving rehabilitation in a geriatric day hospital. Based on analysis of quantitative results of centre of foot pressure (COP) and loss of balance during test conditions on the compliant sponge, they were able to discriminate between fallers and non-fallers.

Individuals vary in how they perceive and utilize information from the visual, vestibular and somatosensory systems. Those whose perception of vertical is based on external cues are considered to have a strong visual dependence. Davlin-Pater (2010) used a computerized rod and frame test where participants are requested to adjust a tilted rod displayed within a tilted frame that was displayed on a white computer screen. Ninety-nine subjects were asked to rotate the rod until they perceived it to be vertical according to gravity. After normalizing the results, the 25 subjects in the upper extreme were considered to have strong visual dependence and the 25 subjects in the lower extreme were considered to not be visually dependent for perception of vertical. They then investigated the effects of visual information on upright standing on fixed and unstable surfaces in the fifty subjects and found that in fixed surface conditions, there was no significant difference between groups. There was a between group difference on unstable surface, standing balance performance in that those that did not rely on visual cues exhibited significantly less body sway compared to those that rely more on visual cues. Therefore, this would indicate those who rely more on vestibular and somatosensory cues are better able to manage standing balance perturbations.

3. PATHOLOGY OF THE VESTIBULAR SYSTEM:

*For a detailed description of the pathology of the vestibular system see *Walsh and Hoyt's Clinical Neuro-Ophthalmology* 4th Ed. Vol 2, Williams & Wilkings, Baltimore, 1985; 652-784.[162] The following is a summary of this material.

The vestibular system is a multimodal system contributing to a variety of functions including postural and ocular motor reflexes, gaze and orientation/perception. Vestibular disorders can be due to central or peripheral lesions within the vestibular system and mechanisms of vestibular deficits include loss of sensory hair cells, alteration of hydrodynamics and motion mechanics of the inner ear, CNS lesions, neural dysfunction or neural paralysis. A number of pathologic conditions, including stroke, Meniere's Disease (Syndrome), trauma, central tumors and degenerative disorders, affect vestibular function. Impairments within the vestibular system, referred to as vestibulopathy, often lead to chronic and disabling dizziness, vertigo, nausea, imbalance and unsteadiness or motion sensitivity.

Under normal circumstances we are unaware of the influence the vestibular system has on our balance and mobility, however, when injury or disease occur, causing a disruption to the integrity and functioning of the system, perceptual manifestations become evident. Imbalance and unsteadiness can lead to falls. Difficulty with gaze control and nystagmus results in blurred vision, oscillopsia, dizziness, vertigo, disorientation and motion sickness. The burden of dizziness on the patient is great but often goes unmanaged and the cost to the both the individual and the health care system can be substantial.

3.1 Peripheral Disorders:

Peripheral vestibular disorders involve the SCC, otoliths, and/or vestibular nerve and symptoms vary depending on the cause and location of the disorder. Causes of peripheral vestibular disorders can be due to ototoxicity, viral or bacterial infections, alteration in fluid dynamics, head trauma, nerve compression, acoustic neuroma or due to otoconial debris in the SCC.

Vestibular neuritis and labyrinthitis are due to viral infections of the vestibular nerve and labyrinth respectively. Labyrinthitis can also be caused by bacterial infections. Vestibular neuritis is reported to be the second most common cause of vertigo due to peripheral vestibulopathy. [52] Symptoms include prolonged vertigo that is exacerbated by head movement, nausea, imbalance and spontaneous horizontal-rotational nystagmus is noted on examination. Typically a viral infection precedes vestibular neuritis by approximately 2 weeks. Symptoms will last for approximately 48 to 72 hours then gradually decrease with time. Balance typically returns to normal after approximately 6 to 8 weeks due to central compensation. However, some people do not recover completely and have lingering symptoms of dizziness, vertigo, and disequilibrium or imbalance.

Meniere's Disease or Syndrome (endolymphatic hydrops) is a disorder of inner ear function that is due to altered flow of the endolymph resulting in dilatation and distention of the endolymphatic duct. It is characterized by hearing loss (partial or progressing to complete) and attacks of vertigo, nausea with or without vomiting. The attacks last at least one (1) hour then gradually abate and they typically feel better in seventy-two (72) hours. Nystagmus may be present during the attack. The person is symptom free between attacks.

Concussion and head trauma account for a number of referrals for treatment of people with symptoms of dizziness and vertigo. Reports of 75 – 90% of traumatic head injuries are classified as mild or concussions.[148] Although MRI and CT scans do not show any intracranial lesions, it is now known that hematomas may occur many hours post injury. With concussive head injuries, the head experiences an acceleration/deceleration force upon impact, causing an impact to the brain inside the cranium. This initiates a cascade of reactions at the neurometabolic level that can persist for up to 48 hours and result in biochemical changes within the brain. During the time of recovery from the biochemical changes, the brain is vulnerable to irreversible cellular injury by a second impact injury.[148]

Head trauma may cause a fistula between the perilymph and the middle ear at the round or oval windows. Fistulas may also form due to strenuous exercise, straining, barotrauma, or penetrating injury of the tympanic membrane. Symptoms include a hearing a “pop” during the precipitating event, sudden vertigo, hearing loss, and tinnitus. Fistulas resolve spontaneously in the majority of cases.

Superior Canal Dehiscence is due to a perilymphatic fistula of the bony labyrinth covering the superior SCC. Symptoms include vertigo, oscillopsia, nystagmus, and imbalance.

Ototoxicity due to alcohol, chemotherapy medications, intravenous gentamicin and other antibiotics, or large doses of ASA has been documented in medical literature. The toxic compounds affect peripheral nerves, however, the exact method is not completely understood.

After age 60, degenerative changes occur within the structure of the vestibular apparatus in that there is a decrease in the density of otoconia of the otoliths as well as decreased vestibular ganglion cells in Scarpa’s ganglion. Additionally, transient ischemia may occur due to diminished or restricted blood flow to the peripheral vestibular apparatus.[62]

The most common cause of vertigo is benign paroxysmal positional vertigo (BPPV) and is caused by otoconial debris either free floating in a SCC or adhering to the cupula of a SCC. According to information released at the American Physical Therapy Association Combined Sections Meeting in Chicago in February 2012, new figures show BPPV typically occurs most frequently in the posterior SCC (41 – 65%), followed by the horizontal SCC (21 – 33%), anterior canal (17%) and in 20% of the cases it is multi-canal involvement. Symptoms are positional nystagmus that lasts less than 60 seconds when the head is moved into a position that places the SCC into the dependent position (i.e. lie supine with head extended and rotated 45°). The patient usually complains of concomitant vertigo. The nystagmus changes direction upon reversing the position (i.e. sit up while maintaining head rotation, with neck in neutral position). Treatment consists of particle repositioning maneuvers.

3.2 Central Disorders:

Central vestibular disorders can result from traumatic brain injury, tumors, vascular (i.e. ischemia, hemorrhage, infarct), as well as degenerative disorders. Difficulty with postural stability, ambulation and falls as well as downbeat nystagmus, ocular tilt reaction and ataxia are all indications of central vestibular disorder. Symptom onset can be gradual or sudden however, it is important to remember that some brainstem lesions can mimic a peripheral dysfunction.

Oculomotor signs commonly associated with cerebellar lesions include inaccurate saccades, impaired smooth pursuit, gaze-evoked nystagmus, positional nystagmus, skew deviation and increased VOR gain. Chiari type I-IV is a congenital anomaly of the caudal cerebellum and caudal medulla that ranges in severity from mild or Type 1 (abnormal posterior fossa structures and dilation of the ventricles) to Type IV, which is associated other neurological abnormalities such as spina bifida. Type I and II may not demonstrate any neurological symptoms until adult life.

Presence of nystagmus that does not decrease or may increase with fixation is indicative of a central vestibular disorder. The direction may be up, down or torsional but it is typically in a single plane and direction of gaze does not change the frequency and it may reverse direction. Other forms of nystagmus that indicate a central vestibular dysfunction are seesaw and periodic alternating.

Halmagyi and Gresty (1979) found that VOR suppression is absent in spontaneous nystagmus due to a central disorder, when the patient is asked to look in the same direction as the nystagmus beat. Thus the nystagmus is present with and without fixation.

Ocular tilt reaction consists of ipsilateral head and trunk tilt, ocular torsion and ocular deviation and is a condition seen in patients with brainstem abscess, MS, or acute Wallenberg's Syndrome.

Lesions of vestibular nuclei where the VIIIth CN enters can mimic peripheral vestibular disorders. Drop attacks can occur due to vestibulobasilar TIA (transient ischemic attack) or posterior circulation TIA. Ataxias result from central lesions. Multiple Sclerosis can result in a central vestibulopathy as demyelination can occur anywhere in the CNS.

Those who suffer migraines can also suffer vertigo in addition to motion sensitivity, phonophobia, photophobia, aural fullness, tinnitus, visual auras, and headaches.

Injury to the vestibular system, whether peripheral or central, produces a range of difficulties that include imbalance and postural instability, difficulty with gaze control due to nystagmus and problems with eye-head coordination and resultant symptoms of vertigo, dizziness, oscillopsia, nausea and motion sickness or sensitivity.

Diagnostic procedures are limited, however, there are a few useful diagnostic tests that are helpful in the diagnosis of peripheral vestibular disorders. As well, MRI and CT scans are used to rule out CVA, tumor, and other diseases of the CNS. Diagnostic tests include:

1. (Bithermal) Caloric Testing
2. Electronystagmography (ENG) or Videonystagmography (VNG)
3. Vestibular evoked myogenic potential (VEMP)
4. Rotary Chair Test
5. Gaze Stability Tests

Although caloric testing is widely used and is considered to be the "gold standard" in peripheral vestibular function, it tests only the horizontal SCC and at low frequency stimulation[122] to warm and cool water. It is often combined with ENG or VNG and tests the horizontal canals while the head is static and not during functional movements. Caloric testing assists in confirming a peripheral vestibular disorder when history and clinical examination suggest presence of a PVD.

ENG/VNG record spontaneous eye movements, smooth pursuit, saccades and OKN either through electrodes placed around the eyes or via video goggles.

VEMP is a test being used since the 1990's. It assesses otolith function –saccule function specifically[122] – and the inferior vestibular nerve.[52] The VEMP is produced via a three-neuron arc involving the saccule, the vestibular nuclei via the inferior vestibular nerve and the motoneurons of the ipsilateral sternocleidomastoid (SCM) muscle. The saccule is sensitive to sound, thus it is stimulated by a series of clicks or tones (between 60 and 94 dB) at a rate of 5 per second. Surface electrodes placed over the SCM record the response of the muscle to the tone via electromyography (EMG). An inhibitory response of the SCM indicates the saccule has been damaged on that side. Similar to Caloric and ENG testing, the VEMP measures response to a stimulus while the head is in a static position, therefore is does not assess function during head movement. The VEMP is identified as being beneficial in identifying vestibular neuritis affecting the inferior vestibular nerve and Superior Canal Dehiscence (SCD).

The rotary chair test assesses the horizontal SCC and the superior vestibular nerve. The patient's head and body are fixed to a chair that rotates under the control of a computer. Eye movements are recorded using electrooculography (EOG) or videooculography (VOG), which records the VOR gain and phase at different frequencies and velocity of rotation. The test is done in the dark to prevent VOR suppression. A disadvantage of this test is the cost of the equipment, which precludes its use in many centres.

Gaze stability tests consist of manual Dynamic Visual Acuity (DVA) or the computerized DVA. In the manual version the patient's head is passively oscillated horizontally and vertically while viewing an eye chart. In the computer DVA, the patient's head is oscillated either passively or actively while visual acuity is identified through identification of an optotype on a computer monitor. Head velocities of 120° to 180° per second trigger the optotype to appear on the monitor and the size of the optotype gradually decreases. With both versions of the DVA, results are expressed as the difference between the visual acuity when the head is stationary and when the head is moving and measures VOR.[52]

Auditory testing is another useful test in diagnoses of PVD such as Meniere's disease and SCD.

4. REVIEW OF LITERATURE

Following peripheral vestibular lesions, sensory deprivation studies in animals show minimal recovery[32] whereas targeted activities in enriched environments (varied visual and surface conditions) demonstrate considerable functional recovery.[156] With reduced or distorted vestibular sensory signals the brain must adjust and recalibrate (learn) spatial frames of reference. Neuro-adaptation to vestibular sensory loss needs to be achieved during life-role activities, importantly in varying environments where spatial and motion cues of other sensory inputs (i.e. visual vertical, tactile surface) are not available, such as in darkness, or can be unpredictable, distorted or illusionary. Although residual impairments may persist throughout life, it is important to remember that people with PVD can recover many functions if they actively engage in goal-directed interventions of ample intensity and volume and consist of activities that will transfer to meaningful, functional activities required for all aspects of life and living.

Most agree that the effectiveness of interventions to maximize recovery of sensory-motor skills and adaptive behaviors is:

a. dependent on task-specificity of the rehabilitation regime or learning experiences including goal precision
b. proportional to the intensity and volume of training.

The Cochrane Database of Systematic Reviews [56] is a comprehensive review of vestibular rehabilitation (VR) randomized controlled studies. The findings demonstrate moderate to strong evidence that VR is a safe, effective management for unilateral PVD. Based on current evidence, it is concluded therapy should systematically encourage functional graded mobility activities on unstable and slowly moving surfaces and be combined with progressively complex visual environments requiring foveation initially on stationary targets[44], then moving targets in predictable and then random patterns.[99] Concurrent graded head movements[135,141] need to be an integral part of the VR program.

Ricci *et al* (2010) published a systematic review regarding the effects of VR in middle age and older adults in 2010. They reviewed nine random control trials (RCT) from 1998 to 2008, with a control group that received no treatment, placebo or another type of intervention. They also found that age was not a limiting factor in response to treatment and that VR in addition to a home program was beneficial in decreasing symptoms of dizziness and imbalance in this population. This finding is consistent with the Cochrane Database of Systematic Reviews.

Current treatment for gaze instability due to loss of VOR consists of rehabilitation techniques that attempt to improve gaze control by

1. enhancing smooth pursuit, saccadic eye movements and OKR.
2. increase the contribution of the remaining vestibular sensors.

It is known that recovery of gaze control is central to managing symptoms of dizziness. Without foveation the ability to maintain visual focus self or environmental motion can result in excessive retinal image slip. Many studies look at the effects of oculomotor strategies and their ability to reduce retinal image slip.

For this purpose, active goal-directed activities requiring foveation, such as tracking a visual target or reading aloud, are essential as adaptation and learning is dependent upon experience. The nervous system needs to be engaged in visual fixation and exposed to graded degrees of retinal image slip in order to recover gaze control. Retinal image slip is the neural signal or “error message” that provides the stimulus that drives neuro-adaptation. Reading aloud is an excellent “task-orientated” exercise for retraining the vestibular system after a peripheral loss for it is not only a functional task requiring foveation, it also requires saccadic eye movements and cognitive processing, and by moving the text or the head side to side, requires smooth pursuit and VOR. Importantly gaze activities used in VR should be graded; initially tracking moving visual targets with head stationary, increasing to active (preplanned) head movements[156] and finally adding passive (unpredictable) head movements.[135,140,141]

Schubert *et al* (2010) investigated the effects of high acceleration during active and passive head movements on gaze stability in those with vestibular loss (VL) compared to normal controls. Eleven subjects were studied - 7 with vestibular loss and 4 control. Each were seated and performed active and passive head rotations while visually fixating on a laser target were performed. Velocities of rotation were not stated except that velocities of less than 120°/second were discarded. Head movement velocity and acceleration were measured with a sensor although they do not indicate where the sensor was placed. Eye movements were recorded using scleral search coils. They do not report results for normal controls except to state that they generated appropriate VOR eye movements. They found that saccadic eye movements were used with the reduced VOR as a compensatory strategy for reduced gaze stability in those with VL.

Herdman *et al* (2007) investigated VOR recovery in BVH (bilateral vestibular hypofunction) in a randomized, double blind, prospective study. A total of thirteen participants were enrolled in a four-week study with a control group of five who received exercises consisting of saccadic eye movements (no head movement) in front of a blank wall and gait and balance exercises. Eight participants received the experimental exercises consisting of Herdman "X1" Exercises, which consist of head movements while foveating on a near target and distant targets. Progressions include addition of eye and head movements horizontally and vertically, with foveation, between two targets placed near and distant from the subject. This study found that VR exercises resulted in statistically improved DVA scores pre to post-therapy ($P = .001$) while the control group did not demonstrate improvement, therefore indicating visual fixation with head movement improves gaze stability during head motion.

A key study, which demonstrates the importance of goal-directed vestibular rehabilitation (VR) consisting of VOR adaptation and balance exercises, was carried out in 1994 by Szturm, Ireland and Lessing-Turner. They compared in-clinic treatment consisting of goal-directed eye and head exercises and balance exercises in various visual and somatosensory conditions, with a home program of eye and head movements and position changes (Cawthorne-Cooksey exercises) for those with chronic PVD and measured effects of the programs on VOR gain and postural control. They demonstrated that goal-directed VR improves VOR compensation compared to the home program of eye and head exercises that did not require foveation thereby confirming other studies that support the view that retinal image slip can be used to facilitate VOR compensation and gaze stability in those with PVD.[26,43,44,48,54,83,135,140,141] While standing postural control improved significantly in the VR group compared to the home exercise group, they were unable to clearly determine if the effect was due to the VR or from residual vestibular input and/or external spatial reference frames.

In 2006, Meli *et al* looked at combined clinic and home vestibular rehabilitation programs and the affects on subjective symptoms, gaze stability and balance in subjects with vestibular disorders of mixed etiology. A single group of 43 participants were involved in the study. Three assessments were carried out; the first at the initial appointment, the second at the end of four weeks clinical vestibular rehabilitation and the third at the end of a follow-up period of 8 months later. Tests included the SF36, Dizziness Handicap Inventory (DHI), Activities-specific Balance Confidence Scale (ABC), observation for spontaneous nystagmus and/or positional nystagmus (using infrared goggles), DVA, SOT and dynamic gait index (DGI) which is a measure of walking balance during eight tasks and quantifies gait dysfunctions. The VR program was carried out twice a week for four weeks and each participant had a subsequent home program to be done twice a day for 20 – 30 minutes each time. They do not describe the exercises done during VR or at home nor do they state if the subjects were to keep a log of the home exercise program thus making it difficult to know what was done during the study and making it difficult to reproduce. After four weeks of treatment, the subjects were to continue the home program for one month during which time a therapist would contact them by telephone to ensure compliance. The subjective symptoms of the group improved pre to post VR. Gaze stability and balance improved significantly pre to post VR but only balance improved significantly at follow-up. This study supports clinic treatment and concomitant home programs for those with vestibular dysfunction. While the authors support theories of concomitant clinical treatment with home exercise programs to be effect in treatment of gaze and balance impairments in those with vestibular disorders, this study does not include details of either program therefore making it difficult to determine the same conclusion.

There is evidence that home exercise programs are as effective as a combined clinical and home program.[156] Kammerlind *et al* (2005) looked at balance outcome measures and perceived symptoms between groups in an RCT (randomized controlled trial) investigating two groups of subjects with UVL; one group received a home vestibular exercise program and the other received a home vestibular exercise program in conjunction with additional clinical physiotherapy treatment. They looked at fifty-four subjects with acute UVL. The home exercises were to be performed daily for 15 minutes for ten weeks. The home exercises consisted of eye movements alone, eye and head movements while foveating on a stationary target, standing with feet together and eyes closed, walking on a line while rotating the head horizontally and then vertically. The group that received additional physiotherapy participated in three 40-minute sessions the first week followed by weekly 40-minute sessions for the remaining nine weeks. The physiotherapy exercises consisted of eye and head movements, standing and walking balance on firm, progressing to uneven and compliant surfaces with eyes open or closed. Further progressions included movements of the head while walking on the various support surfaces and throwing and kicking balls. They found no difference in balance outcome measures or perceived symptoms between groups.

Dizziness is one of the most common complaints of individuals with PVD and it can have a huge impact on activities of daily living.[48] Previous studies have established that gaze stability exercises incorporating foveation and head movement assist in decreasing dizziness and improve visual acuity during head movement.[47,129]

Use of optokinetic backgrounds in VR is beneficial in treating gaze as well as subjective symptoms of dizziness. Chang and Hain (2007) reported a case study of one of the authors who had experienced chronic persistent dizziness that affected his daily life. Treatment consisted of use of optokinetic background while foveating on a stable foreground image. For example, they utilized a virtual reality environment and had the subject sit in the backseat of a stationary car while viewing a train moving horizontally across his visual field. Although the authors do not state exact number of weeks, a chart of dizziness intensity included in the article shows treatment of approximately eight weeks resulted in improvement in the subject’s dizziness with decreased intensity and at two months follow-up the dizziness was gone.

Loader *et al* (2007) investigated the effect of optokinetic stimulation on standing balance in those with PVD. In an RCT, 24 subjects were divided into equal size groups of twelve subjects. Both groups were assessed with the SOT protocol using the EquiTest (NeuroCom International, Inc.) pre and post treatment. The experimental group received computerized optokinetic treatment (COKT) consisting of standing in front of a screen and reading a variety of randomly moving texts that were projected onto the screen. They do not report what type of surface they were standing on. Duration of the COKT was three weeks and consisted of ten sessions, each of which was thirty minutes duration. The control group received equal amount of time and sessions and performed the SOT at each session. They found within significant improvement pre to post treatment within the experimental group on conditions 4 (eyes open, moving support surface, stable visual surround) and 6 (eyes open, moving support surface, moving visual surround), of the SOT. The control group showed significant within group improvement on condition 4 of the SOT only. There was a significant improvement between groups post treatment with the experimental group improving greater than the control group. The results of this study support use of foveation in treatment in VR for PVD as a technique to improve standing balance and gaze stability, as they were required to foveate on a moving target of interest.

Detecting changes in balance, either standing or walking, is an integral part of evidence-based physiotherapy practice. Risk of falling can occur at any age if the vestibular system or the ability to orientate oneself to vertical is compromised. Since balance is maintained when the centre of mass (COM) is kept over the base of support, to assess and identify the effects of vestibular loss on balance performance, patients need to be assessed on unstable and/or moving surfaces and in conditions that manipulate various sources of sensory information such as visual, vestibular and somatosensory.

Perez *et al* (2006) investigated subjects with unilateral vestibular dysfunctions and chronic unsteadiness. They assessed each with the sensory organization test (SOT) of the computerized dynamic posturography (CDP). Then, using the CDP, they determined the maximum point a subject can lean in any direction without loss of balance (end point excursion) and balance exercises were given based on this parameter. After five weeks of treatment, the composite SOT scores had improved for each subject and the pre and post treatment measurements indicated improved balance, as the subjects were able to tolerate increased end point excursions.

More recently various technologies are being developed for VR. An example of this would be the use of large screen displays for opto-kinetic stimulation or full immersion Virtual Reality systems providing visual, sensory and haptic feedback.[72,97]

At Temple University in Philadelphia, Pennsylvania, the Physical Therapy department created a laboratory with a dynamic posturography machine in a virtual reality environment (CAVE) where they study and train postural behaviors in an environment that simulates the real world. The focus of this training is to improve eye-head coordination (gaze control) and to reduce symptoms of dizziness and motion sensitivity through adaptation to a reduced VOR.[72]

The University of Pittsburgh in Pennsylvania also has a virtual reality environment – the Balance NAVE Automatic Virtual Environment (BNAVE). Whitney *et al* (2006) did a study examining head movements in two people with UVL and three healthy controls. The subjects were to navigate a virtual "grocery store" using a joystick to "move" through the aisles as they searched for and located specific items on the grocery store shelves. The subject stood on a force plate (Neurocom International) and an electromagnetic sensor attached to a headband was placed on their head. The grocery store environments were classified as having sparsely populated shelves (products covering 6.7% of the shelves) and densely populated with products covering 50% of the shelf space. Performance measures included the number of correctly located items from each grocery store environment and the average speed of head rotation in degrees/second. Although the investigators recorded head movements they did not report any statistical analysis on their results. Observation of the table included in the study indicates increased speed of head rotation in all subjects when navigating the densely populated grocery store environment and presence or absence of UVL does not appear to be a factor in speed of head movement. The investigators reported all subjects tolerated the CAVE.

The Virtual Reality systems are complex and require a large amount of space dedicated to their use. Additionally they are expensive. These virtual reality systems are not practical for daily clinical use, and most importantly, not practical for use by the clients themselves in their home.

Studies have provided preliminary descriptions of the benefits of commercially available video games in rehabilitation, and show that interactive exercise linked with games can significantly improve players' visual-spatial perception and visual tracking skills [1,2,129] Motor training using random tasks have been demonstrated to improve performance and retention in subsequent sessions and has proven to be more efficacious than repetition of a constant task.[79] Lange *et al* (2009) investigated a number of game-based telerehabilitation studies and noted the greatest advantages include:

1) It is in the client's home therefore allowing breaks to attend to other family duties.
2) Allows for adequate rest between trials.
3) Promotes and encourages increased practice times throughout the day.
4) Computer game scores give instant feedback of performance.
5) All four combine to improve motivation to complete their rehabilitation specially if the vestibular disorder is of long-duration and has become a chronic disorder.

A number of therapeutic exercise gaming and telerehabilitation systems have been developed by Dr. Szturm and colleagues and used in a series of clinical studies.[36,84,155] Combining commercial pressure-tracking devices and inexpensive head-tracking input devices to interact with engaging, targeted exercise activity games, thereby increasing patient motivation and participation in tedious, long-term rehabilitation, the system was designed to incorporate:

1) Tasks which involve various sources of sensory information and which emulate outdoor support surface conditions.
2) Visual tracking tasks with and without head movements.
3) Self-motion and visual-spatial perception.
4) Dynamic balance and locomotor skills.

Assessment is embedded into the treatment/exercise games and automatic tracking of performance is possible through the use of an instrumented, interactive “therapeutic” game that has been developed. This tracking can be used to log compliance, results and compare performance for nearly any exercise/activity and therefore drive progression of the rehabilitation program as well as serve as an objective outcome measure.

To apply these computer-based tracking methods and data quantification procedures to balance and assessment of fall risk, we designed and evaluated a dynamic balance assessment task protocol, which was based on the concept of the SOT, CTSIB and moving platform paradigm.[68,97,104] Construct and predictive validity was evaluated in a cross-sectional observational study of 72 community-dwelling older adults receiving rehabilitation in a Geriatric day hospital (Desai *et al* 2010). Our findings demonstrated that analysis of the extent and amount of center of foot pressure (COP) displacements during targeted tasks and under different surface conditions are an appropriate method to assess dynamic standing balance controls, and can discriminate between fallers and non-fallers.[28] We have also developed a similar assessment system for visual tracking tasks which can be performed in standing on fixed and compliant support surfaces, and during treadmill walking.

Treatment for PVD requires functional-oriented, goal-directed tasks that drive neural plasticity. One of the goals of VR is the functional recovery of the VOR during life activities. This includes visual fixation, with minimal or no dizziness, during active head movement and during ambulation. Evidence indicates exercise programs that are individualized to the patient's deficits are more effective than generic exercise programs.[131,134,136,151,155]

While home exercise programs are commonplace in physiotherapy treatment regimens, monitored home programs for rehabilitation allow access to trained physiotherapists for problem-solving and progression of exercises regardless of physical location (i.e. remote rural areas) and are anticipated to be a cost-effective delivery of rehabilitation in times of financial constraints in both the government and personal finances.

5. METHODS:

5.1 Features and Theoretical Basis of the Game-based Intervention

Modern concepts of learning and neuro-adaptation have been incorporated using a task-specific approach.[73] Consistent with constraint induced movement therapy and treadmill locomotor training [61] participation in meaningful physical activities and intense practice is required to drive neuro-adaptation sufficient to facilitate significant recovery from injury. For adaptation of gaze stability, the nervous system needs to be engaged in visual fixation and exposed to graded degrees of retinal image slip, accompanied by head and target motion.

A greater degree of foveation is required for CL visual tracking, as the participant is required to maintain the game “sprite” coupled to the movement of the computer-controlled target. However, during OL visual tracking the participant is not required to maintain a sprite fixed to a moving target. Open loop visual tracking can be performed through use of peripheral vision as visual acuity is not required for perception of movement.[144] Foveation is required at the turning points of the CL visual tracking task in order to maintain accuracy in the task and compensatory saccades[141] may be incorporated to assist in maintaining foveation at the turning points of head rotation.

With these factors in mind, we hypothesize that a home-based computer gaming rehabilitation program will improve gaze control and balance impairments in those with peripheral vestibular disorders (PVD).

A wireless motion sense computer mouse (Gyration® Technologies, SMK Link Electronics, Camarillo, Calif. USA), which uses inertial sensors to formulate angular motion signals, was used for computer gaming. Visual searching and tracking of targets requires head motion, thus the ease of use and quick responsiveness of the motion sense mouse allowed hands-free interaction with any computer application. Video games require active goal-directed movements and tracking or interaction of game targets of varying precision levels, thus extent of visual search and degrees of foveation vary. Many different games exist which can provide a graded program beginning with:

1. Predictable cyclic movement progressing to random moving targets.
2. Progression from small to large amplitudes.
3. Progression of slow to fast motion.
4. Progression of large to small targets thus requiring increased precision and foveation.
5. Presence of distracters and crowding of other objects.
6. Solid or structured backgrounds (i.e. minimal to strong opto-kinetic stimulation).

Balance training can be incorporated into the rehabilitation sessions by playing the "therapeutic" games (head rotation) while performing graded balance activities:

1. Sitting on a fixed surface then compliant surface.
2. Standing on a fixed surface then on a compliant surface.
3. While walking on treadmill at various speeds, inclines etc. (clinical use).

A compliant sponge pad or different low-cost air bladders (e.g. Swiss disc) are unstable support surfaces now commonly used in balance re-training of clients with peripheral and central nervous system disorders or older adults with a history of falls. A compliant sponge cannot completely reciprocate the normal body forces beneath the feet (i.e. centre of body mass) as the client moves.[16] This increases the magnitude and frequency of body sway, thus increasing balance demands. Used in a systematic and graded fashion, different densities of sponge and air bladders can be used in sitting and then standing to adjust the balance cost. Based on the initial three clinical sessions, the program will be adapted to the participants' specific goals, abilities and tolerance (i.e. dizziness).

5.2 <u>Participants</u>

A total of ten (10) research participants (two men, eight women) ranging in age from 24 to 68 years of age (average age 44.5, SD 14.3 years) were enrolled in the study. All participants had peripheral vestibular disorders confirmed on:

1. ENG (electronystagmography) and caloric testing with results ≥ 25% weakness.
2. Pathological head impulse test.
3. Spontaneous nystagmus assessed with fixation removed (Frenzel lenses).

Eight were diagnosed with unilateral PVD and two diagnosed with bilateral PVD. All participants had access to a home computer.

Exclusion criteria consist of those with CNS disorders (i.e. CVA, Multiple Sclerosis), Vestibular Migraine, Benign Paroxysmal Positional Vertigo (BPPV), recent fractures of the lower extremities or vertebrae, inability to tolerate standing for twenty (20) minutes or dementia.

This research project was conducted with the understanding and written consent of each participant. Methodology and ethics approval for this project was granted by the Human Ethics Research Board at the University of Manitoba, Canada (H2011:371).

5.3 Instruments and Data Recording

The following demographic and clinical data was collected for all participants; age, gender, clinical data (history of disease/injury process, current medications).

The experimental assessment protocol consisted of the following tasks performed in standing for thirty (30) seconds, first on a fixed floor surface, then repeated while standing on a compliant sponge surface:

1. Eyes open (EO) and eyes closed (EC),
2. Performing 2 visuo-spatial cognitive tasks.

As described in Desai *et al* in 2010 a 50.8 cm x 50.8 cm x 10.16 cm sponge pad (compliant surface) was used. A 25.4 cm x 40.64 cm x 1.91 cm wooden board was placed on top of the sponge to distribute the forces equally. Two grades of sponge were used to counterbalance the effect of differences in body weight in compressing the sponge pads. A low support sponge, with a density of 16.016 kg/m^3 and a 25% indentation force deflection (IFD) of 6.82 kg was used for people who weighed less than 55 kg. A medium support sponge, with a density of 22.66 kg/m^3 and a 25% IFD of 13.64 kg was used for people who weighed more than 55 kg. A force sensor array (FSA) pressure-sensing mat (Verg Inc., Manitoba, Canada) was used to compute vertical centre of foot pressure (COP) position for all standing tasks. The FSA pressure mats are constructed of thin, flexible piezo-resistive material and thus can be placed on a variety of support surfaces, including the sponge pad surfaces. The FSA mat consists of an array of 256 piezo-resistive sensors (16 by 16), and each sensor covers a surface area of 2.8 cm^2. Each sensor was sampled at 30 Hz, from which the vertical COP in the anterior-posterior (AP) and medial-lateral (ML) was computed.[36]

Using straps provided by the supplier, inertial motion monitors (SXT monitors, NexGen Ergonomics, Montreal, Canada) were secured to the upper trunk at the level of the sternum, and the lateral aspect of the lower shank just above the lateral malleolus. Calibrated signals for 3D angular velocity were obtained for analysis. Sampling rate was 120Hz.[13]

The Gyration® motion mouse was secured to a headband and used as the computer input device to control on-screen cursor motion with head rotation (left-right). This Air Mouse has inertial sensors used to derive angular position signals. With this simple method, seamless and responsive hands-free interaction with the computer application is made possible. A custom computer application with a visual tracking module was developed, which consisted of tracking a bright visual target moving horizontally left and right on a computer display at a fixed amplitude (80% of the monitor width) at a frequency of 0.4 Hz. A 76 cm monitor was used, positioned at eye-level, 100cm away from the participant. This results in head horizontal rotations of between 30 to 40 degrees, left and right of centre. Two tracking tasks were performed.

1. Open-loop visual tracking (with respect to head) – OL: During this predictable cyclic tracking task only the target (computer) cursor is displayed and participants are asked to rotate the head in concert with motion of the target cursor for 30 seconds. This task does not require continuous foveation to detect a position error.
2. Closed loop visual tracking (with respect to head) - CL: This task consists of two cursors of different colors appear on the monitor. One is the target cursor and the 2nd cursor is slaved to head rotation via the head mounted motion mouse. The task goal is to overlap the two cursors during the cyclic left-to-right cursor motion. In this task foveation is necessary to determine the amount of overlap (error) between the target cursor and the head cursor.

The computer application also generates a logged game file to record coordinates of target cursor and head rotation at 80 Hz for offline analysis of head tracking performance described below.

Following the standing balance assessment, participants were instructed to perform two 30-second walking tasks on a treadmill at a speed of 0.7 mph while performing the OL and CL visual tracking tasks. Before beginning this test participants walked for three to four minutes for treadmill acclimation.

The following outcome measures were also recorded pre and post-intervention:

1. Dynamic Gait Index (DGI): The DGI is a performance-based measure of gait dysfunction, comprised of 8 different gait tasks commonly performed, including walking, walking at different speeds, walking with head movements in pitch and yaw, walking around and over objects, turning and stopping quickly and ascending and descending a flight of stairs. Reliability indexes for the total DGI score in people with unilateral vestibular disorders have been reported to range from 0.64 to 0.88.[90,164,170]

2. Dizziness Handicap Inventory (DHI): The DHI is a self-rating disease-specific scale that quantifies self-perceived handicap attributable to vestibular system disease and has been used in a number of trials involving patients with vestibular dysfunction. The DHI has good test–retest reliability as well as face validity and internal consistency.[64,129]

5.4 <u>Treatment</u>

Each participant attended three, forty-five minute clinical training and education sessions before starting the home program (HP). Sessions consisted of participant training regarding specific exercises and activities to address their specific dysfunction(s) as well as instruction regarding use of all gaming and computer equipment. Upon completion of the clinical sessions a physical therapist (KR) attended the participant's home to set-up the telerehabilitation treatment program and equipment and assess the HP area for fall prevention. Each participant utilized an appropriate sturdy chair during balance activities that may result in a fall and they were instructed to have another adult present during the execution of these exercises. Each participant was asked to complete exercise logs. The physical therapist emailed each participant weekly to monitor progress, ensure completion of the exercise logs, progress exercises and answer any questions. Participants were instructed to contact the physical therapist via telephone regarding any emergent needs.

5.5 Data Analysis

5.5.1 Standing Balance Measures:

As per the methods of Desai *et al* 2010, total path length (TPL) of COP excursions in the anterior-posterior (AP) and medial-lateral (ML) directions was computed for each task. Figure 1 presents a representative picture of a participant's COP during the condition of eyes closed while standing on a compliant sponge surface (ECS). Increased COP excursion has been interpreted as decreased stability and reduced dynamic balance.[76,133] A composite score comprised of the four conditions of the mCTSIB (EO, EC on fixed and sponge surfaces) was computed.[147,152] Total path length was also computed for OL and CL visual tracking conditions on the sponge surface (OLS and CLS). Root mean square (RMS) of ML trunk angular velocity was computed for each task condition. The trunk (head and arms) represents over half of the total body mass, and maintaining control over the motion of the trunk is critical for maintaining stability.[39,57,102]

Figures 1a and 1b: Samples of FSA Mat Profile and COP Displacements

Figure 1a:

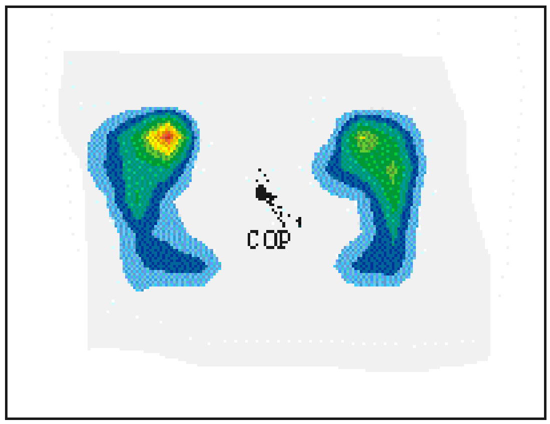


Figure 1a: Presents a snapshot of FSA (Force Sensor Array) standing pressure mat recording.

Figure 1b:

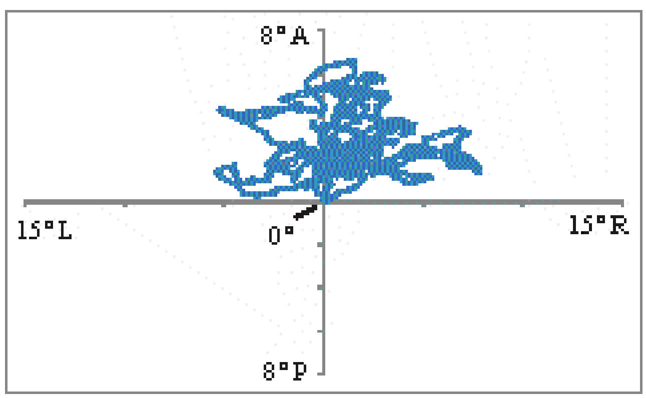


Figure 1b: Presents a representative raw Centre of Foot Pressure (COP) signal for 30 seconds. Displacement shown is in the anterior-posterior (AP) and medial-lateral (ML) directions for eyes closed (EC) condition. L = left; R = right.

5.5.2 <u>Visual tracking Performance Measures:</u>

The coordinates of the computer cursor (reference target) and the user movements (head rotation via head mouse) were used to compute: Coefficient of determination (COD) to represent quality of the visual tracking tasks with head rotation. The reference target and user head movement trajectories for a typical tracking task are presented in Figure 2. Maxima are left most position and minima right most position. The coordinate data of each trial was processed using custom analysis routines written in MATLAB (The Math Works, Natick, MA version R2010a). The first two cycles were excluded to allow participants time to acquire the moving target and begin tracking. A non-linear least squares algorithm was used to obtain a sine-wave function of the target cursor waveform. User motion trajectories were fitted to the function obtained from the target waveform, and COD was determined.

Figure 2:

Representative Sample of Sinusoidal COD (Coefficient of Determination)

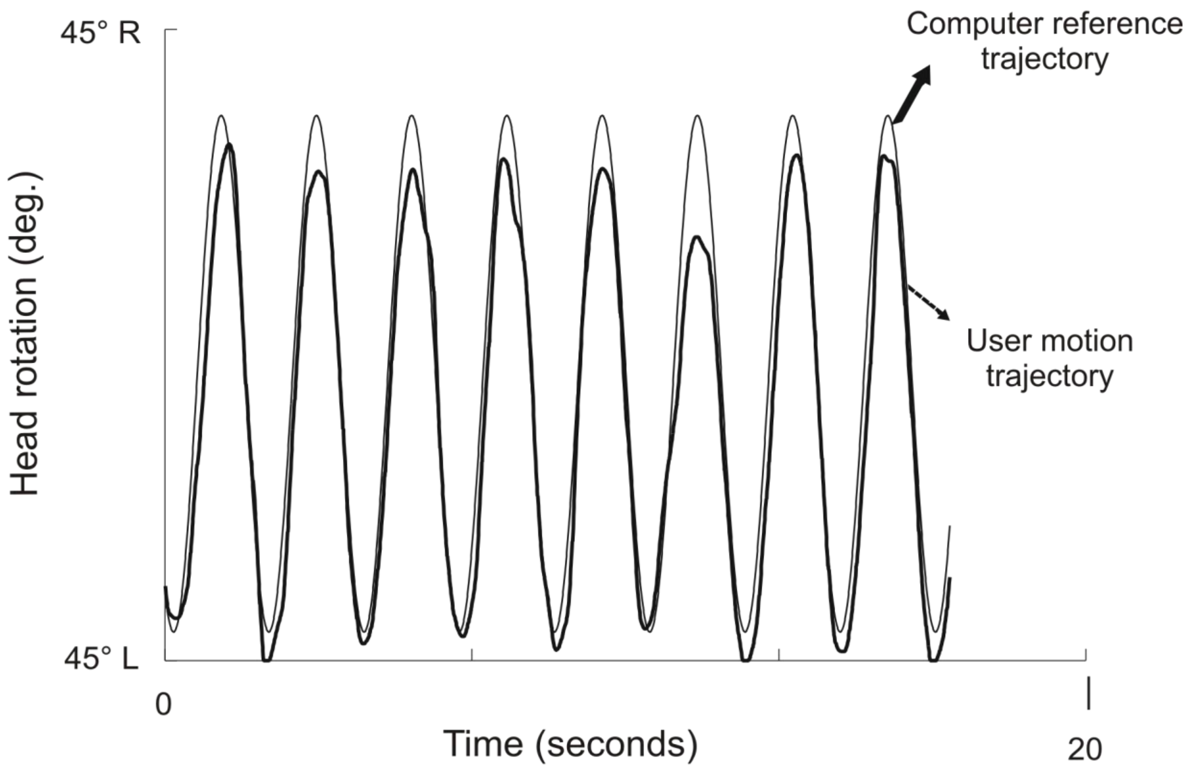


Figure 2: Presented are synchronous plots of the reference cursor motion and user head rotation trajectories (head rotation) for a representative closed loop (CL) visual tracking task.

5.5.3 Gait Analysis:

A power spectral density (PSD) analysis of trunk angular velocity during treadmill walking was computed using a Welch's Averaged Periodogram Method written in MATLAB. Each power spectrum was then normalized to the total signal power and divided into bands with of 0.1 Hz.[106] One of the important features of steady state walking is its relatively constant step rhythm. For example the frequency content of AP shank rotation can be separated in two distinct frequency bands representing swing and stance phases of the step cycle.[174] Figure 3a presents typical plots of shank AP angular velocity and ML trunk angular velocity for seven (7) step cycles during a typical treadmill walk. Vertical linear acceleration of the shank motion monitor is also presented, which displays each successive heel strike acceleration artifact. As presented in Figure 3b, PSD analysis revealed power spectra centered about two bands. The frequency band of 1.0 to 2.0 Hz with the largest percentage of total power would represent angular shank velocity during swing phase. The frequency band of 0.5 to 0.7 Hz with the smaller percentage of total power would represent angular shank velocity during stance phase. Power spectrum of the trunk angular velocity also showed the majority of power similar to these two frequency bands with the trunk primary frequency band occurring during stance phase. The power spectral density of ML trunk angular velocity was separated into three frequency bands for final analysis of treatment effect: (a) percentage of total power in the primary frequency band (PF), (b) percentage of total power in frequencies above PF. denoted as high frequency band (HF), and (c) percentage of total power in frequencies below PF. denoted as low frequency band (LF). For each participant PF, HF and LF were computed pre and post-intervention during treadmill walking while performing the closed loop and open loop visual tracking tasks. A shift in the frequency distribution between the primary step frequency and LF and/or HF would represent a change in step-to-step variation of trunk motion.

Figure 3a:

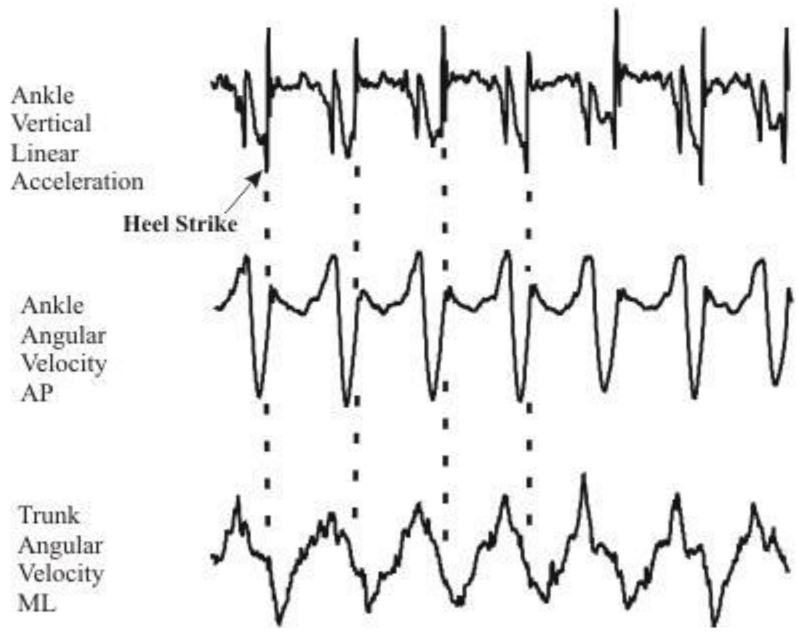


Figure 3a presents plots of vertical acceleration of the ankle motion monitor and corresponding ML trunk angular velocity for walking alone (control) trial. Large positive amplitude spikes in ankle vertical acceleration plots (marked with dotted line) represent acceleration artifacts at initial right heel strike.

Figure 3b:

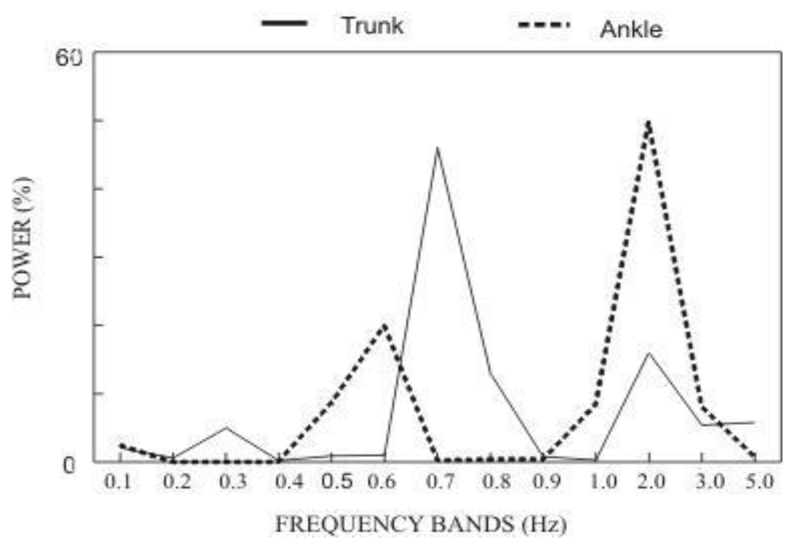


Figure 3b presents power spectral density (PSD) of AP ankle and ML trunk angular velocity signals obtained during a walk alone (control) trail

Figures 4a & 4b present representative histograms of five (5) participants' AP shank angular velocity for OL and CL visual tracking during treadmill walking (OLW and CLW) pre to post-intervention. Each participant was chosen by random selection of the nine enrolled in the study. The PSD was analyzed using Fast Fourier Transform (FFT) and results were separated into three frequency bands for final analysis of treatment effect: (a) percentage of total power in the PF (b) percentage of total power above PF, denoted as high frequency band (HF) and (c) percentage of total power in frequencies below PF. denoted as low frequency band (LF). A shift in the frequency distribution between the primary step frequency and LF and/or HF would represent a change in step-to-step variation of shank motion.

PSD – SHANK Angular Velocity (AP): Pre to Post Intervention for OL and CL visual tracking tasks during treadmill walking.

Figure 4a:

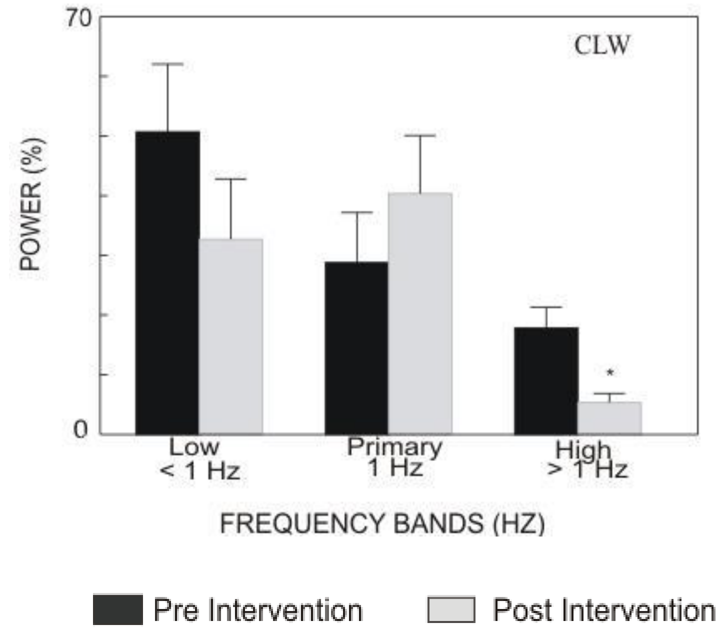
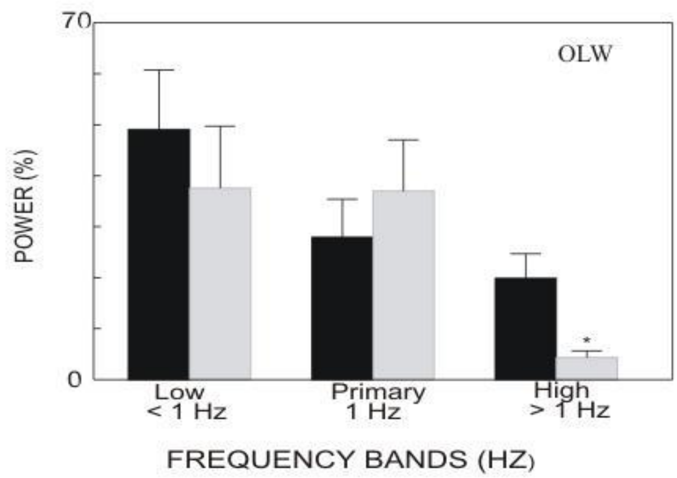


Figure 4b:



Figures 4a and 4b present group mean and standard error mean (SEM) of AP shank angular velocity for closed loop (CL) and open loop (OL) visual tracking during treadmill walking at 0.7 mph. Results are grouped into three frequency bands of Low, Primary and High frequencies. * = significant difference on t-test ($p<0.05$)

5.5.4 **Weekly Data Logs:**

Each participant completed daily logs and submitted the logs weekly to a physical therapist. Daily logs tracked computer games played, duration of computer gaming, position of participant during gaming (i.e. sitting, standing) and if standing, the type of surface standing on (i.e. floor or sponge). Additionally, each participant was asked to record symptoms experienced, duration of symptom exacerbation and any additional comments. The physical therapist contacted each participant through email on a weekly basis and reviewed the data logs. According to email contact and weekly log reports, the physical therapist would progress the home program appropriately for each participant. No telephone calls were recorded as received from any participant throughout the duration of the research study.

5.5 **Statistical Analysis:**

A paired t- test was used to determine effects of exercise pre to post-assessment on standing balance, visual tracking and gait variables.

Non-parametric outcome measures were utilized for questionnaires. The DHI and DGI scores were analyzed within groups for pre to post-intervention time periods using the Wilcoxon Signed Ranks test.

Effect size of the balance, visual tracking and gait variables pre to post-intervention were determined using Cohen's d. Small, moderate, or large effects were identified based on standard criteria of 0.2, 0.5, and 0.8 or greater respectively.[27] Statistical significance was set at $p<0.05$ (two tailed) and all tests were done using Statistical Package for Social Science (SPSS) software for Windows, Version 19 (SPSS Inc. Chicago, IL, USA)

6. RESULTS:

Figure 5 presents representative X-Y plots of ML-AP COP excursion for four tasks carried out while standing on a compliant sponge surface pre and post intervention. As the demand of the task increases a progressive increase in COP excursion is observed. As noted in Figure 5, loss of balance (LOB) occurred during the eyes closed (EC) sponge condition. This was the case for two of the nine participants during the EC sponge conditions pre-intervention. No LOB was recorded during any condition post-intervention. Decreased COP excursion was observed post intervention while standing with eyes open (EOS) and during open loop (OLS) and closed loop (CLS) visual tracking tasks.

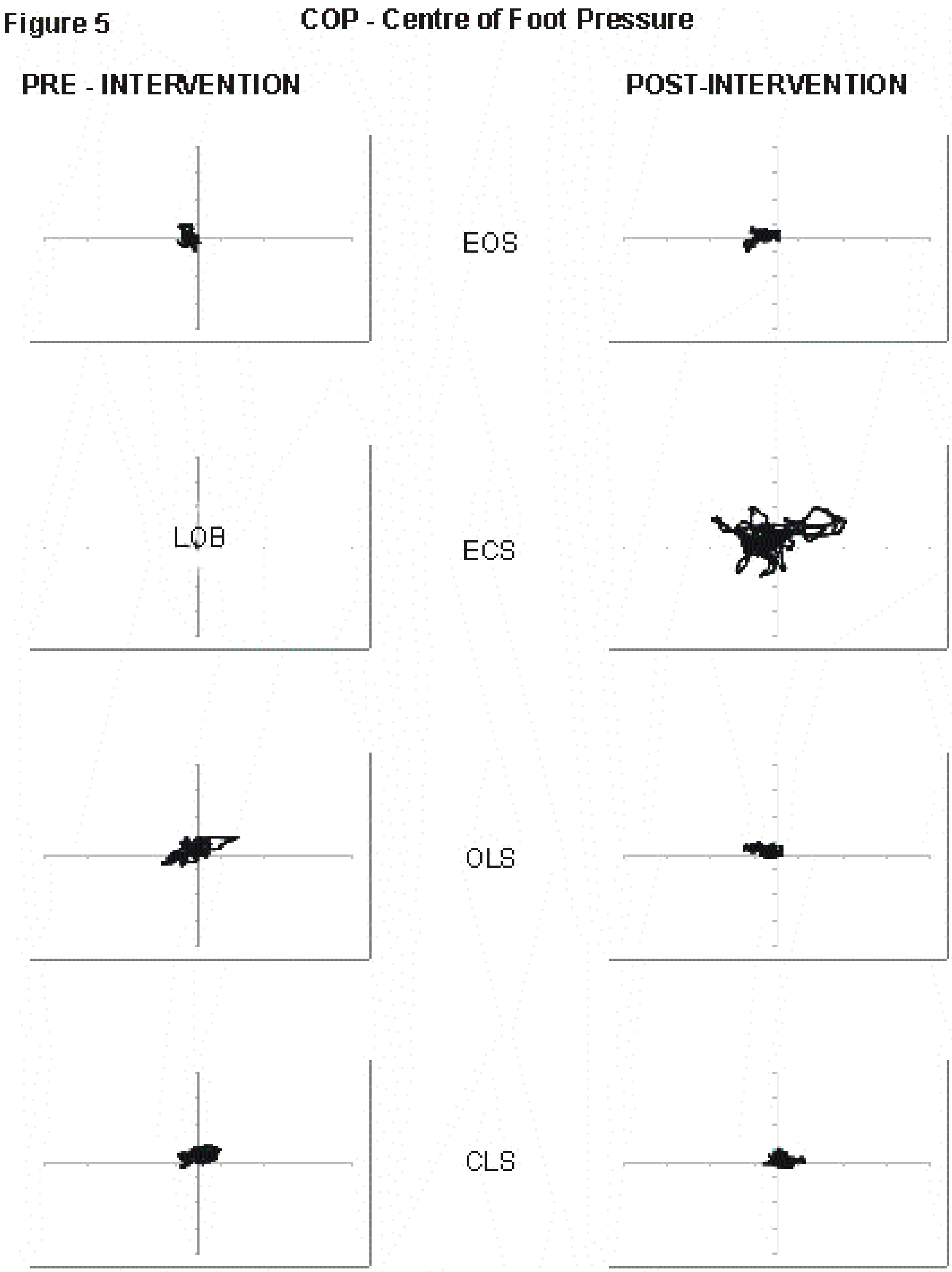


Figure 5 presents representative X-Y plots of medial-lateral (ML) and anterior-posterior (AP) centre of foot pressure (COP) excursions standing on a sponge surface. Conditions consist of eyes open (EO), eyes closed (EC), open loop (OL) and closed loop (CL) visual tracking conditions. LOB = loss of balance.

Figures 6a and 6b present the group mean and standard error mean (SEM) for COP Total Path Length (TPL) pre and post-intervention. As presented in Table 1, the results of the modified Clinical Test of Sensory Interaction in Balance (mCTSIB) demonstrates significant change in balance performance pre to post intervention with decreased COP TPL in both ML ($p = 0.02$) and AP ($p = 0.02$) directions. The EC condition while standing on the sponge surface demonstrates the greatest degree of COP TPL excursion for a single condition in both ML and AP directions and significant decrease in TPL (ML: $p = 0.02$ and AP: $p = 0.02$) pre to post-intervention was observed for this condition. Significant decrease in AP – TPL was also observed for the visual tracking conditions of open loop (OL) when standing on the sponge surface ($p = 0.03$) and closed loop (CL) when standing on the fixed surface ($p = 0.02$). No significant effect of treatment was observed in ML - TPL for open loop and closed loop visual tracking tasks while standing on fixed (OLF, CLF) or sponge (OLS, CLS) surfaces. No significant effect of treatment was observed in COP TPL in the AP direction for open loop visual tracking while standing on a fixed surface (OLF) and closed loop visual tracking while standing on a compliant sponge surface (CLS). For individual conditions, no effect was demonstrated in TPL in either ML or AP direction for standing with eyes open on fixed (EOF) or sponge (EOS) surface conditions.

STANDING BALANCE: CENTRE of FOOT PRESSURE (COP) on fixed and sponge surfaces

Figure 6a:

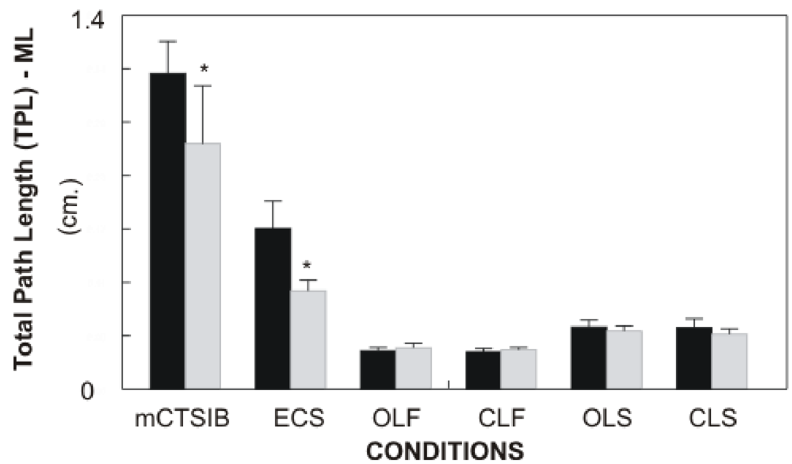
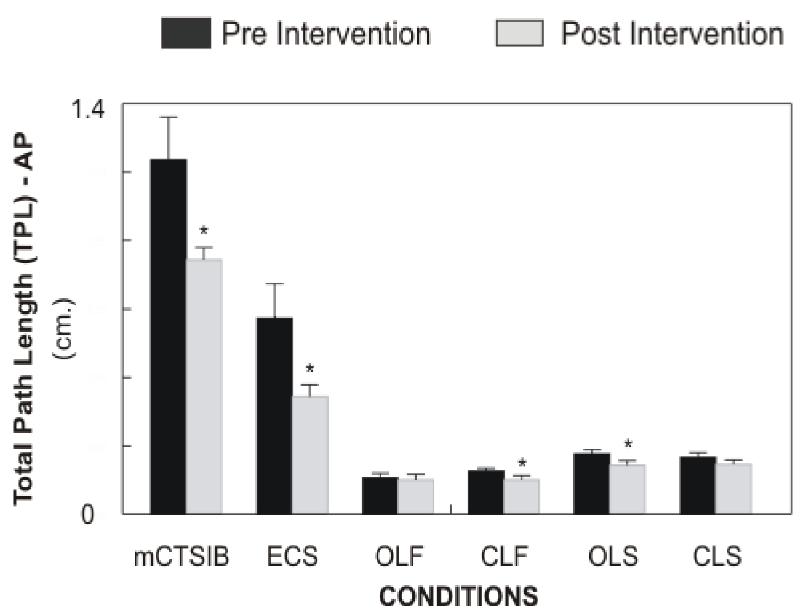


Figure 6b:



Figures 6a and 6b present group mean and standard error mean (SEM) pre and post intervention for COP total path length (TPL) on fixed (F) and sponge (S) surfaces. mCTSIB = modified Clinical Test of Sensory Interaction in Balance (consists of eyes open –EO- and eyes closed –EC- on F and S surfaces). OL = open loop visual tracking task; CL = closed loop visual tracking task.
* = significant difference on t-test ($p<0.05$)

See Table 1 for group p statistics (t-test, $p < 0.05$) and effect size (Cohen's d) of COP Total Path Length (TPL) for ML and AP COP excursions. As presented in Table 1, the effect size for mCTSIB in ML and AP directions are large at 0.9 and 1.0 respectively. Effect sizes for ECS (ML and AP) and OLS (AP) conditions have large effect sizes at 1.0 and 0.9 respectively. Moderate effect size of 0.5 in observed in the CLS (AP) condition. Small effect sizes ranging from 0.1 to 0.3 were observed in EOS (ML and AP), OLS (ML) and CLS (ML) conditions.

TABLE 1: Centre of Foot Pressure (COP) – Total Path Length (TPL) – ML and AP

N = 9 ($p < 0.05$)

VARIABLE	CONDITION	p value (t statistic, df)	Effect Size (d)
TPL ML	mCTSIB	0.02 (2.7, 8)	0.9
	EOS	0.8 (0.2, 8)	0.1
	ECS	0.02 (2.9, 8)	1.0
	OLS	0.6 (0.5, 8)	0.2
	CLS	0.5 (0.7, 8)	0.3
TPL AP	mCTSIB	0.02 (2.7, 8)	1.0
	EOS	0.4 (0.9, 8)	0.3
	ECS	0.02 (2.8, 8)	1.0
	OLS	0.03 (2.6, 8)	0.9
	CLS	0.3 (1.1, 8)	0.5

Standing Balance: COP Total Path Length in ML and AP directions on fixed and sponge surfaces during variety of conditions: EO = eyes open; EC = eyes closed; OL = open loop visual tracking; CL = closed loop visual tracking; s = sponge surface; mCTSIB = modified Clinical Test of Sensory Interaction in Balance (consists of standing EO and EC on fixed and sponge surfaces)

As presented in Table 2, a significant decrease pre to post-intervention was observed in trunk root mean square (RMS) angular velocity for EC conditions while standing on a compliant sponge surface (ML: $p = 0.05$ and AP: $p = 0.02$). Significant decrease was observed pre to post-intervention in trunk AP - RMS for CL visual tracking while standing on the sponge surface ($p = 0.03$). Significant decrease was observed pre to post intervention in mCTSIB RMS angular velocity in ML ($p = 0.02$) and AP ($p = 0.02$) directions. No significant effect of treatment was observed in trunk RMS angular velocity for OL visual tracking while standing on a compliant sponge surface. As well, no significant effect of treatment was observed in ML trunk RMS for eyes open (EO) and closed loop (CL) visual tracking when standing on a compliant sponge surface.

As presented in Table 2, the effect sizes are large for trunk AP - RMS angular velocity OLS, CLS, EOS, and ECS, with results ranging from 1.0 to 2.1. Effect sizes for mCTSIB RMS angular velocity in ML and AP directions was moderate at 0.5 and 0.6 respectively. Moderate effect sizes ranging from 0.5 to 0.7 was observed in ML – RMS angular velocity for OLS, CLS, EOS and ECS conditions.

TABLE 2: STANDING BALANCE - TRUNK RMS Angular Velocity – ML and AP

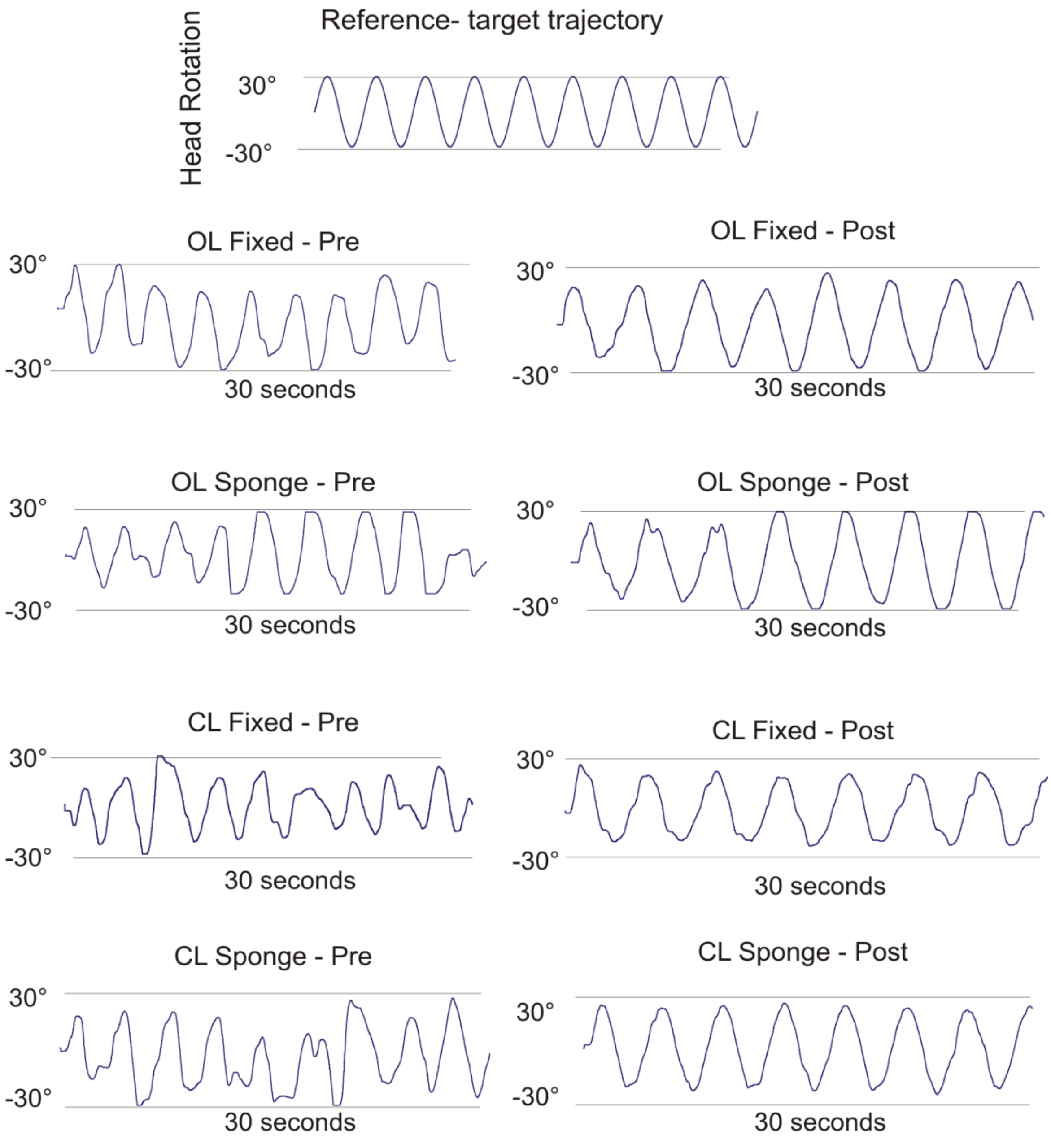
N = 9 (p < 0.05)

VARIABLE	CONDITION	p value (t statistic, df)	Effect Size (d)
RMS Angular Velocity ML	mCTSIB	0.02 (2.8, 8)	0.5
	EOS	0.09 (1.9, 8)	0.7
	ECS	0.05 (2.2, 8)	0.7
	OLS	0.3 (1.0, 8)	0.5
	CLS	0.1 (1.8, 8)	0.7
RMS Angular Velocity AP	mCTSIB	0.02 (3.0, 8)	0.6
	EOS	0.03 (2.6, 8)	2.1
	ECS	0.02 (2.9, 8)	1.5
	OLS	0.07 (2.1, 8)	1.0
	CLS	0.03 (2.5 8)	1.2

Standing Balance: Trunk RMS (root mean square) angular velocity in ML and AP directions on fixed and sponge surfaces during variety of conditions: EO = eyes open; EC = eyes closed; OL = open loop visual tracking; CL =closed loop visual tracking; s = sponge surface; mCTSIB = modified Clinical Test of Sensory Interaction in Balance (consists of standing EO and EC on fixed and sponge surfaces)

Figure 7 presents a representative sample of OL and CL visual tracking tasks on the fixed and sponge surfaces pre and post intervention. A reference trajectory indicating the sinusoidal movement of the target is shown. The magnitudes and consistency of rotation amplitudes across cycles improves post-intervention (i.e. movement of trajectories become more sinusoidal).

Figure 7: **TRACKING TASKS**



Representative sample of open loop (OL) and closed loop (CL) visual tracking tasks on fixed and sponge surfaces.

Figure 8 presents the group mean and standard error mean (SEM) for the Coefficient of Determination (COD) as a measure of gaze stability for each task and surface condition, pre and post-intervention. As presented in Table 3, significant increase pre to post-intervention in COD was observed in four of the six conditions. Open loop ($p = 0.002$) and CL ($p = 0.005$) tracking tasks on the compliant sponge surface as well as CL tracking during treadmill walking at 0.7 mph ($p = 0.001$) demonstrate substantial improvement pre to post-intervention. A significant increase in COD was also observed pre to post-intervention for OL visual tracking while standing on a fixed surface ($p = 0.03$). Improvement pre to post-intervention is observed for CL visual tracking task on a fixed surface and OL visual tracking during treadmill walking conditions however it is not significant.

**GAZE STABILITY – COEFFICIENT OF DETERMINATION (COD)
for OL and CL visual tracking tasks on a variety of surfaces
and during treadmill walking.**

Figure 8:

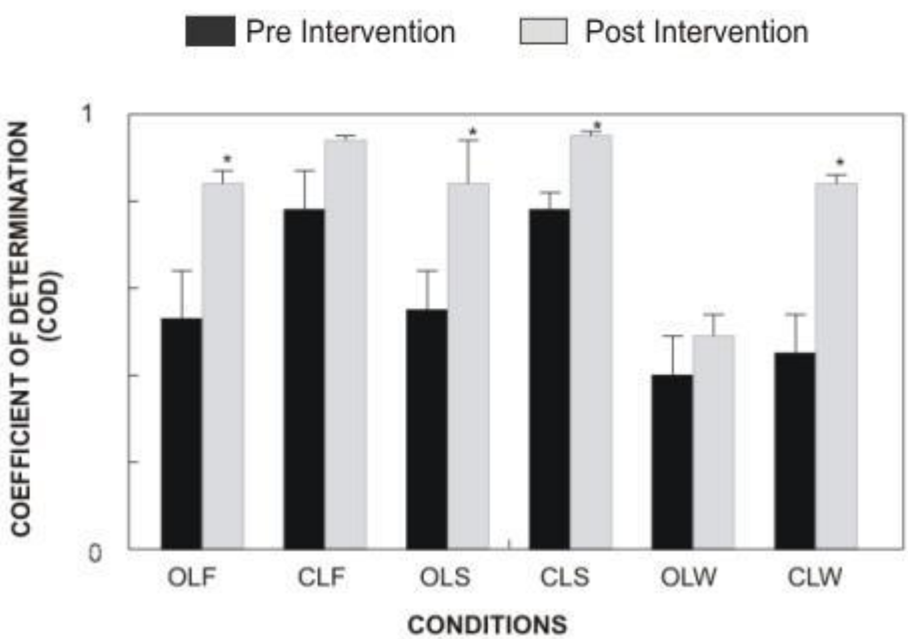


Figure 8 presents group mean and standard error mean (SEM) pre and post intervention for Coefficient of Determination (COD) for open loop (OL) and closed loop (CL) visual tracking tasks while standing on fixed (F) and sponge (S) surfaces and during treadmill walking at 0.7 mph (W).
* = significant difference on t-test ($p<0.05$)

As presented in Table 3, the effect sizes are large for OL and CL tracking tasks on the fixed and sponge surfaces and range from 0.8 to 1.7. Effect sizes are large for OL and CL visual tracking task composite scores at 1.6 and 1.5 respectively. Moderate effect size of 0.7 was observed for CL visual tracking task during treadmill walking. Small effect size of 0.4 was observed for OL visual tracking task during treadmill walking at 0.7 mph.

TABLE 3: GAZE STABILITY: Coefficient of Determination (COD)

N = 9 ($p < 0.05$)

CONDITION	p value (t statistic, df)	Effect Size (d)
OL Fixed	0.03 (2.6, 8)	1.3
CL Fixed	0.1 (1.8, 8)	0.8
OL Sponge	0.002 (4.3, 8)	1.4
CL Sponge	0.005 (3.8, 8)	1.7
OL Walking	0.5 (0.7, 8)	0.4
CL Walking	0.001 (4.8, 8)	0.7
OL Composite (F, S, W)	0.01 (2.5, 8)	1.6
CL Composite (F, S, W)	0.01 (3.3, 8)	1.5

COD (Coefficient of Determination) as measure of gaze stability: visual tracking tasks on a variety of surfaces and during treadmill walking at 0.7 mph. OL = open loop visual tracking CL = closed loop visual tracking; F = fixed surface; S = sponge surface; W = treadmill walking at 0.7 mph.

An example of power spectral density analysis (FFT -Fast Fourier Transform) is presented in Figure 9. Figure 5 presents group means and standard error of means (SEM) of percentage of total power of the Primary frequency, Low frequency and High frequency bands for head rotation during OL and CL visual tracking tasks while standing on fixed and sponge surfaces and during treadmill walking, pre and post-intervention.

PSD – HEAD ROTATION: OPEN LOOP (OL) and CLOSED LOOP (CL) visual tracking tasks on a variety of surfaces and during treadmill walking.

Figure 9:

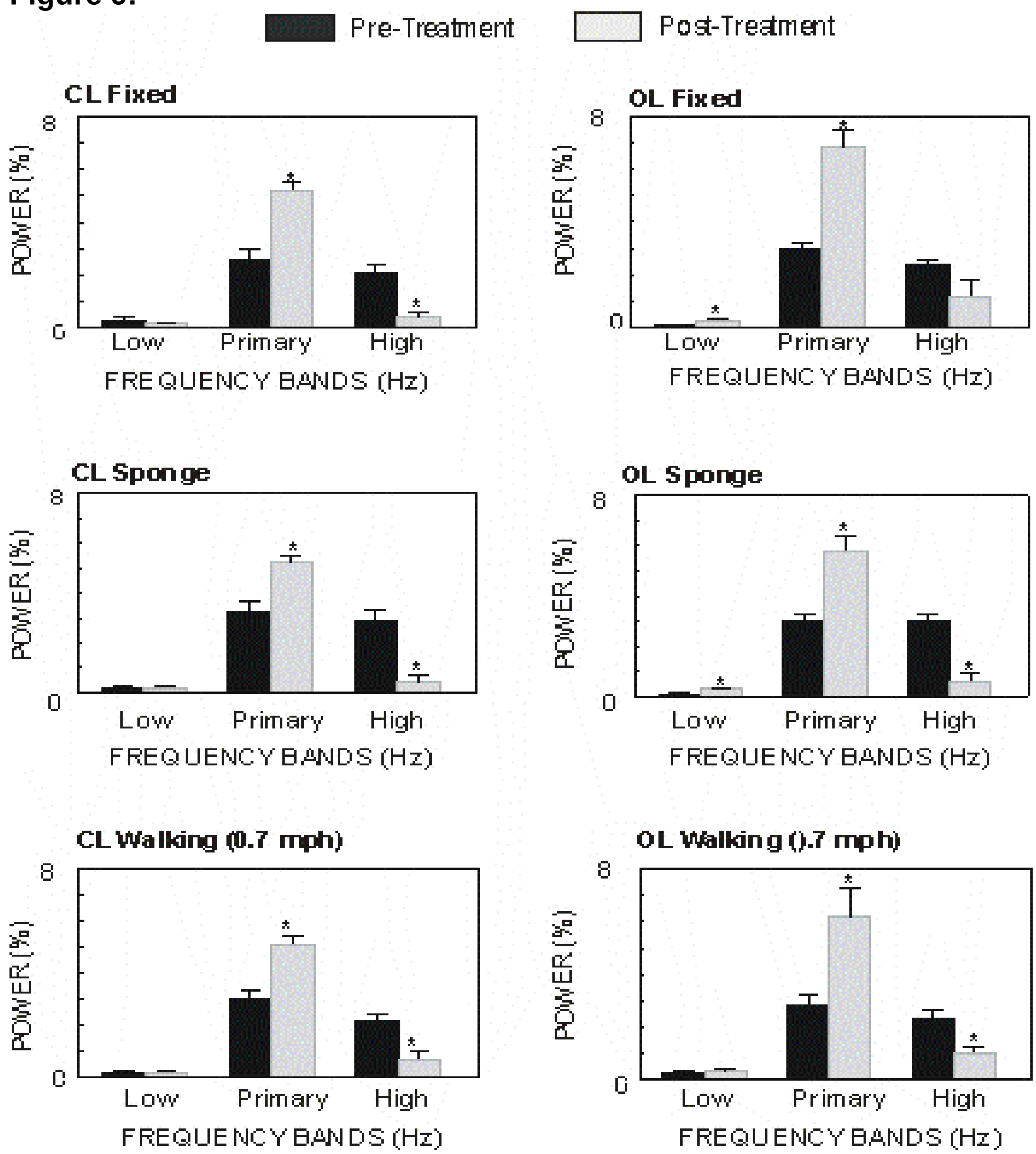


Figure 9 presents group mean and standard error mean (SEM) for open loop (OL) and closed loop (CL) visual tracking for power spectral density of head rotation during standing on fixed (F) and sponge (S) surfaces and during treadmill walking at 0.7 mph (W). * = significant difference on t-test ($p<0.05$)

Gait stability was analyzed using power spectral density analysis of the trunk angular velocity signal. One participant was excluded from FFT analysis, as the data collection was not completed for the required duration of the testing.

Figures 10a and 10b present PSD analysis of trunk Root Mean Square (RMS) angular velocity in ML and AP directions during CLW and OLW conditions, pre and post-intervention. As presented in Table 4, there was a significant shift in power spectral density pre to post-intervention in ML trunk angular velocity during open ($p = 0.01$) and closed loop ($p = 0.01$) visual tracking during treadmill walking. Following treatment (intervention) there was a significant shift in power distribution of trunk motion from the high frequency bands to the primary frequency of the walking step cycle. There was no change in the total power distribution in the low frequency band.

Figure 10a: **GAIT STABILITY – PSD of Trunk RMS ML Angular velocity**

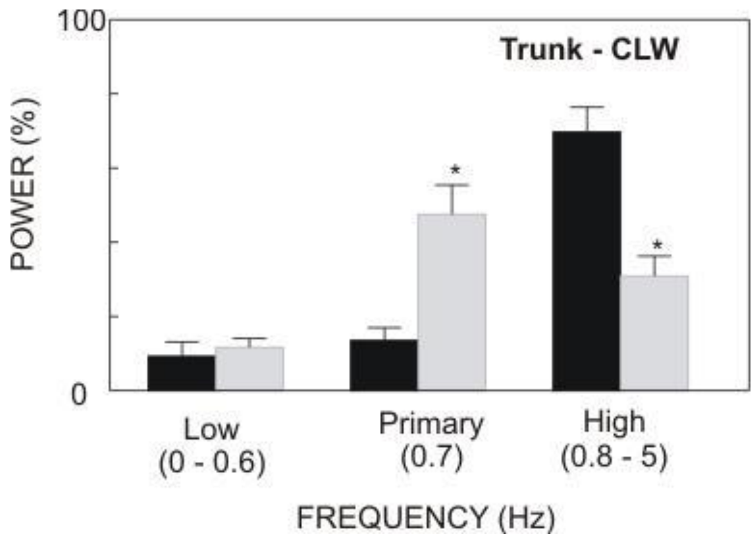
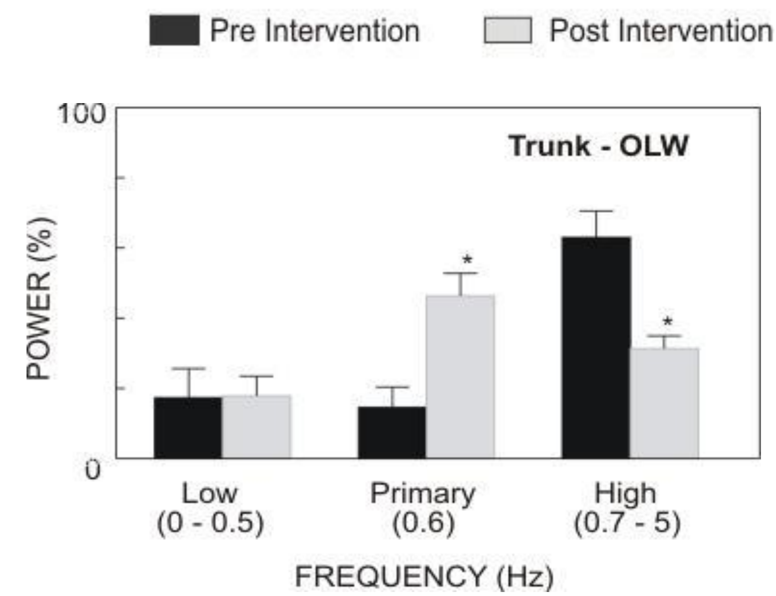


Figure 10b:



Figures 10a and 10b present group mean and standard error mean (SEM) pre and post intervention for the percentage of total power in the three frequency bands (Low, Primary and High) in power spectral density analysis for ML trunk angular velocity. Figure 10a is closed loop (CL) visual tracking and figure 10b is open loop visual tracking (OL) during treadmill walking at 0.7 mph. * = significant difference on t-test ($p<0.05$)

As presented in Table 4, the effect sizes are large for high frequency bands for OLW (> 0.06 Hz) and CLW (> 0.07 Hz) at 1.9 and 2.2 respectively. Large effect sizes of 2.0 were observed for CLW at the primary frequency (0.07 Hz) and 1.8 for OLW at the low frequency (< 0.06 Hz) band. The effect sizes are small for OLW primary frequency (0.06 Hz) and CLW low frequency (< 0.07 Hz) at 0.02 and 0.3 respectively.

TABLE 4: TRUNK PSD (FFT): Angular Velocity - ML

N = 8 ($p < 0.05$)

CONDITION	p value (t statistic, df)	Effect Size (d)
OLW < 0.06 Hz	0.9 (0.1, 7)	1.8
OLW 0.06 Hz	0.01 (3.3, 7)	0.02
OLW > 0.06 Hz	0.01 (3.8, 7)	1.9
CLW < 0.07 Hz	0.5 (0.6, 7)	0.3
CLW 0.07 Hz	0.01 (3.5, 7)	2.0
CLW > 0.07 Hz	0.002 (4.9, 7)	2.2

Gait Stability Measure – Trunk FFT (Fast Fourier Transform) of angular velocity in ML direction: Power spectral density analysis for treadmill walking at 0.7 mph during OL and CL visual tracking tasks. OL = open loop visual tracking; CL = closed loop visual tracking; W = treadmill walking.

Table 5 presents results of Wilcoxan Signs Ranks Test of pre to post-intervention analysis of the Dynamic Gait Index (DGI) and Dizziness Handicap Inventory (DHI). Two participants did not complete the DHI post-intervention. A significant decrease in DHI scores ($p = 0.03$) was observed pre to post-intervention. No effect was observed pre to post-intervention for DGI.

TABLE 5: Wilcoxan Signed Ranks Test Results for DGI and DHI

($\alpha = 0.05$)

ASSESSMENT	PERCENTILES			N	Z – statistic	p - value
	25th	50th(median)	75th			
DGI - Pre	20	22	24	9	1.89	0.13
DGI - Post	21.5	22	24			
DHI – Pre	26	48	52	7	2.12	0.03
DHI – Post	18	24	36			

Percentiles and p-values for Dynamic Gait Index (DGI) and Dizziness Handicap Inventory (DHI) pre to post-intervention.

7. DISCUSSION:

When injury or disease causes disruption to the integrity and functioning of the vestibular system, difficulty with gaze control and balance can occur. Symptoms such as dizziness, blurred vision due to nystagmus or oscillopsia, vertigo, disorientation, imbalance and unsteadiness, which can lead to falls, are common complaints. The primary hypothesis was impairments in gaze control, balance control and levels of dizziness of people with PVD would improve in response to a computer-based vestibular rehabilitation home program.

The main findings of this study revealed that gaze control during head motion while standing on a compliant surface and during walking increased significantly post-intervention. Balance measures of COP total path length (TPL) revealed significantly decreased sway post-intervention. Perception of dizziness as measured by DHI scores decreased significantly post-intervention.

Previous studies have demonstrated that gaze stability exercises improve visual acuity during active head rotation.[52,53,135,141,156] Schubert *et al* (2010) examined gaze of eleven (11) participants. Participants were seated and asked to focus on a stationary target while rotating their heads and then during passive head rotation produced by the therapist. They found significant reduction in gaze position error on a computerized Dynamic Visual Acuity (DVA) test. During the DVA test, target motion velocity and head motion where assessed. It was suggested that an improved VOR gain was partially responsible for the improved gaze control in the PVD group. A similar finding was reported by Szturm *et al* (1994) that showed increased VOR gain following a home training program where participants were asked to read while rotating their head horizontally, vertically and diagonally. It was suggested that exercises that promote varying degrees of retinal image slip in conjunction with head movement are necessary for VOR adaptation in those with PVD. Loader *et al* (2007) examined twenty-four (24) participants with unilateral PVD (12 in Experimental group and 12 in Control group) for ten sessions over three weeks. The experimental group received OKS treatment consisting of standing and reading random moving texts projected onto a blank screen. They observed significant improvements in condition 4 (standing with eyes open on unstable surface) and condition 6 (standing with eyes open, unstable surface, sway referenced) of the SOT. It was suggested that use of OKS such as moving visual targets (i.e. words) assists in improving gaze and balance control in those with unilateral PVD.

Results of COD for OL and CL visual tracking tasks demonstrate improvement post-intervention (see Figure 7) with substantial improvement when standing on the compliant sponge surface and during walking. Open loop visual tracking while standing on the fixed surface demonstrated significant change post-intervention while there was no significant change observed for closed loop visual tracking when performed on the fixed surface.

The use of computer games promotes visual fixation of random moving targets thus incorporating active unpredictable head movements in order to foveate on the target, “capture” the target, select the appropriate action and achieve the goal of the game. Unpredictable head movements can also be generated through the participant’s use of a compliant sponge surface, as the sponge does not reciprocate changes in body position as efficiently as a solid surface therefore leading to increased passive head motion that must be compensated for in order to maintain foveation. The results of substantial improvement in CL visual tracking task during walking post-intervention suggest there may be overflow from treatments that incorporate active visual tracking tasks in conjunction with passive head movements, as seen when standing on a sponge, to improved visual tracking during walking. Scherer *et al* (2008) support this finding in a pilot study of five participants (3 with PVD and 2 normal). They examined the effect of active gaze stability exercises and balance exercises as part of a home treatment program and found improvements in both active and passive DVA scores post-treatment for 2 of the 3 participants and felt the active gaze exercises may have carry-over effects to passive DVA.

Passive motion of the head and trunk is a critical issue to deal with in PVD as it challenges gaze stability.[55,89] Passive motion increases slightly from fixed to sponge surface in standing and increases substantially during treadmill walking.[76] Results of gaze testing (i.e. OL and CL visual tracking tasks) were similar for fixed (F) and sponge (S) surfaces (group means pre-intervention: OLF = 0.53, CLF = 0.78, OLS = 0.55, CLS = 0.78) and decreased substantially during treadmill walking (W) (group means pre-intervention: OLW = 0.40, CLW = 0.45). Differences observed between standing and treadmill walking are likely due to passive head motion. There were significant increases in COD group mean post-intervention for OL visual tracking when standing on the fixed surface (OLF-post = 0.94) and for OL and CL visual tracking conditions standing on the sponge surface (OLS-post = 0.84, CLS-post = 0.95) and CL treadmill walking (W) increased substantially post-intervention (CLW-post = 0.84). There was no effect of intervention for the CL visual tracking condition when standing on the fixed surface. In consultation with graduate students at the vestibular laboratory at the University of Manitoba who carried out a study looking at normal healthy adults (they do not report vestibular symptoms) during visual tracking tasks and treadmill walking, and determined mean COD values for CL visual tracking on the fixed, sponge and treadmill walking to be 0.82, 0.86 and 0.74 respectively. Our post-intervention findings for CLS (0.95) and

CLW (0.84) are greater than the mean for normal healthy adults thus interventions that incorporate foveation of moving targets, as well as moving the head while foveating on a target, used in conjunction with passive motion such as standing on unstable support surfaces (i.e. compliant sponge) or during treadmill walking are key components in treatment of gaze control.

Smooth pursuit is a useful compensatory mechanism for a deficient angular VOR (aVOR) when target velocities are less than 100 degrees/second.[15] The frequency of target motion was set at 0.4 Hz and head rotation amplitude was sixty degrees (60°) peak to peak with head average velocity approximately 60 degrees/second thus during assessment of OL and CL visual tracking tasks the smooth pursuit system was being stimulated.

Passive head motion analysis was carried out by other graduate students in the vestibular laboratory at the University of Manitoba on five (5) participants who did not report vestibular symptoms. In consultation with the graduate students, it was determined that average peak to peak head velocities in the roll and pitch planes for OL visual tracking were 3˚ and 8 ˚ per second for fixed and sponge surfaces respectively and 30˚ per second during treadmill walking at 0.7 mph. Average RMS head angular velocities in the ML direction were 1.2 ˚/sec, 2.8 ˚/sec and 11.0 ˚/sec for OL fixed, sponge and treadmill walking respectively. Thus walking produced significantly more passive head motion than standing. A study by Cromwell *et al* in 2004 looked at head RMS angular velocity during walking with and without foveation and reported normal walking value of

9.4 ± 2.9 ˚/sec. As the demand of the task increased due to foveation demands the passive head motion decreased.

The computer interface and games selected for the present study had the features listed below and through combining inexpensive head-tracking input devices and commercial pressure-tracking devices to interact with engaging "therapeutic" exercise and activity games, assessment tools and home treatment programs were developed.

1. It has been suggested that rehabilitation of gaze stability should incorporate unpredictable head rotations in addition to predictable cyclic head rotations.[7,141] Computer-based home rehabilitation program incorporates predictable and unpredictable head rotations and participants were instructed to play specific computer games that incorporated cyclic and/or unpredictable random head movements depending upon their vestibular deficit.
2. Small amplitude, progress to large target and head amplitudes.
3. Slow, progress to fast head movements.
4. Large, progress to small targets, therefore requiring increased precision of movement and foveation.
5. Presence of distracters and crowding of visual background and/or moving backgrounds.

Examples of computer games used in this study were purchased from Big Fish Games (http://www.bigfishgames.com) and include:

- Action Ball 2
- Aquaball
- Brave Piglet
- Jet Jumper
- X-Avenger

The amount of head motion can also be graded, first by using a standard optical mouse (hand use and no head movement) and progressing to using the head tracking motion sense mouse thereby requiring active head rotation as the participant must move their head to move the game sprite and thus graded retinal image slip is produced which assists with VOR adaptation.[156]

In addition to providing spatial orientation information for upright stability during locomotion, vision supports additional cognitive functions such as navigation and obstacle avoidance.[85] An interesting finding of Szturm *et al* 2013 shows that tracking visual targets during walking results in less trunk motion than walking alone in normal healthy adults. A study by Mamoto *et al (2002)* involving those with PVD examined trunk and head motion while walking and visually fixating on a target and showed decreased trunk motion in the yaw plane and increased trunk motion in the pitch and roll planes. Additionally, they found head angular velocity in the pitch and roll planes was greater in the vestibular disorder group. Decreased trunk motion would minimize passive head motion and therefore assist in stabilizing gaze position during visual tracking tasks, interacting with moving targets or when reading words.

Consistent with these studies, results of trunk angular velocity power spectral density (PSD) analysis during treadmill walking demonstrates a significant shift of energy from high frequency bands toward the primary bands post-intervention for both OL and CL visual tracking tasks. This transfer of power from higher frequencies toward primary frequency is indicative of efficiency of movement and improvement in walking balance. Post-intervention, the decrease in high frequency trunk motion was also accompanied by improved visual tracking. These results demonstrate overflow from treatments that incorporate active and passive head motion during goal-directed visual tracking tasks.

In this regard, Lambert *et al* (2010) have shown that visual acuity (reading letters from an eye chart) does not decrease during treadmill walking in young healthy participants, although visual acuity decreased significantly in participants with PVD. Hillman *et al* (1999) reported on the complexity of vision and vestibular input and effects on head-on-trunk stability during walking and found participants with vestibular deficits performed worse than control participants on walking tasks that required visual acuity. A decline in the ability to foveate and track visual targets in the presence of unpredictable (i.e. due to compliant sponge surface) or passive head motion (passive due to treadmill movement) would have a significant impact on performance of visual-based cognitive tasks for those with decreased gaze and balance control.

Studies have shown that it is more difficult to visually track a target against a structured rather than a blank background and particularly more difficult with the use of a background that moves at a differing speed to the target.[6,99] These factors need to be taken into consideration during VR gaming programs. In keeping with concepts of activity-dependent neuroplasticity, computer games were chosen with a variety of components such as:

- Static OKS background and predictable ocular following to random moving OKS background and random ocular following.
- Searching for static objects within static OKS background to searching for moving objects within a moving OKS background.

Dizziness and unsteadiness are chief complaints in those with PVD. Jacobson and Newman (1990) developed the Dizziness Handicap Inventory as a method to measure self-perception of handicap due to dizziness. Significant decrease in participant perception of handicap due to dizziness was observed post-intervention. This is consistent with studies that suggest gaze stability exercises reduce the perception of dizziness handicap experienced by participants with unilateral PVD.[140]

An important component in VR training is to incorporate moving images or optical flow. For example, moving through a crowded shopping mall or waiting to cross a busy street, the movement of people or traffic through your visual field creates optical flow. These optokinetic conditions can result in increased body sway if you are reliant on visual input for balance control. Chang and Hain (2008) proposed that optical flow, OKS and one’s ability to use stationary objects within one’s visual field to assist with balance control, affected dizziness. They developed a VR program using a series of OKS backgrounds and the use of a stationary "anchor" in the foreground thereby creating optical flow scenarios and challenging stability. The common belief is that the nervous system adapts to the new sensory conditions by down weighting the visual flow and up weighting other sensory inputs (i.e. proprioception) that provide accurate information about the environment and therefore, equilibrium is maintained.[22,111]

Vestibular, visual and somatosensory inputs are important to the normal regulation of stability. Several studies have examined standing balance performance of patients with peripheral vestibular deficits under altered somatosensory and visual conditions.[36,83,156] These studies, Davlin-Peter *et al* 2010, Desai *et al* 2010, and Perez *et al* 2006, have demonstrated that during altered sensory conditions (i.e. unstable support surface with eyes open or closed and corresponding conditions 5 and 6 of the SOT), body sway significantly increased in patients compared to healthy age-matched participants and patients frequently fell. These findings indicated that the loss of an absolute spatial reference provided by a deficient or absent vestibular sense organ together with eliminated or distorted vision or somatosensory spatial information compromises balance control and upright posture is difficult to maintain and falls may occur. During conditions one to three of the SOT or when standing on a fixed surface with eyes closed, individuals with PVD do not lose their balance. Indeed, we observed no falls during eyes open or eyes closed while standing on fixed surface conditions. These findings would indicate that SOT conditions one to three would not serve as good outcome measures in this population.

Results of COP analysis during altered surface and/or visual conditions are consistent with these studies. When one sensory system is altered or diminished (i.e. standing on a solid surface with eyes closed) no effect was observed, however, when two or more sensory systems are altered (i.e. standing on a compliant sponge with eyes closed) significant body sway was observed and there were two (2) losses of balance recorded pre-intervention. Condition 5 of the CTSIB (condition 4 of mCTSIB – sponge support surface and eyes closed) is reported to rely more on vestibular system input and those with PVD have been shown to perform poorly.[147] Our results of COP excursions for mCTSIB were significantly decreased pre to post-intervention in both ML and AP directions indicating adaptation to the diminished vestibular input and possible re-weighting of the vestibular input on the intact side for those with unilateral PVD and/or re-weighting of somatosensory input.

Results of RMS analysis of trunk angular velocity during altered surface and/or visual conditions corroborate the COP analysis. Trunk RMS angular velocity for mCTSIB was significantly decreased pre to post-intervention in both ML and AP directions.

Results of trunk angular velocity PSD analysis (see Figure 9, FFT: Trunk Angular Velocity) indicate significantly decreased trunk motion was observed post-intervention. Results indicate significant improvement in shift of power from high frequency toward the primary frequency band for OL ($p = 0.01$) and CL ($p = 0.002$) visual tracking tasks post-intervention. This shift in power toward the primary frequency for trunk angular velocity indicates improvement in walking stability. In deficient or absent vestibular input, somatosensory and visual input can provide external spatial references to an intact central nervous system and adaptation to balance challenges can occur.

No effect of treatment was found on Dynamic Gait Index (DGI) pre to post-intervention. The DGI is a series of eight (8) walking tasks carried out on a fixed surface. Speed of walking is self-paced. There are no visual tracking requirements during gait and head movements are unidirectional, self-paced and self-limited. Foveation requirements are minimal such as object recognition in order to navigate around or over the object. One flight of stairs is required to ascend and descend. Due to minimal gaze control and balance requirements for study participants during the DGI, a ceiling effect was observed. One criticism of the DGI is that it has a low ceiling effect and does not capture the deficits in those with higher balance function and less impairment.[114]

Computer games were chosen for variety and degree of difficulty and were deemed to be motivating to encourage daily rehabilitation. Review of daily exercise logs completed by 7 of 9 participants revealed time of home program ranged from 1 minute to 105.5 minutes per day (average 35.4 minutes/day). Through the use of the head mounted mouse the ocular following and head motion are blended together while the participant becomes engaged in the game and is motivated to perform their rehabilitation program.

A nervous system that is intact is capable of adapting to new sensory and environmental conditions. For example, rely more on somatosensory information such as proprioceptive signals from muscle spindles and Golgi tendon organs to support upright posture and to make timely corrective adjustments to manage unpredictable conditions or sudden loss of balance. Somatosensory information used in conjunction with foveation is even more important for those with PVD.

8. STUDY LIMITATIONS:

The ability to monitor actual time playing the computer games was limited to participant self-report through manual completion of exercise logs. While this is adequate and common practice, the ability to have games automatically log and send actual time played, scores and levels of game achieved during play would assist with clinician assessment and progression of the home program.

The use of an instrumented treadmill for recording gait variables during treadmill walking would be a useful instrument in determining changes in walking balance. Previous studies comparing normal and those with vestibular disorders [90,105] have shown differences in gait parameters of double support, cadence and step length variability. Seeing changes pre to post-intervention would be a useful measurement of changes in balance control.

Recording head velocity with an inertial sensor during OL and CL visual tracking tasks while standing on a variety of surfaces and during treadmill walking would provide information regarding changes in head motion for each surface and visual tracking task condition. This would provide valuable information regarding degree of passive head movement, head velocity during walking and standing tasks and direction of head motion (i.e. pitch, roll or yaw).

This study did not view actual eye movements, however, identifying eye movements during OL and CL visual tracking tasks on a variety of surfaces may provide further insight with respect to the integration of vision, vestibular and somatosensory inputs. Synchronized and simultaneous recording of head, eye and computer target motions would assist with identifying contributions of VOR, smooth pursuit and saccadic eye movements during vestibular rehabilitation through computer gaming.

9. CONCLUSION:

Dizziness, vertigo, unsteadiness, and imbalance are common complaints heard by clinicians treating vestibular disorders. Investigations in the study of balance control have clearly demonstrated the interaction of vestibular, visual and somatosensory inputs in regulating stability. Several studies [16,33,36,167] have investigated standing balance in elderly or participants with PVD by altering somatosensory input and/or visual conditions and have reported that an absent or malfunctioning vestibular sense organ interferes with balance control, as it is an absolute internal spatial reference. These studies demonstrated that elimination or distortion of one sensory input (i.e. stand on a compliant sponge surface) did not show significant changes in balance control, however distortion or elimination of two or more sensory inputs (i.e. stand on compliant sponge surface with eyes closed, or conditions 5 and 6 on SOT) results in significantly increased body sway and falls may occur. COP results of this study concur with these findings in that conditions on the fixed surface did not demonstrate changes pre to post-intervention whereas conditions that distorted two sensory inputs demonstrated significant changes post-intervention.

Studies show that tasks involving gaze shifts with head rotation result in increases in body sway and altered walking patterns in those with PVD.[138,168] Gaze stability, as measured by COD, improves significantly post-intervention for visual tracking tasks while standing on a compliant sponge surface and during treadmill walking. Normal visual processing of a target whether moving or stationary requires the target be fixated on the fovea of the retina. When the image moves off the fovea (excessive retinal image slip), visual acuity decreases and visual blurring occurs. Use of foveation tasks such as CL visual tracking in conjunction with treadmill walking is a useful tool for assessing gaze stability as it mimics real world events, which is critical for activity-dependent, task-oriented neuroplasticity rehabilitation programs.

This research study has demonstrated that a flexible, monitored computer-based gaming platform for task-oriented rehabilitation of gaze and balance impairment is an effective home treatment program for those with PVD.

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