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Quantifying head acceleration during vestibular rehabilitation

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Quantifying Head Acceleration during Vestibular Rehabilitation

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A dissertation submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

Partial Fulfillment

for the degree of

Doctorate of Philosophy

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Preface

This dissertation seeks to answer questions about the mechanisms of recovery in head movement-based vestibular and balance rehabilitation therapy (VBRT) that focus on symptom reduction. While other areas of VBRT that focus on adaptation and sensory substitution have better-know prescriptions for optimal recovery in terms of intensity and duration, less is known about the optimal intensity of exercises for habituation. By providing better understanding the vestibular stimulation during exercises aimed to reduce symptoms of dizziness, this dissertation hopes to make available both a method for collecting acceleration information and provide an objective goal of head acceleration during head movement-based VBRT for optimal recovery.

Chapter 1, the Introduction, discusses the need for vestibular rehabilitation, as well as its strengths and limitations.

Chapter 2, the Literature Review, explores the historical aspects of VBRT. The vestibular system is also reviewed, specifically emphasizing stimulation of the system. We can then critique VBRT from its current outcomes and note the lack of objective measures of input during VBRT. Previous methods of measurement are discussed, followed by the proposition of a new way of measurement focusing on the input to the vestibular system.

Chapter 3, a draft of the first manuscript intended for submission, “Quantification of Head Accelerations during Vestibular Rehabilitation Exercises,” applies the instrumentation used throughout both studies for collecting objective head movement data, the Polhemus Isotrak II magnetometer (Colchester, VT, USA). Using this
instrumentation, head movements were measured in 52 subjects, ranging in age from 20 to 96 years in age. From these movements, linear and angular accelerations of the head were calculated. Acceleration data was then compared across the age continuum, and the independent variables of dizziness and imbalance were explored. This tested the hypothesis that head accelerations decline as a function of age and dizziness and as a function of age and imbalance. Although some researchers (Pritcher, Whitney, Marchetti, & Furman, 2008) have looked at head velocities during gaze stability exercises across ages, the line of research presented in this manuscript focuses on head accelerations during exercises that promote habituation.

Chapter 4: This second manuscript is entitled “A Mathematical Model for Calculating Stimulation of the Semicircular Canals during Head Movements.” This manuscript takes the information from the magnetometer and describes the process to convert the angular positional data into the angular acceleration in each of the planes of the semicircular canals. Using this mathematical model, both the researcher and the clinician have method for estimating the extent of semicircular canal stimulation during traditional and custom VBRT exercises. Once validated, this technique may be useful in measuring the magnitude of stimulation in VBRT, providing a means of quantifying the intensity of head movement during exercises. This serves not only as an instrument for evidence-based practice, but also as a mechanism to confirm vestibular stimulation for potential custom and innovative vestibular rehabilitation.

Future research programs, in an effort to increase patient independence and reduce the risk of falls, will advance innovative methods of VBRT to improve patient accessibility and compliance. This research presents objective documentation of stimulus
intensity (head accelerations) which could lead to greater specificity in vestibular head movement exercise prescriptions. Through a better understanding of how head accelerations decline with age, dizziness, and imbalance, and the investigation of possible tools for detecting the stimulation of the vestibular system during VBRT, the potential is increased for innovative treatment. This is discussed in Chapter 5, the concluding remarks.

Appendices for this dissertation include a thorough discussion of the Pohlemus Isotrak II magnetometer and its calibration for this work (Appendix A), the Matlab code used in the data collection parameters, (Appendix B), as well as the Matlab code for conversion into the planes of the semicircular canals (Appendix C), as written by Jesse Collins.
## Table of Contents

List of Tables ................................................................................................................... vi

List of Figures .................................................................................................................. vii

Abstract ............................................................................................................................ viii

Introduction ..................................................................................................................... 1

Literature Review ............................................................................................................ 7

Manuscript 1: Quantifying head accelerations during vestibular rehabilitation exercises ........................................................................................................................... 25

Manuscript 2: A method for calculating stimulation to the three separate semi-circular canal pairs during head movements ................................................................................. 47

Concluding Remarks ....................................................................................................... 60

Appendices

**Appendix A:** Calibration and Checks ................................................................. 61

**Appendix B:** Matlab code for data collection and analysis ............................ 83

**Appendix C:** Matlab code for rotation matrix (J. Collins) ............................... 87

References ........................................................................................................................ 90
List of Tables

Table 1: ............................................................................................................................31

Table 2: ...........................................................................................................................40

Table 3: ...........................................................................................................................40

Table 4: ...........................................................................................................................42
List of Figures

Figure 1: ........................................................................................................................... 10
Figure 2: ........................................................................................................................... 11
Figure 3: ........................................................................................................................... 33
Figure 4: ........................................................................................................................... 38
Figure 5: ........................................................................................................................... 39
Figure 6: ........................................................................................................................... 41
Figure 7: ........................................................................................................................... 43
Figure 8: ........................................................................................................................... 50
Figure 9: ........................................................................................................................... 51
Figure 10: ......................................................................................................................... 53
Figure 11: ......................................................................................................................... 54
Figure 12: ......................................................................................................................... 55
Figure 13: ......................................................................................................................... 55
Figure 14: ......................................................................................................................... 56
Figure 15: ......................................................................................................................... 57
Figure 16: ......................................................................................................................... 58
Abstract

Dizziness can often be a serious and confounding condition that ranges in severity from annoying to debilitating and affects many people. The most common and effective treatment for persistent dizziness is vestibular rehabilitation therapy, which falls into three categories: adaptation, sensory substitution, and habituation. While more is known about adaptation and sensory substitution, questions remain regarding the exact mechanisms of recovery for habituation. Precisely, the optimal stimulation to the vestibular system, as measured in intensity of head accelerations, is unknown for habituation treatment. In this dissertation are drafts of two manuscripts. The first explores the average intensity of linear and angular head accelerations in non-symptomatic and symptomatic subjects across age and self-reports of dizziness and imbalance during four commonly-used habituation exercises. The second paper presents a mathematical formula for transposing angular displacement in the traditional anatomical planes to the planes of the semicircular canal pairs for collected data on angular displacement of the head. This mathematical model allows for conversion of measurement from overall head accelerations into angular acceleration in the planes of each paired set of semicircular canals, and increases research and clinical knowledge of vestibular stimulation during head-movement exercises.
Introduction

The immediate aim of this research is to measure linear and angular head accelerations of head movements during traditional vestibular rehabilitation exercises. The long-term goal is to improve delivery of vestibular and balance rehabilitation therapy through a better understanding of the stimulation to the vestibular system during these exercises. Comparisons of head accelerations are made across a 70 year range of adult ages, as well as between those who self-report as dizzy or imbalanced versus those who do not report dizziness or balance problems. The methods and results reveal a unique means of collecting head accelerations during head-movement based vestibular rehabilitation exercises, and, within the scope of this literature review, are the first description of head accelerations across continuums of age and vestibular pathology. Both the methods of data collection as well as the results have clinical significance, and set up a program of future research.

Background

Vestibular and balance rehabilitation therapy (VBRT) exercises were first reported in the literature in the 1940’s by two British physicians, Cawthorne and Cooksey (Cooksey, 1946). Modern VBRT has grown from this foundation, with traditional exercises requiring the dizzy patient to move both eyes and head, with noted reduction of patient symptoms and with improvement in the ability to stand, walk, and perform other functions of daily life (Herdman 2007; Corna, et al., 2003; Cowand, Wrisley, Walker, Strasnick, & Jacobson, 1998). VBRT holds specific importance in current research and clinical practice for two reasons. First, dizziness affects up to 40% of the population with
numbers increasing with age (Neuhauser, 2007). Second, dizziness in the general population has been shown to increase the risk of falls twelve-fold, and falls are the leading cause of death and injury in those over 65 years of age (Agrawal, Carey, Santina, Schubert, & Minor, 2009; Centers for Disease Control and Prevention [CDC], 2006). Fortunately, VBRT has also been shown as an effective treatment for the majority of long-standing dizziness, and has been demonstrated to reduce falls as well (Badke, Miedaner, Shea, Grove, & Plye, 2005; Macias, Massingale, & Gerkin, 2005).

Historically, VBRT exercises have evolved from Cawthorne-Cooksey’s original exercises, which ranged from seated exercises to walking up and down inclines with eyes closed, to their modern state, which are classified based upon the goals of adaptation, sensory substitution, and habituation. Reported benefits of VBRT include improved gaze stability during passive and active head movements, increased independence, improved gait speed, stronger standing balance, and reduced symptoms, as measured by both subjective patient report and decreased falls (Badke et al., 2005; Badke, Shea, Miedaner & Grove, 2004; Bonan et al., 2004; Brown, Whitney, Marchetti, Wrisley, & Furman, 2006; Cohen & Kimball, 2004; Cowen, et al., 1998; Deutsch, 2009; Horning & Gorman, 2007; Lubetzky-Wilnai & Kartin, 2010; Silsupadol et al., 2009). Opportunities for improvement in both VBRT practice and research remain. Questions remain regarding the ideal exercise prescription for optimal recovery, specifically for those exercises aimed at symptom reduction, including the optimal intensity of stimulation to the vestibular system (Schubert & Whitney, 2010). Quantification of rotational and translation head movements would provide a more precise measure of stimulus intensity during head movement exercises. Another area for improvement is patient compliance and continued
adherence, especially with home-based exercises. Reported compliance with long-term VBRT is at best 70% through patient self-report, with patient discomfort, lack of confidence with exercises, and other limiting co-morbidities cited as the major obstacles (Forkan et al., 2006). Creative but objectively-based treatment delivery and long-distance monitoring options that can quantify patient movement are but two routes that would help accomplish better compliance. The quantification of head accelerations during traditional exercises for habituation, as presented in this study, can provide direction towards developing normalized, objective measures. These objective normative data are applicable to both clinicians and researchers, in both traditional VBRT and when looking to other modalities of delivery, such as tele-practice or innovative gaming delivery, to increase patient compliance during VBRT and to provide outreach to remote populations.

Purpose

The primary goal of the studies presented in this document is to introduce and validate a unique approach to head movement measurements for use during VBRT. This approach would better quantify the intensity of head movements used during traditional and innovative VBRT modalities, such as computer or video-game based models. Traditional VBRT exercises consist primarily of horizontal or vertical head shakes in the seated, standing, and/or walking conditions. Traditional exercises may also include bending up or down, or turning right or left while seated or standing (Cohen & Kimball, 2004; Herdman & Whitney, 2007). Non-traditional exercises incorporate head movements into other activities, such as dance, martial arts, or video games (Alpert et al., 2009; Schmid, Van Puymbroeck & Koceja, 2010; Clark & Kraemer, 2009; Betker,
Szturm, Moussavi & Nett, 2006). While these modalities all have been shown to reduce patient symptoms and reduce falls, further investigation is needed to better understand intervention characteristics that contribute to successful rehabilitation outcomes. Objective quantification of head movement stimulus parameters are an essential first step.

The two primary aims for this study are:

1. Measure head accelerations during traditional VBRT exercises to determine if head accelerations vary as a function of age and self-report of dizziness and balance function. The completion of this goal begins the process of creating normative data for the amount and type of head acceleration in traditional exercises.

2. Create a novel method of quantifying stimulation of the peripheral vestibular system during head movement-based vestibular rehabilitation through converting linear and angular head displacements into accelerations in the peripheral vestibular system, specifically the semicircular canal pairs, during vestibular exercises. The researcher and the clinician could then objectively assess the amount of stimulation to each of the semicircular canal pairs and more acutely focus on the area of dysfunction.

Postulates

While one could justifiably assume that head accelerations during VBRT exercises would decrease as a function of age, this has not yet been reported in the literature. Head velocities have been explored across ages and etiologies, and while velocity and acceleration are related, velocity alone does not explain the stimulation to
the vestibular end organs (Pritcher et al., 2008). While this study did not find a relationship between age and head velocities during a gaze stability task, it was postulated that head accelerations during traditional VBRT exercises vary as a function of age.

It is also suggested that those reporting dizziness, balance problems, or both will have reduced head accelerations compared to those not reporting dizziness or balance difficulties. While those with dizziness and imbalance report difficulties with head movements, the degree of decrease in head acceleration has not yet been reported in the literature (Herdman, 2007, Jacobson & Shepard, 2008, Neuhauser, 2007). The covariance of head accelerations with both age and dizziness and with both age and imbalance was also explored, since theoretically, there will be a stronger relationship when these factors are evaluated simultaneously.

Finally, this document proposes a mathematical formula for transposing general head displacement measurements from the traditional anatomical axes into the planes of the semicircular canal pairs. A measurement system such as a magnetometer can collect information regarding angular displacement of the head, and the known time constants between points. Those angular displacements are transposed into a new coordinate system matching the position of the semicircular canal pairs using a rotation matrix. From the new coordinate system and the time constants, the amount of angular acceleration for each semicircular canal paired set is calculated.
Significant Contributions/Importance of Study

Objectively quantifying head accelerations during head movement-based vestibular rehabilitation exercises provides another opportunity for concrete treatment goals and outcomes that can validate vestibular stimulation during VBRT. Potentially, these goals would be comparative measures of head acceleration at baseline and at end of the treatment course, to show improvement corresponding with daily head movements. Therapy goals could also be based upon normative data of head acceleration during vestibular rehabilitation exercises. Another potential application is the use of patient monitoring through the duration of vestibular rehabilitation as predictive measures for successful remediation.

The relationship between head accelerations and age, dizziness, and imbalance will be explored and support the goal of establishing a normative data set. Finally, with the mathematical formula demonstrating the amount of acceleration in the planes of the semicircular canal pairs, both researchers and clinicians can better assess the specificity of the interventions utilized in VBRT through estimation of stimulation in each individual semicircular canal pair. This specificity could allow for more targeted intervention development and application, based upon distinct patient site-of-lesion.
Literature Review

Overview

This literature review guides the reader through the physiology of the human vestibular system and the treatment of vestibular system dysfunction. Methods of measurement of vestibular and balance function and intervention are discussed, leading the reader to a better understanding of the strengths, limitations, and gaps in knowledge in the field that this study seeks to address. Specifically, this study serves to meet the need to better quantify vestibular stimulation during vestibular rehabilitation focused on habituation.

Dizziness and Falls

Dizziness accounts for a large number of visits to both primary physicians and specialists, as it is the second-most common medical complaint among adults over 40 (Agrawal et al., 2009). Dizziness has been strongly linked with falls, which are the leading cause of death and injury in adults over 65 (CDC, 2006). It is believed that the prevalence of dizziness and balance disorders may be even greater, given findings that primary physicians often do not screen for balance problems or refer patients who report dizziness (Danhauer, Celani, & Johnson, 2008). Additionally, the cost of falls, ranging from the immediate cost of injury to the prolonged treatment for those thus injured, is estimated at $28.2 billion for the year 2010, and is growing with the increased population over age 60 (Davis et al., 2010; Hasson, Mansson, Ringsberg, & Hakansson, 2008; Love & Allen, 2011).
When a disease or disorder is determined to be of this magnitude, two main questions are asked: what causes the disorder, and how is it best treated?

**Etiology of Dizziness**

Dizziness is a broad term that, depending on how it is presented by the patient, is expressed in different ways: light-headedness, lack of coordination, a spinning sensation, or simply a lack of confidence in footing or gait. The etiologies for dizziness can vary as much as the meanings implied by the word. Dizziness can result from dysfunction in many regions, from the central nervous system, to declines in the peripheral somatosensory system, to visual/oculomotor dysfunction, to dysfunction of the vestibular system (Agrawal et al., 2009; Herdman, 2007; Jacobson & Shepard, 2008).

Vestibular system dysfunction can manifest as a range of symptoms, in terms of sensation, intensity, and duration. Vertigo is commonly defined as the illusions of self-motion or motion of the surround, and is associated with vestibular dysfunction (Schubert & Minor, 2004). Vertigo is not the only symptom of vestibular dysfunction. Long-term, untreated vestibular disorders can also cause limited balance confidence and increased motion sensitivity with body or head movement. Variables that affect vestibular function include injury, disease, biology, as well as age-related loss of function. The effect of these variables on a person’s dizziness and balance function are also influenced by central factors, such as physical or emotional stress, anxiety/depression, central nervous dysfunction, vision, peripheral sensitivity, medications, physical activity level, and overall health (Herdman, Hall, & Delaune, 2012; Yardley & Redfern, 2001). For
example, two individuals of the same age may both have unilateral vestibular hypofunction, but with very different reports of symptoms and functional impairment.

**Vestibular Physiology**

Part of the complex manifestation of dizziness symptoms stems from the elegant but intricate anatomy of the peripheral vestibular system. The peripheral human vestibular system, with five receptors bilaterally, is part of the membranous labyrinth and is embedded within the petrous portion of the temporal bone. This system is composed of the otolith organs and the semicircular canals. The otolith organs consist of the kidney-bean shaped saccule and utricle which sit at an approximate orthogonal angle to each other, with the utricle in the same plane as the horizontal semicircular canal (Jacobson & Shepard, 2008). The orientation of the otolith organs and the semicircular canals is illustrated in Figure 1. Three semicircular canals (SCCs) are found at angles approximately orthogonal to each other and work in paired sets. The right posterior canal is paired with the left anterior (RPLA), the right anterior with the left posterior (RALP), and the two horizontal canals (HSCC), also known as the lateral canals (Fife, 2010). The HSCC pair are in a plane approximately 30° from the transverse plane, following the line between the tragus and the lateral corner of the ocular orbit. The RALP and LARP canal planes are offset 45 degrees from sagittal as illustrated in Figure 1. The vestibular end organs are quite small— a diameter of only 4mm for the SCCs and 4-6mm² surface area for the otoliths. Due to their location and size, direct, isolated aphysiologic stimulation can be challenging (Fitzpatrick & Day, 2004).
Figure 1: Orientation of the semicircular canals and otolith

Stimulation of the Vestibular System

To study the effective stimulation of the vestibular system during vestibular rehabilitation exercises, it is important to understand the mechanisms of stimulation. Acceleration is required to activate the vestibular end organs. The otolith organs are sensitive to linear acceleration in the transverse and vertical planes. The otolith organs are composed of receptors, or hair cells, embedded in a thin gel-like substance with microscopic calcium carbonate crystals on top. When linear acceleration occurs, or static tilt, the calcium carbonate crystals and the gelatinous structure bend the receptors within, creating the process of neural response in the central nervous system. The SCCs are, as suggested by their shape, sensitive to angular acceleration in their respective planes. The semicircular canals are fluid-filled tracts with a widening at the end called the ampulla, at the adjoining ends, much like a ring with a gem at the top. Within the ampulla is the cupula, which contains hair cell receptors that transmit the signal to the vestibular nerve. When the head turns (angular acceleration), fluid is displaced in the opposite direction, creating displacement of the cupula and stimulates the hair cells within, and is shown in
The vestibular system is composed of five matched pairs (bilateral SCCs and otolith organs), also referred to as co-planar pairs, which work together to support balance system function. These matched pairs are considered redundancies, as, in a properly-functioning vestibular system, one head movement provides equal but opposite stimulation to each half of each pair. In this manner, the matched pairs work through a “push-pull” mechanism of excitation and inhibition, or pull-push, depending on the direction of canal fluid acceleration. The matched pairs also rely on a tonic firing rate to allow for the possibility of excitation and inhibition. With injury to one side, the resting firing rate is reduced or extinguished, and the “mismatch” of the resting firing rate from the opposite side can cause a person to feel intense vertigo. With central compensation of
the system, the tonic firing rates adjust at the vestibular nuclei, bringing the system back into equilibrium, and reducing the symptoms of vertigo. This compensation is promoted by movement of the subject, just as movement constraint reduces repair at the level of the vestibular nuclei (Lacour & Tighilet, 2010).

Treatment of Dizziness

Management options for vestibular dysfunction include medical, surgical, and rehabilitative interventions. In the use of prescriptive medications, the most common types of prescriptions are a strong antihistamine such as meclizine or a sedative such as diazepam, either of which can be helpful in treating acute cases of vertigo (Jacobson & Shepard, 2008). If an antihistamine or sedative is used for extended periods of time, however, it can impede central mechanisms of recalibrating the system (Kuo et al., 2008). Another treatment modality for vestibular impairment is surgery. Surgery has limited applications, as it is only useful in specific cases, such as labyrinth oblation in extreme cases of Meniere’s disease, and for bony labyrinth reconstruction or plugging of the superior (anterior) canal with Superior Semicircular Canal Dehiscence (Ward et al., 2012). Occasionally, the use of corticosteroids is indicated when there is a sudden onset of vertigo, especially when associated with hearing loss. Corticosteroid treatment needs to occur within two days of symptom onset to be effective (Shupak, Issa, Golz, Kaminer, & Braverman, 2008).

Rehabilitation Management of Vestibular Pathology

Vestibular rehabilitation includes the broad scope of interventions targeting impairments associated with vestibular dysfunction including positional vertigo of
mechanical origin (ie. BPPV), gaze and gait instability, imbalance and motion intolerance. Canalith repositioning maneuver has been found effective in treating positional vertigo, but only in those with either objective or subjective reports of vertigo during the Dix-Hallpike technique (positive BPPV)(Shepard et al., 1993).

Patient responsiveness to vestibular rehabilitation stems from the fact that visual, vestibular, and proprioceptive sensory input, along with other interactions throughout the nervous system work together to provide functional balance and a stable world view (Jacobson & Shepard, 2008). Most of the aforementioned treatments target a specific (and often rare) etiology, and none address long-standing dizziness. The use of vestibular and balance rehabilitation (VBRT) exercises, however, have been proven effective across most etiologies for dizziness. The breadth of literature supporting the use of VBRT exercises shows not only a decrease in symptoms, but also increased gait function, decreased falls risk, increased independence, and overall increase in quality of life (Whitney, Hudak & Marchetti, 1999; Herdman et al., 2012; Macias et al., 2005). The line of research presented in this dissertation, therefore, focuses on head movement-based VBRT exercises, what we know about them, and what we still have to learn.

**Efficacy of VBRT**

Historically, effective rehabilitation was first discussed in the literature by two otolaryngologists, Cawthorne and Cooksey, over half a century ago (Cooksey, 1946). The exercises they proposed and used ranged from seated gaze stability exercises to exercises that would now be deemed unsafe, such as walking up and down stairs with eyes closed (Schubert & Whitney, 2010). Nonetheless, the Cawthorne-Cooksey
exercises remain the basis of modern vestibular and balance treatment (Nardone, Godi, Artuso, & Schieppati, 2010).

Vestibular rehabilitation takes on many forms and includes varying goals. Traditional VBRT exercises fall into the categories of adaptation, habituation, and sensory substitution. Vestibular adaptation is when the vestibulo-ocular reflex (VOR) is actively exercised using gaze stability intervention after vestibular insult. This is the subset of VBRT that is best understood. Exercises for adaptation are done in both the horizontal plane and the vertical plane, with the concrete goal of improved dynamic visual acuity, and are measured by ability to clearly see a visual target with head velocities between 60-180 degrees/second.

The second subset of traditional VBRT is sensory substitution. In this modality, a system other than the vestibular system is “recruited” to help compensate for the lost vestibular input. Use of the cervical ocular reflex (COR) is a common substitution strategy used in case bilateral hypofunction. While the person without vestibular lesions relies little to nothing upon the COR for visual clarity during active head movements, it is beneficial for those with bilateral hypofunction to call upon this substitution strategy (Zee, 2007). Recently, saccade substitution for unilateral and bilateral vestibular hypofunction has been shown in numerous studies as a strong replacement for VOR. For example, substitution can involve training of voluntary saccades (eye movements not linked to vestibular function) to assist in maintaining clear vision with head movement after bilateral hypo-function of the vestibular system (Schubert & Zee, 2010). The efficacy of sensory substitution has been shown both in non-human primate studies (Dichgans et al., 1973) and in human studies (Schubert & Zee, 2010; Tian, Crane, &

Habituation is the third subset of traditional VBRT exercises. Vestibular habituation was first reported in the literature in 1984, and has since been adapted into both test and treatment (Norrè, 1984; Smith-Wheelock, Shepard, & Telian, 1991). Modern exercises for habituation tend to stem from the Motion Sensitivity Test (MST), first reported by Smith-Wheelock and colleagues (1991). These exercises focus on the reduction of symptoms of dizziness and disequilibrium through repeated exposure to the offending movement(s) (Clendaniel, 2010). Exercises used in habituation testing and treatment are based upon the ability to provoke the symptoms and the duration of the symptom, but have not yet been measured in terms of either velocity or acceleration of the head. While it is assumed that this is a central process of vestibular rehabilitation, the exact mechanisms are unknown (Herdman & Whitney, 2007). Animal studies point to changes in NMDA receptor signaling and GABA receptor expression level after habituation of motion sickness-provoking movement, but the full mechanism in humans is still poorly understood (Wang et al., 2012). Nonetheless, exercises intended as habituation exercises have been shown to have efficacy across a range of symptoms (Clendaniel, 2010).

Unfortunately, as part of the recovery process, exercises in any of the three categories of VBRT can be associated with short-term exacerbation of symptoms before notable improvement is noted. Once improvement begins, changes to the system response may be gradual and difficult for patients to detect on a week-by-week basis.
Anecdotal experiences reported by clinicians indicate that their patients often find the exercises repetitive, uninteresting, and ultimately disturbing, due to the symptoms they evoke. For these reasons, clinicians report that keeping patients engaged in more long-term rehabilitation can be challenging, and have looked to various modes and technologies to continue to encourage patient participation and long-term compliance.

**Alternative forms of VBRT**

In seeking newer modalities for VBRT delivery, clinicians and researchers have looked to video games and virtual reality to improve or at least augment both the assessment and treatment of vestibular disorders. These modes have been proven effective in those with central or neuromuscular disorders, as well as “general” dizziness and balance disorders (Betker et al., 2006; Betker, Nett, Kapadia, & Szturm, 2007; Clark & Kraemer, 2009; Deutsch, 2008; Deutsch, 2009; Gil-Gomez, Llorens, Alcaniz, & Colomer, 2011; Yamada et al., 2011). Multiple lines of investigation remain for both traditional and novel approaches to VBRT, all which seek to encourage the patient to continue treatment and promote more effective treatment (Schubert & Whitney, 2010). Improvements have been reported with all these non-traditional forms of VBRT, with outcomes measured as improved balance confidence, increased independence, reduced falls, and increased balance as measured by center-of-balance testing (Logghe, et al., 2010). While many of these modalities focus on postural stability, the inclusion of head acceleration data would strengthen understanding of the component of vestibular stimulation during these modalities of rehabilitation.
Quantification of Vestibular Function and Rehabilitation Methods

Traditional data collection methods analyze the output of the vestibular system for both diagnostics and treatment outcomes. From the perspective of the audiologist, the vestibular system is tested by measuring the vestibulo-ocular reflex either using electroneystagmography, video nystagmography, with stimulation to the vestibular system from positional placement, active movements (testing for BPPV), caloric, or full-body rotation. The vestibulo-collic reflex is a relatively new area of testing, looking at the output of stimulation of the vestibular system via changes in the myogenic potential of the sternocleidomastoid muscle in cVEMP, or in changes in myogenic potential of the inferior oblique muscle in oVEMP (Jacobson, McCaslin, Piker, Gruenwald, & Tegel, 2011). Adding to this knowledge is input from the physical therapist or occupational therapist to include measurement of the vestibular system for balance stability and center of balance testing, typically via Dynamic Platform Posturography or other force-plate testing. Other testing methods include measurement of the tibial reflex (part of the vestibulo-spinal reflex) during unexpected forward or backwards displacement (Corna et al., 2003).

As mentioned, within otologic and audiologic settings, stimulation to the vestibular system is most often measured by the vestibulo-ocular reflex (VOR) through ocular motion detection. One way of measuring the VOR is via caloric stimulation through video nystagmography (VNG), which relies on infrared recordings of the eye, with the movement analysis of most software systems focusing on the pupil. Limitations to VNG include shifting of the goggles and poor calibrations which can reduce accuracy of the recordings. For a thorough review of ENG and VNG recordings, see Jacobson &
Shepard (2008). Scleral search coils (usually monocular) can also be used to record the VOR, but can be uncomfortable for the subject to wear (Scherer, Shelhamer, & Schubert, 2011). Finally, galvanic stimulation of the vestibular system can be measured not only by objective nystagmus production, but also by reduction or exacerbation of caloric response (Gladd et al., 2011). Rotational chair tests, especially sinusoidal harmonic acceleration tests, measure the input/output function of gain and latency while providing natural stimulation to the bilateral horizontal canals (Jacobson & Shepard, 2008). This one method does provide measurement of acceleration but cannot be expanded to natural body or head movements during VBRT exercises and due to cost and size, is not utilized in most clinical settings.

Another option for measuring stimulation of the vestibular system is through the vestibulo-spinal reflex (VSR). Again, galvanic stimulation can be used, this time to measure vestibular response/interruption in the soleus H-reflex pathway (Kennedy, Cresswell, Chua, & Inglis, 2004). Vestibulo-spinal reflex is more commonly measured using Vestibular Evoked Myogenic Potentials (VEMP) as a change in myogenic activity either at the sterno-cleido-mastoid (SCM) muscle, as seen in cVEMP, or in the inferior oblique muscle, as seen in oVEMP following a loud click stimulation (Janky & Shepard, 2009; Zuniga, Janky, Nguyen, Welgampola, & Carey, 2013). Rather than an auditory response, this is known to be a vestibular response to the sound-pressure impact with the loud click stimuli. The lower leg reflex is also recorded during standing quick translations during Computerized Dynamic Platform Posturography. Nonetheless, with both methods, the stimulation to the vestibular system is still being measured by the output of a secondary system.
Vestibular rehabilitation exercises, especially those focused on habituation, are evaluated subjectively, via patient report of the experience of the exercises and their effects on their symptoms. Studies on the effectiveness of VBRT report outcomes either partially or fully based on subjective reports of dizziness by the patient (Badke et al., 2004; Badke et al., 2005; Cowand et al., 1998; Gottshall & Hoffer, 2010; Herdman et al., 2012; Nardone et al., 2010; Sanford, et al., 2010; Schmid et al., 2010). The objective outcome assessments in these studies do not measure vestibular stimulation, but are focused on the output of vestibular function: standing balance via platform posturography and improved vestibulo-ocular reflex through improved dynamic visual acuity. Typical results in studies on the vestibular system are based upon measuring the output of the vestibular system through the vestibular reflexes as well as subjective report from the patient, as cited above.

The improvement of balance function is also reported using subjective patient reporting tools. Three commonly-used tools for self-report of dizziness and imbalance are the Dizziness Handicap Inventory (DHI), the Activity-Specific Balance Confidence Scale (ABC) and the Motion Sensitivity Quotient (MSQ). The DHI was developed by Jacobson in 1990 and has been translated for use in numerous countries to assess dizziness (Jacobson & Newman, 1990). The DHI consists of twenty-five questions, to which the patient answers “yes”, “sometimes” or “no”, for two, one and zero points, respectively. The highest possible score of 100 would indicate complete handicap from dizziness. With excellent test-retest reliability (Pearson’s r = 0.97) and strong correlates to functional balance assessment, this scale has been used clinically and throughout the literature for calculating outcomes of rehabilitation, with a change in DHI of 18 points
(95% confidence interval) being significant (Cowand et al., 1998; Jacobson, Newman, Hunter, & Balzer, 1991; Vereeck, Truijen, Wuyts, & Van de Heyning, 2006).

The ABC scale was developed in 1995 as an attempt to provide a broader assessment of activities of daily life for the elderly, focusing on those who have a fear or risk of falls (Powell & Myers, 1995). The ABC consists of sixteen activities with varying amounts of difficulty. The patient is asked to rate each item on a confidence scale from 0% to 100%. The average of those responses indicates the overall confidence score, with smaller numbers indicating no confidence and larger numbers indicating strong confidence. Initially compared to a device known as the Falls Efficacy Scale along with functional balance assessment, the ABC has a good test-retest reliability and strong positive correlation between low ABC scores and poor balance test results (Powell & Myers, 1995). Additionally, the DHI and the ABC have a strong correlation, emphasizing the impact of vestibular dysfunction on activities of daily life (Whitney et al., 1999).

The Motion Sensitivity Test (MST) is an examination that focuses on the patient’s report of dizziness, in terms of severity and duration, on sixteen specific movements (Smith-Wheelock et al., 1991). From this test is calculated the Motion Sensitivity Quotient (MSQ), from which improvement during habituation-focused vestibular rehabilitation is quantified. In each of the sixteen exercises, the patient is asked to rate severity of dizziness from 0 (none) to 5 (severe) and indicate duration. Duration is converted into a scalar figure, as symptom duration of 5-10 seconds is classified as 1 point, 10-30 seconds for 2 points, and greater than 30 seconds for 3 points. The quotient is converted to a percentage by multiplying the total exercises by the total points, then
dividing by 2048, which is the maximum possible score. An MSQ of zero indicates no symptoms provoked in any position, and of 100 indicates severe, persistent symptoms in all conditions (Smith-Wheelock et al., 1991; Akin & Davenport, 2003). Subsequent testing for validity and reliability indicates good test validity and very strong reliability across testers and test sessions, as well as strong specificity (80%) and sensitivity (100%) (Akin & Davenport, 2003).

In the area of objective measures, movement analysis is an option for assessment of vestibular stimulation through head acceleration, yet historically has had limited application to VBRT. For the purposes of this study, it is important to briefly discuss the ways that movement is analyzed, with emphasis on those used in the evaluation of vestibular rehabilitation tests and exercises. Crude timing of movements, for example, gait speed in terms of steps/second, or the time it takes to perform a set of exercises, is a commonly used method of determining normalcy for movement as well as patient improvement (Baloh, Jacobson, & Ying, 2003; Cohen & Kimball, 2004; Jassen et al., 2012).

Force plates are another mode of motion analysis used to quantify VBRT exercises, especially in relationship to the vestibulo-spinal reflex. With a force plate system, the subject’s weight distribution is measured by one or more strain gauges embedded into a platform or floor area where the patient either stands or walks. Force plates are used either during gait analysis or during standing balance or center of balance testing (De Carli et al., 2010; Sutherland, 2005). While a force plate system is useful in determining the functional output of the vestibular system in terms of the vestibulo-spinal
reflex it is ineffective in measuring direct stimulation of the vestibular system during exercises.

Video recording with subsequent or simultaneous computerize video analysis is a common method of motion analysis. In video analysis, the subject has markers placed strategically, either all over the body or all over the head or both, to serve as reference points. While moving, the subject is then recorded by two or more video cameras to create a three-dimensional representation of the subject’s movement through space (Kunin, Osaki, Cohen, & Raphan, 2007; Keshner & Dhaher, 2008). This is an effective way to measure head movements as well as head and trunk accelerations during vestibular rehabilitation exercises (Keshner & Dhaher 2008). Unfortunately, the cost of this type of system limits its broad-spread application, as the typical set-up for moderate to high-quality recordings start at $60,000 and require six or more cameras mounted in a larger room.

A more cost-effective form of movement analysis is magnetometry. Magnetometry uses a magnetic sensor placed on the subject to measure movement within a magnetic field. These devices can return data regarding position in six degrees of freedom in real-time, with data collection rates of 60Hz or greater, depending on the complexity of the system. The advantages of magnetometry are that changes in light or movements that would otherwise obscure markers used in video analysis do not affect the system. Metal objects or exogenous magnetic fields, however, can interfere with the devices. Additionally, recordings must be made at a reasonable distance (within 60 inches) of the device to ensure accuracy of recording. An advantage of this system is that a six-degrees-of-freedom magnetometer returns not only linear coordinates (inches in X,
Y and Z dimensions from an origin defined by a stationery transmitter), but also angular orientation in terms of azimuth (yaw), elevation (pitch) and roll. Although magnetometry provides all six degrees of freedom, in the scope of this literature review magnetometry has not been highly utilized in research of vestibular and balance rehabilitation therapy, and has been principally used in gait analysis as a validation tool for gait assessment (Raffin, Bonnet, & Giraux, 2012; Lang et al., 2012).

Summary

Evidence supporting efficacy of treatment for those with dizziness is desirable to optimize care. Instrumentation specific to recording head movements in the clinic as a measure of exercise intensity during habituation exercises is lacking. Without a feasible and quantifiable measure of exercise intensity during repeated head movement exercises, clinicians are left relying solely on patient self-report of symptoms to assess intervention effectiveness. Addressing this gap in the vestibular rehabilitation literature is essential if rehabilitation science is to design treatment protocols to systematically explore optimal treatment parameters for patients with motion intolerance or chronic subjective dizziness.

This project aims to fill this gap by answering questions like: How much does a person, on average, move her head during habituation other and head movement-based vestibular exercises? Is there a difference across age? Does a decrease in subjective symptoms correlate with an increase in head acceleration during habituation exercises within a patient? Does a patient report of less frequent and less intense symptoms of dizziness or imbalance correlate with faster head movements? Are faster head movements seen after a successful course of vestibular rehabilitation including
habituation exercises? How much should a person move her head in head movement-based vestibular rehabilitation exercises for successful remediation? After a significant sample of this objective data is collected we can start to answer the question of how much should a person move their head in head movement-based vestibular rehabilitation exercises.

In summary, researchers and clinicians need to go beyond patients’ subjective report of symptoms for outcome measures, and work toward a finite goal of defining “normal” head accelerations. Objective quantification of head acceleration during exercises would provide a strong supplement to the subjective patient report currently used as the outcomes measure in habituation exercises. Stimulation of the vestibular end organ, as quantified by head accelerations in the planes of the SCCs and otolith organs, is needed to fully define the stimulus of the vestibular end organ during VBRT and how patient movements change (or do not) depending on level of subjective dizziness.
Manuscript 1: Quantification of head acceleration during vestibular rehabilitation exercises

Abstract:

Objective: The first purpose of this study is to investigate a new method of measuring head movements during habituation vestibular rehabilitation exercises. The second is to determine the relationship between head accelerations during traditional vestibular and balance rehabilitation exercises and age, dizziness, and imbalance.

Study Design: Descriptive, cross-sectional

Setting: University setting

Subjects: Fifty-two subjects, ranging from age 20-96. All were volunteers, with the majority (34) reporting neither dizziness nor balance difficulties.

Outcomes Measures: Head accelerations were calculated from linear and angular displacements as measured by magnetometry.

Results: Head accelerations decreased over age and dizziness and over age and imbalance during four habituation exercises.

Conclusions: Head acceleration varies as a function of age, dizziness, and imbalance during head-movement based VBRT (habituation) exercises. The magnetometry measurement method used could be applied across the course of treatment to establish predictive measures based upon change in acceleration over time. More diverse subject sampling is needed to create normative data.
Key Words: Acceleration, Vestibular Stimulation, Habituation, Magnetometry

Background

The human peripheral vestibular system is composed of five sensors on each side which respond uniquely to accelerations of the head. The otolith organs, consisting of the saccule and utricle, are sensitive to linear accelerations in the horizontal and vertical plane, respectively (Jacobson & Shepard, 2008). Three semi-circular canals (SCCs), as suggested by their shape, are sensitive to angular (rotational) accelerations within their physically-paired planes and work as a bilaterally redundant system in three orthogonal planes.

Negative factors in vestibular function include injury, disease, genetics, as well as age-related loss of function (Herdman, 2007). The effect of these factors on a person’s dizziness and balance function are also influenced by central factors, such as physical or emotional stress, anxiety/depression, central nervous dysfunction, vision, peripheral sensitivity, medications, physical activity level, and overall health (Yardley & Redfern, 2001; Herdman, Hall, & Delaune, 2012). Given this array of etiologies, two individuals of the same age may both have unilateral vestibular hypo-function, but with very different reports of symptoms and functional impairment.

The use of vestibular and balance rehabilitation therapy (VBRT) has been proven effective for treating dizziness across peripheral and central vestibular dysfunction (Brown et al., 2006; Cowand et al., 1998). The breadth of literature supporting the use of VBRT shows not only a decrease in symptoms, but also improved gait speed, decreased
falls risk, increased independence, and overall increase in quality of life (Whitney, Hudak, & Marchetti, 2010; Herdman et al., 2012; Macias, Massingale, & Gerkin, 2005).

Vestibular and balance rehabilitation therapy (VBRT) takes on many forms and goals. The goals of traditional VBRT exercises fall into the categories of adaptation, habituation, and sensory substitution. Exercises for adaptation have the main goal of improving the vestibulo-ocular reflex (VOR) through central adaptation of the neural firing rate in an unbalanced system, and therefore improving the patient’s function through clearer vision during head movements. These movements are typically done at a rate of 60 degrees per second or higher, as to maximize the VOR system (Herdman, 2007). The exercises can be done in both the horizontal plane and the vertical plane, with outcomes measured as improved dynamic visual acuity (Cohen & Kimball, 2004; Herdman & Whitney, 2007). This acuity is measured by ability to clearly see a visual target with head velocities between 60 and 180 degrees/second. Sensory substitution seeks to train another system to augment for the reduced vestibular input so that the patient is better balanced. By training and enhancing another system, such as quick eye movements for target acquisition, a person without VOR input can maintain better visual clarity with head movements. Exercises for habituation seek to reduce patient-reported symptoms of dizziness with head movement with specifically-prescribed head movements for exercises. The theory of habituation is to reduce a sensory response by repeated exposure (Shepard, Telian, Smith-Wheelock, & Raj, 1993; Clendaniel, 2010). Exercises used in habituation testing and treatment are based upon the ability to provoke the symptoms, but have not yet been measured in terms of either velocity or acceleration.
of the head. Of all the therapy types, the intensity of movement required for efficacy is least understood in the area of exercises to promote habituation.

**Current Quantification of Vestibular Rehabilitation**

Habituation exercises for vestibular therapy are traditionally evaluated subjectively, through patient report. Typical queries include: Do the exercises make the patient dizzy? Does repeated use of the exercises decrease symptoms and improve patient function? As a result, most current VBRT literature on the effectiveness of VBRT presents data based on subjective reports of dizziness by the patient. There is minimal literature that indicates what in the vestibular system is being stimulated with habituation exercises, and the intensity needed to create a change in the patient’s symptoms. The literature is strongly weighted, therefore, at looking at indirect outcomes, through subjective reporting by the patient (Norrè, 1984; Cowand et a., 1998; Pritcher et al., 2008).

Currently, quantitative measures of the head movement and acceleration are lacking in habituation exercises. It is important to know that when treating vestibular injuries, the exercises are in fact stimulating the vestibular system (the independent variable), if that is the goal. The ability to objectively assess improvement in head accelerations during habituation exercises of vestibular rehabilitation would allow the clinician an objective report the outcomes of therapy, in addition to the subjective report by the patient. The inclusion of the measurement of head accelerations during habituation exercises, therefore, would likely lead to improved documentation of evidence-based practice.
At this point, therefore, many questions remain unanswered. How much should a person, on average, move her head during habituation exercises? Is there a difference across age? Does a decrease in subjective symptoms correlate with an increase in head movements for a patient? Does a “better” subjective, patient-reported score of dizziness correlate with faster head movements? As baseline data are collected to answer these, we can begin to explore the question of how much a person should move her head in VBRT exercises for habituation to achieve maximal improvement (symptom reduction).

In summary, researchers and clinicians need the opportunity to advance input and outcome measurements beyond patients’ subjective report of symptoms for treatment goals and measurement. The addition of information regarding head acceleration during habituation exercises would provide a concrete supplement to the current standard of subjective outcomes measurement. Stimulation of the vestibular end organ, as quantified by head accelerations, is needed to determine what is being stimulated in the vestibular during habituation exercises. Further, patient head movement changes relative to their subjective dizziness and imbalance reports remain poorly understood, and would benefit from quantitative analysis.

This study aims to quantify both linear and angular accelerations during specifically-prescribed head movement-based VBRT exercises across ages and dizziness/balance function. This data is then applied over an age continuum, across these sets of variables: a) age and subjective report of dizziness and b) age and imbalance.
Materials and Methods

Subjects:

This study was approved by the James Madison University Institutional Review Board. Subjects were recruited via word of mouth, educational presentations, and paper fliers posted at local establishments. Fifty-two subjects participated in this study. The subjects were all community-dwelling volunteers and received no compensation for their participation. Subject ages ranged from 20 to 96, with average age of 45, and a median age of 27 years. Normal, dizzy, and imbalanced subjects were identified by self-report. The dizzy group reported symptoms of dizziness and/or balance issues for at least three months, and scored higher than 10 on the Dizziness Handicap Inventory (DHI), with scores for subjects in this study ranging from 0 to 68 (Jacobson, Newman, Hunter, & Balzer, 1991). The imbalanced group was determined by taking each subject’s score on the Activity-Specific Balance Confidence Scale (ABC) and subtracting that number from 100 (Powell & Myers, 1995). For example, if a person has an ABC score of 84%, their Imbalance score would be 16, indicating a low self-report of imbalance (i.e., 100-84=16). Subjects classified as neither imbalanced nor dizzy scored below a 10 on the DHI and below 25 for the Imbalance Score. Group distribution is seen in Table 1.
Prior to participation, subjects completed a brief four-question survey to indicate that they were in overall good health, and did not foresee any physical or time-commitment limitations in completing the study. Additionally, the subjects were asked to complete a set of tests commonly administered within rehabilitation settings. The Mini-Mental State Exam (MMSE) to screen for memory/cognitive issues that could interfere with the subject’s ability to comprehend the tasks requested of them, with a cut-off criteria of 24 for inclusion (Folstein, Folstein, & McHugh, 1975). The Berg Balance Scale (BBS) was administered to assess falls risk, and anyone falling into the category of “severe falls risk” (a score less than 20) was excluded (Berg, Wood-Dauphinee, Williams, & Maki, 1992). Finally, the subjects were given the option to receive three hours of diagnostic evaluation, consisting of a hearing test and video nystagmography (VNG), however none accepted.
In addition to the BBS and the MMSE, all subjects completed three subjective assessments of dizziness, balance, and mental state. The Dizziness Handicap Inventory (DHI) is a commonly-used questionnaire that consists of 25 questions which have been sub-divided into physical, emotional, and functional groupings (Jacobson et al., 1991). The DHI has been cited in the literature both as a screening tool and as a measure of improvement (Cowand, et al., 1998; Badke, et al., 2005). The Activity-Specific Balance Scale (ABC) is a sixteen-question survey in which the patient states her confidence, in terms of percentage, for certain activities, ranging from walking around the house to walking outside on icy sidewalks (Powell & Myers, 1995). The Hospital Anxiety and Depression Scale (HADS) (Zigmond & Snaith, 1983) is composed of fourteen statements where the patient must mark whether the statements do or do not pertain to them, on a scale of zero (does not at all pertain) to three (strongly pertains). The HADS was added to the screening protocol as anxiety and depression can significantly impede a person’s ability to recover from vestibular insult (Yardley & Redfern, 2001). All surveys were completed prior to collection of objective movement data using the Polhemus Unit. These scales were used to create group placement and also used for within-subject comparisons.

Instrumentation:

Objective data for this study was collected using a magnetometer manufactured by Polhemus (Colchester, Vermont, USA). The Polhemus Isotrak II Magnetometer provides position in X, Y, Z from an origin defined from a stationery transmitter and angles of azimuth (A), elevation (E) and roll (R). Briefly, azimuth is relative to the ceiling in the transverse plane; elevation and roll are relative to planes horizontal to
gravity, roll in the coronal plane and elevation in the sagittal plane. Magnetometry utilizes a magnetic field, as produced by a stationery transmitter and displacement of another magnet (receiver) within that field, as shown in Figure 3. The unit reports the six measures at a rate of 60Hz. Accuracy of measurements is 0.254 centimeters for linear data and 0.013 radians for azimuth, elevation, and roll if all measurements are within 0.762 meters of the transmitter. Recordings can be made at distances up to 1.524 meters from the stationary transmitter or greater, but with decreased accuracy.

*Figure 3:* Orientation of the Polhemus unit during this study.
Protocol

The Polhemus receiver was affixed at approximately the top of the subject’s head using a stocking cap and high-grade Velcro. In instances when the receiver was noted to slip, a headband (either plastic or elastic) was added to the headgear.

The subjects where then instructed to perform four different exercises taken from the Motion Sensitivity Quotient (MSQ). The MSQ is a series of exercises used both diagnostically and as treatment for dizziness (Shepard, Telian, Smith-Wheelock, & Raj, 1993). Starting in an upright and seated position the subject was instructed to move repeatedly in the following manner:

Exercise 1: Nose to Left Knee,

Exercise 2: Nose to Right Knee

Exercise 3: Horizontal Head shake (“no”) and

Exercise 4: Vertical Head shake (“yes”).

Data were collected for 15 seconds in each condition. For the Nose-to-Knee conditions, the subjects were given explicit directions: “Before you bend down, turn your head to point your nose to your knee. Then, move your nose to your knee by try to only bend at your waist.” For each of the exercises, visual markers were provided to reduce variability in terms of distance of movement. For the Nose-to-Knee exercises, subjects were asked to put their feet on set markers. For horizontal and vertical head movements, the subjects were given visual points of reference for head movement, and the subjects
were asked to alternate their gaze between two spots on the wall. The subjects also had a laser pointer mounted on the side of the head to “point” to the images, to ensure the subjects moved their heads, and not just their eyes, to move from one target to the next.

To guarantee proper, safe, and standardized movement, the instructions were first demonstrated to the subject prior to data collection. The subject then performed three to five movements at a slow pace, then three to five movements at a faster pace, all prior to data collection. This also ensured that the head-mounted receiver was firmly attached, and would not slip during data collection.

Data Analysis:

Data collected from the Polhemus Unit were recorded and processed through Matlab Student Edition R2011a (Natick, MA, USA). At intervals of 0.0167 seconds, X, Y, Z, azimuth (A), elevation (E), and roll (R) were collected from the Polhemus unit and saved. Post data-collection processing calculated acceleration, both linear and angular, from three-dimensional displacement with the following formulas:

\[
\text{Linear Displacement}(i) = \sqrt{(X(i) - X(i-1))^2 + (Y(i) - Y(i-1))^2 + (Z(i) - Z(i-1))^2}
\]

\[
\text{Linear Velocity}(i) = \frac{\text{Linear Displacement}(i)}{t}
\]

\[
\text{Angular Displacement}(i) = \sqrt{(A(i) - A(i-1))^2 + (E(i) - E(i-1))^2 + (R(i) - R(i-1))^2}
\]
\[
\text{Angular Velocity}(i) = \frac{\text{Angular Displacement}(i)}{t}
\]

\[
\text{Acceleration}(i) = \frac{\text{Velocity}(i) - \text{Velocity} (i - 1)}{t}
\]

The subscript \((i)\) represents the time index. As data was collected incremented at 60 Hz, \(t\) represents the time interval of 0.0167 seconds during this study.

Statistical analyses used multiple linear regression, a repeated measures multivariate analysis of variance (MANOVA) as well as two-way analyses of variance (ANOVA), using a significance level of 0.05. For comparative analysis purposes, the average accelerations, both linear and angular, for each exercise were normalized to a z-score. The z-score normalizing allowed for the average linear and angular accelerations for each exercise, which varied greatly between exercises, to be combined into one score. The z-scores for all four exercises were then averaged for each individual, creating an overall averaged z-score across all eight conditions (four exercises, two types of acceleration). This overall z-score was used for the regressions over age and dizziness, and age and imbalance. Additionally, group differences (dizzy vs. non and imbalanced vs. non) were independently evaluated with linear regression and ANOVA for linear and angular accelerations in each of the four exercises. SPSS statistical software (Version 20.0, SPSS Inc., Chicago, IL, USA) was used for all statistical analyses.
A challenge in the analysis of any data looking at the independent variables of age, dizziness, and imbalance is that these independent variables are naturally correlated. This is seen in Figure 7 below where the three factors that influence vestibular functions (age, DHI, ABC) are plotted for each of the 52 participants. Clearly, older subjects are more likely to be dizzy and imbalanced. It is also clear that there are uneven distributions of these three scores across their ranges, for example most participants are either < 40 or > 60 years. As a result of this co-linearity, averaged normalized results are presented first, followed by a breakdown into two sets of the two predictors (age & DHI; and age & ABC). Finally, an analysis by age in a selection of only those subjects who are neither dizzy nor imbalanced is presented. As seen in Figures 7, the analysis of age with normal vestibular function is a very exclusive selection of the subject lying along the lower right edge.

Results

An average z-score was created by combining linear and angular accelerations across all four exercises. This z-score was then analyzed with the following parameters:

1) As a function of age for those who reported neither dizziness nor imbalance
2) As a function of age and dizziness
3) As a function of age and imbalance

Overall analyses of head accelerations were compared in each group, combining the accelerations of all four exercises. Significant MANOVA reveals predictable regression based upon age and dizziness self-report ($r^2 = 0.404$, $p < .001$) and based upon age and imbalance ($r^2 = 0.580$, $p < .001$). Regression planes were created to fit the data,
and are found in Figure 4 and Figure 5. These planes show the decline of head acceleration to both increased age and dizziness (Figure 4) and increased age and imbalance (Figure 5).

Figure 4: Regression plane showing the relationship of overall average head acceleration to dizziness and age.
Figure 5: Regression plane showing the relationship to overall average head acceleration and age and imbalance.

While Figures 4 and 5 show averaged normalized accelerations, Tables 3 and 4 below shows effect sizes for eight different regressions over age (angular and linear accelerations measured in each of the four exercises) for two different (but related) sets of predictors. All slopes are negative, as expected. Linear and angular accelerations with significance indicated (*) as presented in Table 2 and Table 3 are still significant even after Bonferroni correction.
Tables 2 and 3 provide overviews of the multiple regressions of linear and angular accelerations across exercises. In Table 2, the independent variables are age and dizziness, as calculated from the DHI. In Table 3, the independent variables are age and imbalance, as calculated from the ABC. The groupings of age and dizziness and age and imbalance are significantly correlated with linear head acceleration in Exercise 1 and 4, while with Exercises 3 and 4, angular acceleration has the significant correlation.

Table 2:

*Head Acceleration by Age, Dizziness*

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Linear Acceleration $r^2$</th>
<th>Angular Acceleration $r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Nose to Left Knee</td>
<td>0.257*</td>
<td>0.061</td>
</tr>
<tr>
<td>2: Nose to Right Knee</td>
<td>0.068</td>
<td>0.028</td>
</tr>
<tr>
<td>3: Horizontal Head shake</td>
<td>0.150</td>
<td>0.311*</td>
</tr>
<tr>
<td>4: Vertical Head shake</td>
<td>0.224*</td>
<td>0.393*</td>
</tr>
</tbody>
</table>

*p ≤ 0.00625

Table 3:

*Head Acceleration by Age, Imbalance*

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Linear Acceleration $r^2$</th>
<th>Angular Acceleration $r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Nose to Left Knee</td>
<td>0.318*</td>
<td>0.062</td>
</tr>
<tr>
<td>2: Nose to Right Knee</td>
<td>0.130</td>
<td>0.035</td>
</tr>
<tr>
<td>3: Horizontal Head shake</td>
<td>0.145</td>
<td>0.297*</td>
</tr>
<tr>
<td>4: Vertical Head shake</td>
<td>0.208*</td>
<td>0.371*</td>
</tr>
</tbody>
</table>

*p ≤ 0.00625
Head accelerations for those subjects without dizziness (DHI < 10) or imbalance (average ABC > 75) were also explored. A line of best fit was calculated across age, using average z-score of head accelerations across all four exercises, as seen in Figure 6. Thus controlling for both dizziness and imbalance by selecting only those who were not dizzy or imbalanced no significance is found (p = 0.10) with a two tailed analysis, although a marginally significant trend is indicated with a one-tailed test (p=.05).

Figure 6: For those subjects with neither dizziness nor imbalance, a scatter-plot demonstrating the negative regression of z-score of head accelerations with age, average ABC > 75, DHI < 10
With the subgroup of subjects with neither dizziness nor imbalance, each exercise was then analyzed for effect size, in the negative regression of acceleration (linear or angular) versus age. As seen in Table 4, trends are noted for angular acceleration in Exercise 3, the horizontal head shake, and both linear and angular acceleration in Exercise 4, the vertical head shake. While Figure 6 shows the averaged, normalized head accelerations, Table 4 shows effect sizes for eight different regressions over age (angular and linear accelerations measured in each of the four exercises). All slopes are negative, as expected. Only angular acceleration during the vertical head shake was significant, but this significance does not withstand a Bonferoni correction.

Table 4:

Effect Sizes of Regressions of head acceleration by age selecting only those subjects with neither dizziness nor imbalance

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Linear Acceleration r^2</th>
<th>Angular Acceleration r^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Nose to Left Knee</td>
<td>0.051</td>
<td>0.006</td>
</tr>
<tr>
<td>2: Nose to Right Knee</td>
<td>0.007</td>
<td>0.046</td>
</tr>
<tr>
<td>3: Horizontal Head shake</td>
<td>0.001</td>
<td>0.087</td>
</tr>
<tr>
<td>4: Vertical Head shake</td>
<td>0.086</td>
<td>0.183*</td>
</tr>
</tbody>
</table>

*Indicates significance (n=34)

The relationship between the three independent variables: age, imbalance, and dizziness, was explored. As revealed in Figure 7, there is a strong correlation between all
three variables. Figure 7 also clearly demonstrates the clustered distribution of subjects, with those with stronger balance and less dizziness at the younger end of the scale and those at the older end of the spectrum showing greater heterogeneity of symptoms.

Figure 7: Graphic depiction of relationship between independent variables of age, dizziness, and imbalance

Discussion

Head accelerations show a significant downward trend as a function of age, imbalance, and dizziness in each of three of four exercises and in the aggregate. When
subjects with either dizziness or imbalance are removed from the analysis, a marginally-significant trend over age is noted across all exercises combined. However, the combined factors of age and dizziness, and the combined factors of age and imbalance reveal strong predictive regressions. When each exercise is scrutinized for significant effect, in both groupings (dizzy vs. non and imbalanced vs. non), Exercise 1 (Nose-to-Left-Knee) has significant decrease in linear head accelerations, Exercise 3 (Horizontal head shake) has significant decrease in angular head acceleration, and Exercise 4 (Vertical head shake) shows a significant decrease in both linear and angular head accelerations.

Significance is found in Exercise 1 (Nose-to-Left-Knee) and not Exercise 2 (Nose-to-Right-Knee). As the order of exercises was not randomized in this study, those with more trepidation for the exercises (dizziness, age, or imbalance) may have gained confidence after the first exercise. There may also have been a learning effect. This study will need to be repeated or extended with the exercises recorded in random order to exclude this possibility.

The consistency of significant decline in angular head accelerations shown in Exercises 3 (horizontal head shake) reveals another area for exploration. In a 2008 study of head velocities during gaze stability exercises, a difference was not seen across ages in a horizontal gaze stability exercise, similar to Exercise 3 (Pritcher, Whitney, Marchetti, & Furman, 2008). Although acceleration and velocity cannot be directly compared, using head acceleration measures during gaze stability exercises could further improve this line of study. Adding head acceleration measures also opens for question the impact of
location of target in gaze stability exercises, as the targets for this study were on the right and left, and gaze stability targets are generally in the center.

This study presents a novel approach to providing objective data of head acceleration, the input to the vestibular system, during habituation exercises for vestibular rehabilitation. The angular acceleration data provide an overview of overall stimulation to the semicircular canals, and the linear acceleration data provide an overview of movement-induced input to the otolith organs. The regression of head acceleration by age is a first step in establishing a normative data set.

While the study presents interesting data using a novel approach, limitations are present in the study that may reduce the study’s strength. The subjects recruited in this study were all volunteers from the local community and are not part of a clinical population. To more comprehensively describe how dizziness and imbalance affect movements during habituation exercises, a larger clinical sample size is needed, as the majority of subjects in this study were asymptomatic, and the symptomatic subjects were commonly at the older end of the age continuum. To improve and expand on this study, there needs to be more subjects in the 35-65 year age range, more young, dizzy subjects (under 65) and a greater number of older (over 65) non-dizzy subjects.

Even with all the aforementioned considerations, findings in this study have potential for use in current clinical practice, by quantifying the intensity of head acceleration during habituation exercises, and comparing them to age-based averages. The measurement of intensity of head acceleration, if explored across the course of treatment for those with head-motion provoked dizziness, may also provide a predictive
measure for overall outcomes of habituation-based vestibular rehabilitation, by comparing head acceleration across treatment to those made at baseline. Additionally, the ability to quantify the intensity of head accelerations in innovative rehabilitation modalities, such as video game play, validates these modalities as potential use as vestibular rehabilitation.
Manuscript 2: A method for calculating stimulation to the three separate semi-
circular canal pairs during head movements

Abstract:

Determining the effective stimulation to the vestibular end organ during vestibular
and balance rehabilitation therapy (VBRT) is generally derived from the subjective
response of the patient. The development of objective measure for determining the
degree and intensity of stimulation to the vestibular system during VBRT can provide
more concrete data in support of therapy and provide information useful in evidence-
based practice. This same objective data can also serve as a validation tool for innovative
and alternative delivery of VRBT intervention. This paper provides a description of the
mathematical manipulation of surface measure of accelerations from a head-mounted
sensor to predict the angular acceleration presented in the planes of the three separate
planes of the semicircular canals (SCCs) during head motion. Using this technique, data
obtained can be from used to provide objective SCC acceleration data during both normal
head movement and VBRT.

Keywords: Angular acceleration, semi-circular canals, vestibular stimulation, vestibular
rehabilitation, VBRT, magnetometer
**Vestibular Rehabilitation: Overview**

Evaluation of vestibular rehabilitation exercises is limited to the output of the system (VOR and VSR) and subjective patient report to quantify stimulation of the vestibular end organ. Vestibular adaptation exercises are quantified in terms of objective measures of increased VOR accuracy and gain, and sensory substitution exercises are created with the goal of improvement in terms of both VOR and improved postural stability in both static and dynamic conditions (Herdman & Whitney, 2007). However, outcome assessment of habituation exercises relies on patient self-reporting of symptom improvement (or lack of) and improved quality of life (Clendaniel, 2010). While this is effective for determining patient-focused treatment goals, it leaves measurement of evidence-based practice at the mercy of subjective patient report (Badke, Shea, Miedaner, & Grove, 2004; Yarley & Redfern, 2001).

**Limitation of Vestibular Assessment**

It is fortunate that the skull, specifically the temporal bone, provides a strong and protective home for the vestibular end organs. Unfortunately, this protective barrier limits isolated stimulation of the vestibular end organs. Caloric testing can stimulate the horizontal canals unilaterally, however, the stimulation is at one slow rate only and is not consistent with natural head movement. Rotary chair testing provides more realistic rates of stimulation, but provides only bilateral stimulation in one plane of function, leaving no information about two other planes of function for the semi-circular canals. While VEMP testing has improved the ability to isolate utrical and saccular function at
contralateral and ipsilateral vantages, respectively, there remains controversy in the field of vestibular assessment regarding the true function being measured. Although galvanic stimulation has improved some of the isolated assessment, clinical interpretation of galvanic stimulation has not yet emerged. Measurement of stimulation to all and each of the separate vestibular receptors during natural movements has not yet been reported.

What the clinician and researcher both need is a better way of measuring stimulation to the vestibular end organs during VBRT exercises. The ability to correlate objective movement and stimulation in the planes of the vestibular end organs with patient report of sensitivity would provide both objective measures and better definition to site-of-lesion.

**Orientation of SCCs in the head**

The horizontal SCCs (HOR) are along a plane approximately 30 degrees elevated above horizon. The two other paired sets, the right posterior and left anterior (RPLA) are 45 degrees to the left the mid-sagittal plane, while the right anterior and left posterior (RALP) are 45 degrees to the right of the same midline (from foramen magnum to nose), as shown in Figure 8.
Figure 8: Planes of the SCCs- Horizontal pair (HOR) in green, right posterior and left anterior (RPLA) in blue, and right anterior, left posterior (RALP) in red.

While it is possible to measure overall head accelerations in terms of linear and angular acceleration, no system to our knowledge has yet quantified movements in each of the three separate planes of the semicircular canals simultaneously.

Mathematical Rotation of Data into the Planes of the SCCs

Traditional planes of measurement (in a standing person) follow the x-axis or mid-sagittal axis running from posterior to anterior, the y-axis from left to right (or medial to lateral - like an arrow through each ear), and the z-axis from superior to inferior, (like an arrow down the spinal column) as shown in Figure 9. For the purposes of this study, azimuth is defined as movement around the z-axis, roll is defined as movement around the x-axis, and elevation is movement around the y-axis (Figure 9). In anatomical terms, elevation would be defined as flexion/extension of the neck, and
azimuth defined as rotation. To transform these measurements from a sensor atop the head in the aforementioned planes into the planes of the semi-circular canal pairs, rotation is required in two axes: the y-axis and the z-axis.

In order to create the proper rotation for the planes of the semicircular canals, a rotation must first be made in the y-axis, as although the z-axis is tilting from pointing inferior all the way to superior and slightly back to accommodate the 30 degree offset of the HSCC. Although the z-axis is the one moving, the rotation is in the y-axis. The amount of rotation referred to in the formula below as “$\beta$” as shown in Figure 9.

Rotation in the y-axis is defined as such (Goldstein 1980, pp. 146-147 and 608; Arfken 1985, pp. 199-200).

\[
y axis rotation = \begin{pmatrix}
\cos \beta & 0 & -\sin \beta \\
0 & 1 & 0 \\
\sin \beta & 0 & \cos \beta
\end{pmatrix}
\]
As the change is needed from zero degrees to 210 degrees, $\beta$ for these purposes is $210^\circ$. The angle is calculated as $210^\circ$ based upon the orientation of the positive $z$-axis for the sensor for the magnetometer used in this study, the Polhemus Isotrak II (Colchester, VT, USA). Rotating the $z$-axis requires a “turn” of the $y$-axis, resulting not only in the change in the $z$-axis, but also a change in the $x$-axis, so it is now oriented so that the positive $x$-axis is pointing posterior and at a downward angle.

For the rotation into the planes of the anterior and posterior canal pairs, a rotation in the $z$-axis is needed as seen in Figure 9.

Rotation in the $z$-axis is defined as such (Goldstein 1980, Arfken 1985):

$$z\text{ axis rotation} = \begin{pmatrix} \cos \varphi & \sin \varphi & 0 \\ -\sin \varphi & \cos \varphi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The magnitude of rotation is 135 degrees; therefore, $\varphi$ for our purposes is $135^\circ$. The $135^\circ$ shift comes from rotating the positive $y$-axis on the Polhemus sensor until it is orthogonal to the plane for movement for the RALP canals. To rotate the $y$-axis around, the “turn” must take place in the $z$-axis. This turn brings the $y$-axis to align with the LARP canals and the $x$-axis to align with the RALP canals.

A change in the $x$-axis, which would offset the original measurement of roll, is unnecessary for this formula, as the semi-circular canals are raised up and to the side, but are not aligned obliquely in the skull. Therefore, to create a matrix rotation for all the
planes of the semicircular canals, both 3 x 3 matrices are multiplied together, then by the three-by-one matrix of roll, elevation, and azimuth to create the following:

\[
\begin{pmatrix}
RPLA \\
RALP \\
RHLH
\end{pmatrix}
= 
\begin{pmatrix}
cos135 \ast cos210 & sin135 & -cos135 \ast sin210 \\
-sin135 \ast cos210 & cos135 & sin135 \ast cos210 \\
sin210 & sin0 & cos210
\end{pmatrix}
\begin{pmatrix}
Roll \\
Elevation \\
Azimuth
\end{pmatrix}
\]

These angles for rotation are calculated based upon the assumption that the sensor coordinates have been measured in the aforementioned coordinate system. Nonetheless, if initial recordings are not along the traditional planes, but with a known, set deviation, the formula can be easily adapted.

Inanimate controls were used to demonstrate the application of this formula. For the first example, the sensor was placed on top of a sphere with movements made solely in azimuth (as best possible). From this, the raw data reflects movements isolated in azimuth as shown in Figure 10.

![Figure 10: Angular data collected with movement isolated in the azimuth](image)
However, once the SCC rotation matrix is applied, the reader can easily see that the estimated stimulation is in all three planes of the SCC pairs, but mainly in the HSCC (Figure 11). This confirms the concept that a horizontal headshake stimulates the HSCCs the most, but also suggests that a horizontal headshake stimulates the RALP and LARP pairs a significant amount as well.

![Graph showing angular position in degrees over time for different orientations.](image)

*Figure 11:* Data in the azimuthal plane transposed into the planes of the SCC.

Similar data can be seen when the sphere is placed upon an axis similar to 45° off-axis, as seen in Figure 12, and moved in a sinusoidal pattern. This explicit movement was to attempt to isolate movement in the LARP canal pairs.
Figure 12: Set-up for recording in a plane 45° to the left of the sagittal plane.

The raw data for this data collection is seen in Figure 13, revealing movement in azimuth, elevation, and roll.

Figure 13: Movement attempting to isolate the LARP canals
The transposed data reveals estimated stimulation in the SCCs planes as seen in Figure 14. Note that although the estimated stimulation is greatest in the LARP canals, there is stimulation in all three canals.

*Figure 14*: Data transposed to the planes of the SCCs from attempted isolation of stimulation to the LARP canals

For stimulation in the RALP canals, a similar set-up was used as seen in Figure 12, but angled 45 degrees to the right of midline. Data recorded from movements that attempted to mimic stimulation solely in the RALP canals is shown in Figure 15.
Figure 15: Angular data collected with movement attempted to be isolated in the plane of the RALP canals

The transposed data reveals estimated stimulation in the SCCs planes as seen in Figure 16. Note that again, while the majority of estimated stimulation is in the plane of RALP canals, there is still a significant amount of estimated stimulation in all three canals.
Figure 16: Data transposed into the planes of the three SCC pairs with movements attempting to isolate the RALP canals.

Discussion:

Results above provide a method for starting with data on azimuth, elevation and roll from a sensor atop the head and frame shifting the coordinates so that the angles now match the three angles of the human semicircular ducts.

Until now, there are no reports in the literature regarding exact SCC stimulation during head movement-based vestibular and rehabilitation exercises and activities of daily life, where patients with vestibular and balance insults report decreased function. Using a six -degrees-of-freedom unit which records angular position at set time intervals, knowing the placement of the head-mounted receiver, and using the rotation matrix provided for the planes of the SCCs, the researcher and the clinician can quantify stimulation to the SCCs during both head movement-based VBRT exercises and
activities of daily living. These measurements have the potential to create objective outcome measurements, aid in the identification of site-of-lesion for vestibular dysfunction, and guide development of VBRT technologies (i.e., complementary and alternative medicine, Virtual Reality, and video-game focused innovations).
Concluding Remarks

In conclusion, this paper and the research presented within advance the understanding of vestibular stimulation during head movement-based VBRT exercises. The knowledge base is also expanded in terms of both linear and angular head accelerations during four vestibular exercises across age and patients’ report of dizziness and imbalance. A contribution of this research is the semicircular canal rotation matrix presented in the second manuscript. With this mathematical formula, researchers and clinicians have the ability to calculate the amount of stimulation in each of the planes of the semicircular canals during basic head movements, using measurements of head displacement via magnetometry. This information can better inform clinicians as to what is happening when certain movements evoke symptoms, and aid in evidence-based treatment. For researchers, this provides an objective option for testing the treatment’s ability to stimulate the proper system, rather than relying solely on subjective reports from patients.

This research presents many opportunities for further development. The mathematical rotation matrix for the otolith organs is still to be explored. Additional subjects across a more continuous age span are needed to create norms for head accelerations during traditional VBRT exercises. The use of off-the-shelf gaming systems has yet to be explored across an age span and with a patient population, and then compared with the aforementioned norms. Once these are established, the foundation will be laid for creation and development of innovative modes of delivery for VBRT.
Appendix A: Equipment Checks and Calibration

The Polhemus Isotrak II is a magnetometer that provides positional data in six degrees of freedom: X, Y, Z, azimuth, elevation, and roll. The unit operates at a resolution rate of 60Hz with one receiver (as used with this research). All measurements are accurate to 0.10” for linear data and 0.75 degrees for angular data if all measurements are within 30” of the transmitter. Recordings can be made at distances up to 60”, but with decreased accuracy.

The unit is limited to recordings made within five feet of the transmitter, and is also limited to recording in the positive X-axis. This means that if any movement of the receiver is made in the negative x-axis (“behind” the transmitter), the data is inaccurate, and therefore unusable. The same is true of rotation in elevation, as any recording made with elevation at 90 degrees (or 270 degrees) results in unreliable assessment of the other two measurements, due to Gimble lock, which is explained at Figures 10 and 11.

Static Test of Accuracy/Equipment Check

To guarantee the integrity of the output of the Polhemus unit, multiple static and dynamic tests were performed. The first static tests were linear measures to determine if the X, Y, and Z measures returned by the unit were correct. The distance from the transmitter to the receiver was measured using a yardstick, and the data (in inches) returned from a “ping” command were compared for accuracy. The receiver was then moved a foot in the X axis, static measurements taken via yardstick, and then compared to the data collected in a ping command. This was repeated for movements in the Y and
Z axes. Figure 1 shows the relationship of the transmitter to the receiver for both calibration and research purposes.

![Figure 1: Equipment Set-up for Calibration. Note transmitter suspended from the ceiling, and receiver resting on surface below.](image)

The angular measurements were also checked for accuracy. For this test, a protractor was printed and affixed to a flat surface. The determination of “neutral” was decided as facing away from the transmitter (“tail” of the cord pointing towards the transmitter in the x-axis), with the flat portion of the receiver flush to the flat surface, as seen in Figure 2. Recordings in this position are found in Table 1.
The receiver was then moved 90 degrees in the azimuth only. See Figure 3 and Table 2.

**Figure 2:** Polhemus receiver in the “neutral” position

*Table 1* Recordings in the neutral position

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>A</th>
<th>E</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>-1</td>
<td>-35</td>
<td>2</td>
<td>-1</td>
<td>178</td>
</tr>
</tbody>
</table>

**Figure 3:** Polhemus receiver in the moved 90° in azimuth only
Table 2

*Output with movement in azimuth*

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>A</th>
<th>E</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>1</td>
<td>-35</td>
<td>93</td>
<td>-1</td>
<td>-177</td>
</tr>
</tbody>
</table>

Next, the receiver was returned to the neutral position, and rotated on its side, approximately 90 degrees in roll (Figures 4 and 5).

![Figures 4 and 5: Polhemus receiver in neutral position, then moved 90° in roll](image)

Table 3

*Output for 90° offset in roll only*

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>A</th>
<th>E</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>-1</td>
<td>-35</td>
<td>2</td>
<td>7</td>
<td>-93</td>
</tr>
</tbody>
</table>
The receiver was then flipped on its side, situated approximately 90 degrees. The change in angle would be in roll if it were receiver-dependent, and in elevation if transmitter-dependent. Positioning of the receiver is seen in Figures 6 and 7, with output seen in Table 4.

![Figures 6 and 7: Polhemus receiver moved 90° in azimuth and 90° in roll](image)

Table 4

*Readings obtained with receiver offset of 90° in azimuth and 90° in roll:*

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>A</th>
<th>E</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>1</td>
<td>-35</td>
<td>88</td>
<td>6</td>
<td>-91</td>
</tr>
</tbody>
</table>

The receiver was then flipped on its side approximately 45 degrees. The change in angle would be in roll if it were receiver-dependent, and in elevation if transmitter-dependent. Placement of the receiver is seen in Figures 8 and 9, with the output seen in Table 5.
For test of elevation, there were limitations for what is known as the “Gimble lock”. This is a software addition by the manufacturers of the Polhemus unit that looks like errors when the elevation completely vertical, as the azimuth and roll are dependent on knowledge of the elevation. Therefore, if the elevation is 0 degrees or at the ±180 degree point, confusion occurs regarding the correct measurement for azimuth and roll.

Due to this limitation, elevation was tested with approximately 45 degree offsets. First, elevation (in reference to the both transmitter and receiver) was tested with the
receiver in “neutral” position. Placement of the receiver can be seen in Figures 10 and 11, and output data found in Table 6.

Table 6

*Offset of 45° in elevation only*

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>A</th>
<th>E</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>-1</td>
<td>-33</td>
<td>3</td>
<td>48</td>
<td>-175</td>
</tr>
</tbody>
</table>

Next, the receiver was placed at 90° offset in azimuth and the elevation, relative to the receiver, was set at 45° offset, as shown in Figures 12 and 13. Output in this position is found in Table 7.
Table 7

Receiver set at 90° offset in azimuth and 45° in elevation only

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>A</th>
<th>E</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>0</td>
<td>-35</td>
<td>95</td>
<td>51</td>
<td>-166</td>
</tr>
</tbody>
</table>

Dynamic Equipment Tests

Once the static tests convincingly demonstrated the relationship between the receiver and the transmitter, dynamic tests were used to demonstrate timing precision and accurate movement in the six degrees of freedom, and to determine the best placement of the receiver for research purposes.
The first dynamic tests checked linear movement by moving 1 meter in the linear axes. This was done without a timer, simply to assess the displacement. Again, limitations of distance and of the positive X-axis were observed as expected.

The second dynamic tests determined the point of reference for the measurements of angles as reference of the receiver (smaller piece) or the transmitter (larger piece). The following figures describe the dynamic tests:

*Figure 14: Receiver moved 90° right to 90° left probe in neutral position, facing television, ½ cycle per second with metronome*
When elevation changes more than 45 degrees, a change in azimuth appears at the limits, with a slight change in roll (likely due to human error). This is an example of the Gimble Lock as discussed previously.

\textbf{Figure 15}: Receiver moved 45° right to 45° left, in roll only, neutral position. The graph in roll represents the threshold of ±180 at neutral position.

\textbf{Figure 16}: Receiver moved 45° up and 45° down, change in elevation only.
Figure 17: Example of Gimble Lock
Figure 18: 90° offset in azimuth, 180° changes in roll as relative to the receiver, elevation as relative to the transmitter.

Figure 19: 90° offset in azimuth, movement elevation as relative to the receiver, in roll as relative to the transmitter.
Figure 20: 90° offset in roll, elevation as relative to the receiver, azimuth as relative to the transmitter

Figure 21: 90° offset in elevation, roll as relative to the receiver, azimuth as relative to the transmitter
In the next two figures, the receiver was moved to a 90 degree roll to the right (as in Figures 4 and 5) and then rotated up 30 degree elevation in the Z-axis. This is as if it were mounted on the side of the subject’s head. Again, the Gimble Lock errors are apparent in X, azimuth, and roll.

Figure 22: As if mounted on the side of the subject’s head, head moving in azimuth (horizontal head shake)

Figure 23: Large movements of the receiver moving in elevation (vertical head shake- “nodding yes”) showing Gimble Lock errors
In our assessment of the receiver/transmitter relationship, the “straw theory” was developed. In this theory, the perspective of azimuth, elevation, and roll (as reported by the Polhemus unit) are based upon the perspective of an outside viewer, and can be described by “which way would make a marble roll out of the straw.”

For the recording of azimuth, the viewer’s perspective would be looking from above or below, (looking down from the transmitter suspended from the ceiling) as seen in Figure 25.

Figure 24: Small movements of the receiver moving in elevation (vertical head shake- “nodding yes”) showing Gimble Lock errors

Figure 25: Perspective of the viewer determining the angle of Azimuthal movement
For recording/measuring elevation, viewer’s perspective would be looking from the side of the transmitter, along the Y-axis, as demonstrated in Figure 26.

Similarly, in the straw theory, viewer’s perspective would measure roll through the perspective along the cord that attaches to the back of the receiver, as seen in all prior Figures. Figures 27 and 28 demonstrate the straw theory, as movement in elevation would cause a marble to roll out of the red straw, and movement in roll would cause a marble to roll out of the yellow straw.
Data collected during active movements in these planes support the straw theory, as well.

Figure 27: Movements in elevation (red straw tips up and down)

Figure 28: Movement in roll (yellow straw tips up and down)
Next test demonstrates that readings from the Polhemus Isotrak II would parallel subject recordings. The third dynamic test was used to determine the best placement for research purposes, as well as the accuracy of recording a subject as opposed to a foam ball. Again, movements were matched to a metronome at one beat per second. First, the receiver was placed on the side of the head, as seen in Figures 29 and 30. This was the initial site of recording for pilot data when it was erroneously believed that the recordings were relative to the receiver, not the transmitter.

Initially, the receiver (small piece) was mounted on the side of the head, posterior to the helix. This was an attempt to match placement of the semicircular canals as shown in Figures 29 and 30. Note the placement of the transmitter (big piece) in relation to the subject and the receiver.

*Figure 29: Subject with receiver on side of head (circled in red), transmitter above (circled in black)*
With the receiver in the “side of head” placement, head shake left to right (shaking head “no”) was recorded. Note that if the recordings were truly transmitter-dependent, movement would be in azimuth. If truly receiver-dependent, displacement would primarily be in elevation.

Figure 30: Subject with receiver on side of head (circled in red), transmitter above (circled in black)
In each case, you would expect any receiver-dependent measurements to be in elevation and any transmitter-dependent measurements to be in azimuth.

Due to the confounding results noted with this placement, recordings were made with the transmitter placed on top of the subject’s head, as seen in Figure 33.
With the sensor placed on the top of the head, new recordings were made. In this case, the recordings were more consistent, with most displacement measured in azimuth, and minimal displacement in roll, as shown in Figure 36.

*Figure 34 and 35: Subject with receiver on top of head*

*Figure 36: Subject with receiver on top of head, shaking head left and right (shaking head “no”)"
In summary, while the Polhemus Isotrak II allows for measurement in six degrees of freedom, there are significant limitations in the X-axis and the angular measurements. It is not only important to know these limitations and idiosyncrasies, but to model the data collection and subsequent data analysis around them in order to avoid erroneous data.

Figure 37: Subject with receiver on top of head with head shake in the vertical plane. Note that the majority of change is tracked in elevation, as expected.
Appendix B: Matlab Code used in Data Collection

Part 1: Collection Loop

%Collection Parameters
clear;
subName = input('Enter subj initials: ','s');
trial = input('Enter trial sequence (B,M,E): ','s');
disp(['Ready to test ' subName]);
times=[15 15 15 15];
start=clock;
for tnum=1:4
    s4=serial('COM4');
    set(s4,'BaudRate',115200);
    fopen(s4);
    q=input(['Type Enter for trial ' num2str(tnum) ' or any letter to exit'],'s');
    if ~isempty(q)
        break
    end
filename = [subName trial num2str(tnum)];
[X Y Z A E R npnts]=xAHcontinuous60Hz(s4,times(tnum));
timeFromStart=clock-start;
save (filename);
x=1:npnts;
subplot(2,3,1)
plot(x,X(1:npnts))
axis([1 npnts 0 60]);
title('X');
subplot(2,3,2)
plot(x,Y(1:npnts));
axis([1 npnts -36 36]);
title('Y');
subplot(2,3,3)
plot(x,Z(1:npnts));
axis([1 npnts -65 0]);
title('Z');
subplot(2,3,4)
plot(x,A(1:npnts));
axis([1 npnts -180 180])
title('Azimuth');
subplot(2,3,5)
plot(x,E(1:npnts))
axis([1 npnts -180 180]);
title('Elevation');
subplot(2,3,6)
plot(x,R(1:npnts))
axis([1 npnts -180 180]);
title('Roll');
disp('          X      Y       Z      Azimuth  Elevation Roll');
disp(['mean=  ' num2str(mean(X),'% 10.0f') '       ' num2str(mean(Y),'% 10.0f') '       ' num2str(mean(Z),'% 10.0f') '       ' num2str(mean(A),'% 10.0f') '       ' num2str(mean(E),'% 10.0f') '       ' num2str(mean(R),'% 10.0f')])
disp(['range=  ' num2str(range(X)) '    ' num2str(range(Y)) '    ' num2str(range(Z)) '    ' num2str(range(A)) '    ' num2str(range(E)) '    ' num2str(range(R))])
disp(['Finished with test ' filename]);
fclose(s4) %
delete(s4)
clear s4
end

Part 2: 2nd Collection Loop

%getDataContinuousMode
function [X,Y,Z,A,E,R,npnts] = xAHcontinuous60Hz(s4,timer)
pL=(timer*60)-1; %predicted lenght of the arrays
X=zeros(pL,1);
Y=zeros(pL,1);
Z=zeros(pL,1);
A=zeros(pL,1);
E=zeros(pL,1);
R=zeros(pL,1);
i=1;
fprintf(s4,'C') % puts Pohlehmus in continuous mode
fprintf(s4,char(17))
while i < pL
  out=fscanf(s4);
  if length(out) >= 45
    S1=out(3:10);
    try
      X(i)=str2num(S1);
    catch
      X(i)=NaN;
    end
    S2=out(11:17);
    try
      Y(i)=str2num(S2);
    catch
      Y(i)=NaN;
    end
    S3=out(18:24);
    try
      Z(i)=str2num(S3);
    catch
      Z(i)=NaN;
    end
    S4=out(25:31);
    try
      A(i)=str2num(S4);
    catch
      A(i)=NaN;
    end
    S5=out(32:38);
    try
      E(i)=str2num(S5);
    catch
      E(i)=NaN;
  end
end
end
S6=out(39:45);
try
R(i)=str2num(S6);
catch
    R(i)=NaN;
end
    i=i+1;

end

end
fprintf(s4,char(19))%suspends continuous mode

npnts=i-1;
Appendix C: Matlab Code used in Rotation Matrix – Author: Jesse Collins

function [attitudeSCC] = jessecalcsforannie(R,E,A)
% Function for Annie Hogan to convert Polhemus unit
% angular data output into SCC coordinate system angular data
% written by Jesse G. Collins
% 2013-03-03
% Inputs:
% R = Roll vector of data
% E = Elevation vector of data
% A = Azimuth vector of data
% Outputs:
% attitudeSCC = matrix of angular data in the SCC coordinate system
%   attitudeSCC(1,:) = RPLA
%   attitudeSCC(2,:) = RALP
%   attitudeSCC(3,:) = HOR
% Also, this function will create a new figure and plot the values across
time
% Example:
% [attitudeSCC] = jessecalcsforannie(R,E,A)

%%% Define "Jesse Collins Matrix"
JCM=[cosd(135)*cosd(210) sind(135) -cosd(135)*sind(210); ...
    -sind(135)*cosd(210) cosd(135) sind(135)*sind(210); ...
    sind(210) 0 cosd(210)];

% Define time vector
t=[1:length(R)]./60;

%%% Now, let's clean up that Roll data (since your transmitter is upside-down)
Rfixed=R;

% This for-loop with a conditional constructs the new Rfixed values to be
% continuous and centered about -180
for r=1:length(R)
    if R(r)>0
        Rfixed(r)=R(r)-360;
    end
end

% Here I add 180 to center the fixed Roll values about zero, and multiply
% by -1 to account that the transmitter was upside-down when the values
% were acquired
Rfixed=(Rfixed+180)*-1;

%%% Assemble the time series vector of angles in the form:
%%% [Roll; Elevation; Azimuth]
attitude=[Rfixed'; E'; A'];

% Now, multiply by the JCM to transform to the new system:
% [RPLA; RALP; HOR]

% This operation is allowable because remember for matrix multiplication
% the inside indices have to match:
% EG: JCM is 3x3 and the matrix of angles through time is 3x(number of data samples)
attitudeSCC=JCM*attitude;

%%% Now, let's plot the data
colorstring='bkr';
figure
hold on

for r=1:3
   plot(t,attitudeSCC(r,:),colorstring(r))
end

legend('RPLA','RALP','HOR')
title('Angle [deg] vs. time [sec] in the SCC coordinate system')
xlabel('Time, [sec]')
ylabel('Angle, [degrees]')
References


