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Quantification of Head Acceleration during Vestibular Rehabilitation Exercises

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Abstract

Purpose: Vestibular rehabilitation exercises have been proven to reduce symptoms and diminish the risk of falls in those with dizziness and balance impairments. 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 explore the relationship between head acceleration measurements during select traditional vestibular rehabilitation exercises and the variables of age, dizziness, and poor balance confidence.

Research Design: A descriptive, cross-sectional study, in a university setting.

Study Sample: Fifty-two participants, ranging in age from 20 to 96 yr. All were volunteers, with the majority (34) reporting no history of dizziness or balance confidence.

Data Collection: Head accelerations were calculated from linear and angular displacements as measured by magnetometry.

Results: Head accelerations decreased with increasing age, dizziness, and low balance confidence during four habituation exercises.

Conclusions: Head acceleration varies as a function of age, dizziness, and low balance confidence during head movement–based vestibular and balance rehabilitation therapy (habituation) exercises. The magnetometry measurement method used could be applied across the course of treatment to establish predictive measures based on change in acceleration over time. More diverse participant sampling is needed to create normative data.

Key Words: acceleration, balance confidence, dizziness, habituation, magnetometry, vestibular rehabilitation, vestibular stimulation

Abbreviations: ABC = Activity-Specific Balance Confidence Scale; DHI = Dizziness Handicap Inventory; VOR = vestibulo-ocular reflex; VRT = vestibular and balance rehabilitation therapy

BACKGROUND

Dizziness and poor balance are reported in approximately of one-third of the >40-year-old adult population. Those adults with reported dizziness are ≥12 times more likely to fall than those who do not report any dizziness (Agrawal et al, 2009). Other, more recent reports suggest an even higher rate of falls in those with dizziness and balance issues, especially among those with hearing loss, nearing 50% of a hearing-impaired clinical population (Criter and Honaker, 2013). Falls are a serious concern for both individuals and for the populous, as they are the leading cause of death and injury, and result in a rising annual health-care expense cost from ~$23.8 billion in 2005 to ~$31 billion in 2015 in the United States alone (Stevens et al, 2006; Burns et al, 2016).

Negative factors in vestibular function include injury, disease, and genetics, as well as age-related loss of function (Herdman, 2007). The effect of these factors on a person's dizziness and balance function is also influenced by

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central factors, such as physical or emotional stress, anxiety/depression, central nervous dysfunction, vision, peripheral sensitivity (i.e., peripheral neuropathy), medications, physical activity level, and overall health (Yardley and Redfern, 2001; Herdman et al, 2012). Given this array of etiologies, two individuals of the same age may both have similar diagnostic results, but with very different reports of symptoms and functional impairment.

The use of vestibular and balance rehabilitation therapy (VRT) has been proven effective for treating dizziness across peripheral and central vestibular dysfunction (Cowand et al, 1998; Brown et al, 2006). The breadth of literature supporting the use of VRT 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 et al, 1999; Macias et al, 2005; Herdman et al, 2012).

VRT takes on many forms and goals. The goals of traditional VRT exercises fall into the categories of adaptation, sensory substitution, and habituation. 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. Subsequently, adaptation exercises improve the patient's function through clearer vision during head movements. These movements are typically done at a rate of ≥60°/sec, 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 and Kimball, 2004; Herdman and Whitney, 2007). This acuity is measured by ability to clearly see a visual target with head velocities between 60 and 180°/sec. Second, sensory substitution seeks to train another system (e.g., vision) 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. Finally, exercises for habituation are specifically prescribed head movements that aim to reduce patient-reported symptoms of dizziness. The theory of habituation is to reduce a sensory response by repeated exposure (Shepard et al, 1993; Clendaniel, 2010). Exercises used in habituation testing and treatment are based on 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. Therefore, the intention of the research presented in this article is to expand the understanding of the degree and type of movements found in traditional habituation-focused VRT.

CURRENT QUANTIFICATION OF VESTIBULAR REHABILITATION

Habituation exercises for vestibular therapy are traditionally evaluated subjectively, through patient report. Typical queries include the following: Do the exercises make the patient dizzy? Does repeated use of the exercises decrease symptoms and improve patient function? As a result, most current literature on the effectiveness of VRT 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. Therefore, the literature is strongly weighted at looking at indirect outcomes through subjective reporting by the patient (Norrè, 1984; Cowand et al, 1998; Pritcher et al, 2008).

Currently, quantitative measures of the head movement and acceleration are lacking in habituation exercises. If treating vestibular injuries is the goal, then it is important to know that the exercises are in fact stimulating the vestibular system (the independent variable). The ability to objectively assess improvement in head accelerations during habituation exercises of vestibular rehabilitation would allow the clinician to objectively 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, many questions remain unanswered. How much should a person, on average, move his or 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 his or her head in VRT exercises for habituation to achieve maximal improvement (symptom reduction).

This study aims to quantify both linear and angular accelerations during specifically prescribed head movement–based VRT exercises across age, dizziness, and balance confidence. These data are then applied over an age continuum, across these sets of variables: (a) age and subjective report of dizziness and (b) age and balance confidence.

MATERIALS AND METHODS

Participants

This study was approved by the James Madison University Institutional Review Board. Participants were recruited via word of mouth, educational presentations, and paper fliers posted at local establishments. Fifty-two participants took part in this study. The participants were all community-dwelling volunteers and received no compensation for their participation. Participant ages ranged from 20 to 96 yr, with average age of 45 yr and a median age of 27 yr.

Before participation, participants 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 participants were asked to complete a set of tests commonly administered within rehabilitation settings: The Mini-Mental State Exam screened for memory/cognitive issues that could interfere with the participants' ability to comprehend the tasks requested of them, with a cutoff criterion of 24 for inclusion (Folstein et al, 1975). The Berg Balance Scale was administered to assess falls risk, and anyone falling into the category of "severe falls risk" (a score <45) was excluded (Berg et al, 1992). Finally, the participants were given the option to receive 3 hours of diagnostic evaluation, consisting of a hearing test and video nystagmography; however, none accepted.

In addition to the Berg Balance Scale and the Mini-Mental State Exam, all participants completed two subjective assessments of dizziness and balance. The Dizziness Handicap Inventory (DHI) is a commonly used questionnaire that consists of 25 questions that have been subdivided 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 Confidence Scale (ABC) is a 16-question survey in which the patient states his or her confidence, in terms of percentage, for certain activities, ranging from walking around the house to walking outside on icy sidewalks (Powell and Myers, 1995). All surveys were completed before collection of objective movement data. These two scales were used to create group placement and also used for within-participant comparisons.

Normal, dizzy, and poor balance confidence participants were identified by self-report. The dizzy group reported symptoms of dizziness and/or balance issues for at least 3 months, and scored >16 on the DHI, with scores for participants in this study, across the total cohort, ranging from 0 to 68 for all participants (Jacobson et al, 1991). The poor balance confidence group was determined by taking each participant's score on the ABC, with those scoring <75% balance confidence classified as having "poor balance confidence" (Powell and Myers, 1995). Participants classified as neither poor balance confidence nor dizzy scored <16 on the DHI and >75 on the ABC score (Jacobson et al, 1991; Skipper and Ellis, 2013). Group distribution is shown in Table 1.

Instrumentation

Objective data for this study were collected using a magnetometer manufactured by Polhemus (Colchester, VT). Using an origin defined from a stationery transmitter, the Polhemus Isotrak II Magnetometer provides position in X, Y, and Z. Additionally, the magnetometer provides the 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 uses a magnetic field, as produced by a stationery transmitter and displacement of another magnet (receiver) within that field, as shown in Figure 1. The unit reports the six measures at a rate of 60 Hz. Accuracy of measurements is 0.254 cm for linear data and 0.013 radians for azimuth, elevation, and roll, if all measurements are within 0.762 m of the transmitter. Recordings can be made at distances up to 1.524 m from the stationary transmitter or greater, but with decreased accuracy.

Protocol

The Polhemus receiver was affixed at approximately the top of the participant'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 participants were then instructed to perform four different exercises taken from the Motion Sensitivity Quotient. The Motion Sensitivity Quotient is a series of exercises used both diagnostically and as treatment for dizziness (Shepard et al, 1993). The four exercises were chosen as they appear to maximize head movement, are repeatable over a short time, and are also able to be performed seated, to maximize participant safety. All exercises were demonstrated for the participants before data collection. Starting in a seated and upright position, the participant was instructed to move repeatedly in the following manner:

(1) Exercise 1: Nose to left knee
(2) Exercise 2: Nose to right knee
(3) Exercise 3: Horizontal headshake ("no")
(4) Exercise 4: Vertical headshake ("yes")

Data were collected for 15 sec in each condition, and the conditions were in the order above for all participants (nonrandomized). For the nose-to-knee conditions, the participants 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, but *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

Table 1. Participant Group Demographics

Group	N	Mean Age	Range	SD
Dizzy	10	77.6	20–95	20.97
Nondizzy	42	34.26	20–90	21.82
Poor balance confidence	12	80.83	67–95	7.60
No issues with balance confidence	40	35.35	20–90	23.19
Neither poor confidence nor dizzy	45	40.72	20–90	25.84
Both poor confidence and dizzy	7	85	78–95	5.44

Notes: n = 52. SD = standard deviation.

the nose-to-knee exercises, participants were asked to put their feet on set markers. For horizontal and vertical head movements, the participants were given visual points of reference for head movement, and the participants were asked to alternate their gaze between two spots on the wall. The participants also had a laser pointer mounted on the side of the head to "point" to the images, to ensure that participants 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 participant before data collection. The participant then performed three to five movements at a slow pace, then three to five movements at a "fast" pace (defined to the participants as "as fast as comfortably possible"), all before data collection. This also ensured that the head-mounted receiver was firmly attached, and would not slip during data collection. During the data collection, the participants were asked to do all exercises "as fast as comfortably possible."

Data Analysis

Data collected from the Polhemus unit were recorded and processed through Matlab Student Edition R2011a (Natick, MA). At intervals of 0.0167 sec, 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:

$$\text{Linear displacement}_{(i)} = \sqrt{(X_{(i)} - X_{(i-1)})^2 + (Y_{(i)} - Y_{(i-1)})^2 + (Z_{(i)} - Z_{(i-1)})^2}$$

$$\text{Linear velocity}_{(i)} = \frac{\text{Linear displacement}_{(i)}}{t}$$

$$\text{Angular displacement}_{(i)} = \sqrt{(A_{(i)} - A_{(i-1)})^2 + (E_{(i)} - E_{(i-1)})^2 + (R_{(i)} - R_{(i-1)})^2}$$

$$\text{Angular velocity}_{(i)} = \frac{\text{Angular dsplacement}_{(i)}}{t}$$

$$\text{Acceleration}_{(i)} = \frac{\text{Velocity}_{(i)} - \text{Velocity}_{(i-1)}}{t}$$

Figure 1. Orientation of the Polhemus magnetometry unit during this study with a participant (receiver and transmitter circled). (This figure appears in color in the online version of this article.)

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

Statistical analyses used multiple linear regression and hierarchical multiple regression, as well as two-way analyses of variance, 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 (nonnormalized data can be found in the Appendix). 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. 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 poor balance confidence
(2) As a function of age and dizziness
(3) As a function of age and poor balance confidence

SPSS statistical software (Version 24.0, SPSS Inc., Chicago, IL) was used for all statistical analyses.

RESULTS

A hierarchical multiple regression was performed to determine if age, dizziness, and poor balance confidence were predictive (related) with the average head acceleration (z score) as the outcome variable. Age was entered first into the statistical model, followed by dizziness, and lastly off-balance. By examining the R^2 (variance explained) in the first model as well as the change in variance explained (ΔR^2) from model 1 to model 2, and model 2 to model 3, we can examine the unique contribution of each predictor.

The results indicated that age was a significant predictor of average head acceleration [$F_{(1,50)} = 27.87, p < 0.001$] and accounted for 35.8% (R^2) of the variance in the outcome. When the next predictor (i.e., dizziness) was added, the total model was also found to be significant [$F_{(2,49)} = 19.60, p < 0.001$]. More importantly, dizziness uniquely accounted for an additional 8.7% ($p = 0.008$) of the variance in the outcome. Finally, when off-balance was added, the total model was again found to be significant [$F_{(3,48)} = 13.33$, $p < 0.001$]. However, while the amount of variance explained increased the amount of unique variance accounted for by the predictor, it was not statistically significant (i.e., $\Delta R^2 = 0.01$, $p = 0.35$). The regression estimates, as well as measures of association, for the model containing all three predictors are provided in Table 2.

Table 3 shows effect sizes for eight different regressions. These eight regressions utilize the variable of age for two different (but related) sets of predictors, scrutinizing angular and linear accelerations, as measured in each of the four exercises. All slopes are negative, as expected. Linear and angular accelerations, with significance indicated (*) as presented in Table 2, are still significant, even after Bonferroni correction.

Table 3 provides an overview of the multiple regressions of linear and angular accelerations across exercises. The independent variables are age and dizziness, as calculated from the DHI, and age and poor balance confidence, as calculated from the ABC. The groupings of "age and dizziness" and "age and poor balance confidence" are significantly correlated with linear head acceleration in Exercises 1 and 4, while with Exercises 3 and 4, angular acceleration has the significant correlation.

Head accelerations for those participants without dizziness (DHI <16) or poor balance confidence (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 2. After controlling for both dizziness and poor balance confidence by selecting only those who were without dizziness or poor balance confidence, no significance is found ($p = 0.121$) with a two-tailed analysis.

With the subgroup of participants with neither dizziness nor poor balance confidence, 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 (horizontal headshake), and both linear and angular acceleration in Exercise 4 (vertical headshake). While Figure 2 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, but did not reach statistical significance.

Table 2. Regression Coefficients, Zero-Order, Squared Partial, and Squared Semipartial Correlations for Age, Dizziness, and Poor Balance Confidence

Predictor	β	*t*	*r*	pr^2	sr^2
Age	−0.32	−2.11*	−0.598	0.08	0.05
Dizziness	−0.32	−2.40*	−0.576	0.11	0.07
Poor balance confidence	−0.14	−0.94	−0.538	0.02	0.01

Note: *$p < 0.05$.

The relationship between the three independent variables—age, poor balance confidence, and dizziness—was explored. As revealed in Figure 3, there is a strong correlation among all three variables. Figure 3 also clearly demonstrates a clustered distribution of participants: 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.

DISCUSSION

For normal daily activities, from walking to running, to quickly turning to watch for traffic, human head velocities are up to 550°/sec, and head accelerations reach up to 6,000°/sec^2 (Das et al, 1995; Grossman et al, 1988). For exercises aimed to improve symptoms of dizziness, however, there is no objective data to show that, while the symptoms are decreasing, the patient is returning to normal rates of movement. Researchers and clinicians need the opportunity to advance input and outcome measurements beyond patients' subjective reports 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 (see the Appendix for average head acceleration data across exercise by age, low balance confidence, and dizziness, to compare the study data with these aforementioned normal daily head accelerations). Stimulation of the vestibular end organ, as quantified by head accelerations, is needed to determine what is being stimulated in the vestibular system during habituation exercises. Further, patient head movement changes relative to their subjective dizziness and poor balance confidence reports remain poorly understood, and would benefit from quantitative analysis.

Head accelerations in this study show a significant downward trend as a function of age, poor balance confidence, and dizziness in each of three of four exercises and in the aggregate. When participants with either dizziness or poor balance confidence 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 poor balance confidence, reveal strong predictive regressions. When each exercise is scrutinized for significant effect, in both groupings (dizzy versus non

Table 3. Effect Sizes of Head Acceleration by Age/Dizziness and Age/Poor Balance Confidence

Exercise	Age/Dizziness Linear Acceleration r^2	Age/Dizziness Angular Acceleration r^2	Age/Poor Balance Confidence Linear Acceleration r^2	Age/Poor Balance Confidence Angular Acceleration r^2
1. Nose to left knee	0.277*	0.060	0.282*	0.048
2. Nose to right knee	0.080	0.045	0.083	0.024
3. Horizontal headshake	0.139	0.323*	0.147	0.290*
4. Vertical headshake	0.235*	0.388*	0.209*	0.372*

Note: *$p \leq 0.01$.

and poor balance confidence versus non), the significant decrease in accelerations are found in the following:

- Exercise 1 (Nose to-left-knee) in linear head accelerations
- Exercise 3 (Horizontal headshake) in angular head acceleration
- Exercise 4 (Vertical headshake) in both linear and angular head accelerations

Statistical 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 poor balance confidence) 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 Exercise 3 (horizontal headshake) 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 et al, 2008). Although acceleration and velocity cannot be directly compared, using head acceleration measures during gaze stability exercises could further expand this line of study. From our results, we also ponder 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, all via a less-utilized tool, magnetometry. The use of magnetometry has benefits and limitations, for both research and clinical applications. As magnetometry uses a magnetic field to obtain linear and angular displacement from a set point, the room must be clear of metal objects, including file cabinets

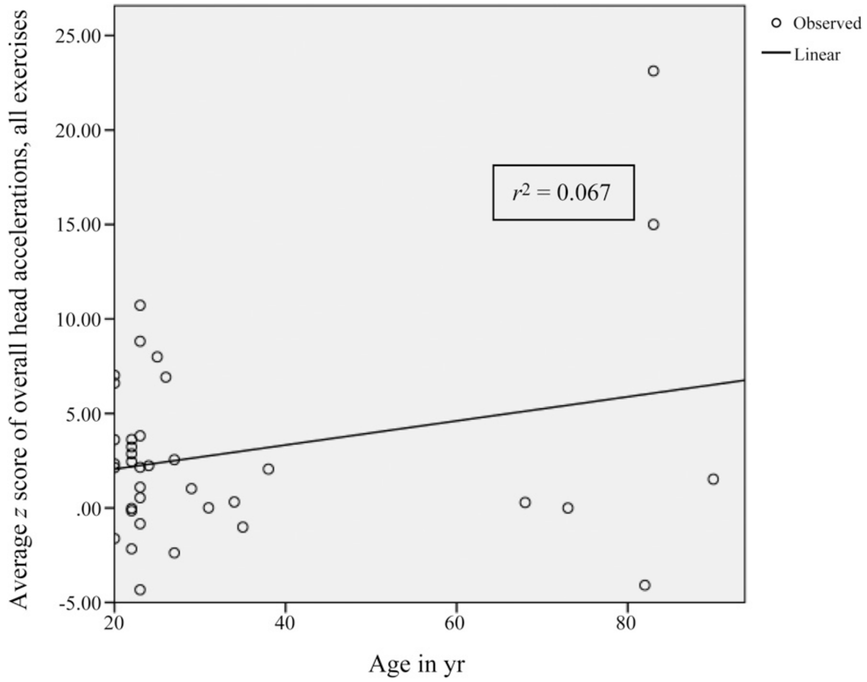

Figure 2. For those participants with neither dizziness nor poor balance confidence, a scatter-plot demonstrating the negative regression of z score of head accelerations with age, ABC >75, DHI <16.

Table 4. Effect Sizes of Regressions of Head Acceleration by Age Selecting Only Those Participants with Neither Dizziness Nor Poor Balance Confidence

Exercise	Linear Acceleration r^2	Angular Acceleration r^2
1. Nose to left knee	0.053	0.011
2. Nose to right knee	0.004	0.027
3. Horizontal headshake	0.012	0.135*
4. Vertical headshake	0.076	0.223*

Notes: n = 37. **p* < 0.05.

and computers, for approximately a 5′ diameter from the transmitter. The receiver(s), while small, must be securely attached to the participant, to minimize linear and angular slip. While video-based motion analysis is often cited in the literature, the benefits of a magnetometry system include the high-frequency linear and angular data collection, regardless of receiver visualization or orientation (very helpful with full-turn angular movements), as well as a much lower price point as compared to commercial video-analysis systems. The system used does not include software, which allows flexibility for the data-collection parameters, but could be a hurdle for the average clinician. Nonetheless, the rate of data collection and flexibility in movement both show great potential when collecting angular and linear data for the field of vestibular rehabilitation. In this study, 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 that may reduce its strength. The participants recruited in this study were all volunteers from the local community and are not part of a clinical population, therefore creating a risk of undiagnosed vestibulopathy in the control groups. To more comprehensively describe how dizziness and poor balance confidence affect movements during habituation exercises, a larger clinical sample size is needed. The majority of participants in this study were asymptomatic, and the symptomatic participants were commonly at the older end of the age continuum. To improve and expand on this study, an increase in participants in the 35- to 65-yr age range, dizzy participants <65 and nondizzy participants >65, are needed.

A challenge in the analysis of any data looking at the independent variables of age, dizziness, and balance confidence, is that these independent variables are naturally correlated. This is seen in Figure 3, where the three factors that influence vestibular functions (age, DHI, ABC) are plotted for each of the 52 participants. Clearly, older participants are more likely to be dizzy and have poor balance confidence. 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 yr of age. As a result of this colinearity, averaged normalized results are presented first, followed by a breakdown into two sets of the two predictors (age and DHI; and age and ABC). Finally, an analysis by age in a selection of only

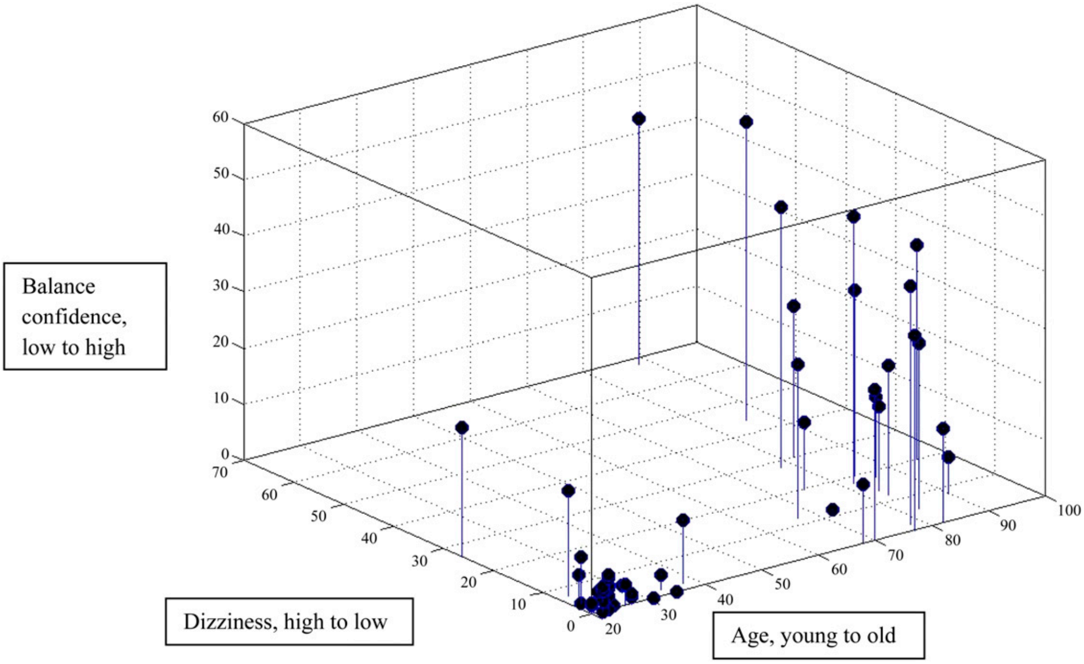

Figure 3. Graphic depiction of relationship between independent variables of age, dizziness, and poor balance confidence. (This figure appears in color in the online version of this article.)

those participants who are neither dizzy nor have poor balance confidence is presented. As illustrated in Figure 3, the analysis of age with normal vestibular function is a very exclusive selection of participants.

CONCLUSION

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. While adaptation exercises, focusing on VOR, have objective measures of head velocity, the lack of objectivity in the baseline and progress in habituation exercises creates an area of need for both clinicians and researchers. 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 of potential use as vestibular rehabilitation.

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APPENDIX: NONNORMALIZED DATA

Table A1. Exercise 1 (Nose to Left Knee) Linear Acceleration (m/sec^2)

Off-balance (ABC <75)	No (n = 40)	Yes (n = 12)
Mean	780.00	476.42
Median	744.50	431.00
Minimum	442.00	216.00
Maximum	1,299.00	1,138.00
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	766.52	472.30
Median	744.50	494.50
Minimum	216.00	230.00
Maximum	1,299.00	860.00
Older (>65)	**No (32)** **(range = 20–38)**	**Yes (20)** **(range = 67–95)**
Mean	830.38	560.45
Median	751.50	467.00
Minimum	464.00	216.00
Maximum	1,299.00	1,138.00

Table A2. Exercise 1 (Nose to Left Knee) Angular Acceleration (degrees/sec^2)

Off-balance (ABC <75)	No (40)	Yes (12)
Mean	3,517.53	1,695.32
Median	1,511.50	927.90
Minimum	593.00	391.00
Maximum	21,850.00	10,011.00
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	3,574.93	1,017.78
Median	1,371.00	953.40
Minimum	391.00	457.00
Maximum	21,850.00	1,683.00
Older (>65)	**No (32)**	**Yes (20)**
Mean	3,870.31	1,823.74
Median	1,535.00	1,117.00
Minimum	593.00	391.00
Maximum	21,850.00	10,011.00

Table A3. Exercise 2 (Nose to Right Knee) Linear Acceleration (m/sec^2)

Off Balance (ABC <75)	No (40)	Yes (12)
Mean	658.93	514.73
Median	636.89	438.42
Minimum	305.69	204.82
Maximum	1,041.70	1,363.40
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	654.80	503.25
Median	636.89	489.89
Minimum	204.82	340.73
Maximum	1,363.40	881.74
Older (>65)	**No (32)**	**Yes (20)**
Mean	648.37	589.32
Median	636.89	506.91
Minimum	305.69	204.82
Maximum	1,041.7	1,363.4

Table A4. Exercise 2 (Nose to Right Knee) Angular Acceleration (degrees/sec^2)

Off balance (ABC <75)	No (40)	Yes (12)
Mean	1,851.16	1,358.04
Median	1,373.90	1,034.80
Minimum	469.66	366.60
Maximum	9,434.20	4,940.30
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	1,880.90	1,134.53
Median	1,378.90	1,115.70
Minimum	366.60	672.40
Maximum	9,434.20	1,792.20
Older (>65)	**No (32)**	**Yes (20)**
Mean	1,780.50	1,668.34
Median	1,356.05	1,115.70
Minimum	469.66	366.60
Maximum	9,434.20	4,940.30

Table A5. Exercise 3 (Horizontal Headshake) Linear Acceleration (m/sec^2)

Off balance (ABC <75)	No (40)	Yes (12)
Mean	137.16	81.78
Median	118.33	73.71
Minimum	68.18	46.63
Maximum	378.32	124.15
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	134.27	82.83
Median	118.33	80.83
Minimum	58.59	46.63
Maximum	378.32	117.61
Older (>65)	**No (32)**	**Yes (20)**
Mean	140.95	97.86
Median	118.94	88.48
Minimum	68.18	46.63
Maximum	378.32	190.51

Table A6. Exercise 3 (Horizontal Headshake) Angular Acceleration (degrees/sec^2)

Off-balance (ABC <75)	No (40)	Yes (12)
Mean	1,201.45	633.70
Median	1,037.15	468.73
Minimum	466.66	226.13
Maximum	3,924.00	1,558.60
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	1,211.64	477.35
Median	1,082.20	456.74
Minimum	432.78	226.13
Maximum	3,924.00	687.34
Older (>65)	**No (32)**	**Yes (20)**
Mean	1,330.19	654.80
Median	1,154.70	526.92
Minimum	669.78	226.13
Maximum	3,924.00	1,558.60

Table A7. Exercise 4 (Vertical Headshake) Linear Acceleration (m/sec^2)

Off-balance (ABC <75)	No (40)	Yes (12)
Mean	176.71	122.65
Median	154.13	106.52
Minimum	87.50	61.86
Maximum	296.03	278.20
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	176.69	111.89
Median	154.13	98.71
Minimum	77.97	61.86
Maximum	296.03	186.30
Older (>65)	**No (32)**	**Yes (20)**
Mean	187.76	126.59
Median	191.04	110.07
Minimum	87.50	61.86
Maximum	269.03	278.20

Table A8. Exercise 4 (Vertical Headshake) Angular Acceleration (degrees/sec^2)

Off-balance (ABC <75)	No (40)	Yes (12)
Mean	1,019.87	537.66
Median	931.63	424.35
Minimum	323.18	197.42
Maximum	3,053.50	1,150.70
Dizzy (DHI >16)	**No (42)**	**Yes (10)**
Mean	1022.25	431.24
Median	956.62	426.36
Minimum	323.18	197.43
Maximum	3,053.50	649.63
Older (>65)	**No (32)**	**Yes (20)**
Mean	1,149.94	522.43
Median	995.47	457.42
Minimum	566.52	197.43
Maximum	3,053.50	1,150.70