THE EFFECT OF VIBROTACTILE FEEDBACK ON HEALTHY PEOPLE AND PEOPLE WITH VESTIBULAR DISORDERS DURING DUAL-TASK CONDITIONS

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Submitted to the Graduate Faculty of

University of Pittsburgh in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2013

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCES

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University of Pittsburgh, 2013

Vibrotactile feedback (VTF) has been shown to improve balance performance in healthy people and people with vestibular disorders in a single-task experimental condition. However, typical balance activities occur in a multi-task environment. Dual-task performance can degrade with age and in people with vestibular disorders. It is unclear if the ability to use VTF might be affected by dual-task conditions in different age groups and people with vestibular disorders. The purposes of this dissertation are to investigate in healthy young and older adults, and people with vestibular disorders: 1) balance performance in a dual-task paradigm under various sensory conditions while using VTF, 2) reaction time during dual-task performance under different sensory conditions while using VTF, and 3) the effect of testing duration and visit on VTF use.

Three study visits were included in this dissertation study: one screening visit and two experimental visits. Twenty younger and twenty older subjects were recruited in the first study to determine if VTF was affected by age. Seven people with unilateral vestibular hypofunction (UVH) and seven age-matched controls were recruited in the second study to investigate the effect of vestibular dysfunction.

The results showed that young and older adults use VTF differently, depending on the underlying sensory integration balance task. Older adults increased postural sway during fixed platform conditions, but both young and older adults decreased postural sway during sway-referenced platform conditions. Reaction times on the secondary cognitive tasks increased more while using the VTF in older adults compared with young adults. This finding suggested that using VTF requires greater attention in older adults. The trial duration and visit also affected postural sway performance while VTF was applied. Similar postural sway results were found when comparing people with UVH and age-matched controls. However, no group difference was found between people with UVH and age-matched controls in the magnitude of postural sway, which suggested that people with UVH were able to use VTF under dual-task conditions similar to normal adults. Our data also indicated that people with UVH require more attentional resources to perform secondary cognitive tasks while using VTF.

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PREFACE

Five years ago, I decided to come to the United States for advanced training in research. It was a very critical decision in my life. To make this decision, I had to give up a good job and a chance of promotion, leave my family and friends, go alone to a foreign land and speak different language in which I was not skilled. It was really a big struggle for me. However, to receive such an honor, a Doctor of Philosophy degree, was worth all of the effort. This honor should also belong to those people who have helped me in my academic field and my life.

I would like to acknowledge my advisor, Dr. Susan L. Whitney, for her support and guidance; I could never have achieved this Ph.D degree without her help. She is also the model of my future career. I would like to acknowledge my co-advisor, Dr. Patrick J. Sparto, for his continuous help, support and guidance. I would like to acknowledge my committee numbers, Dr. Joseph M. Furman, Dr. Patrick J. Loughlin and Dr. Mark S. Redfern, for their thoughtful and insightful comments. I would also like to acknowledge Dr. Kathleen H. Sienko, for her vibrotactile feedback system and her terrific research in the field of vibrotactile feedback.

I would like to acknowledge the Eye & Ear Institute Staffs, Anita Lieb, Pamela Dunlap, and Susan Strelinski, and my colleagues, Abdulaziz Alkathiry, Bader Alqahtani, Brooke Klatt, Faisal Asiri, Kefah Alshebber, Mohammad Almohiza, Mohammad Alshehri, Saud Alsubaie and Sahar Abdulaziz. Without their help, this dissertation would never have done.

Finally, special thanks go to the study participants, my family and friends. Because of your participation and support, I was able to defend my dissertation in front of my committee and accomplish this degree. My special and deep thanks are for my wife, Polly, and my unorn` bady girl, Nana, for your company at our sweet home.

1.0 INTRODUCTION

Falls in the elderly are devastating for the individual and have social and economic ramifications. In the United States, approximately 16% of older persons (age≥65) reported falling at least once during the past three months and 31% of those experienced an injury that required medical care[1] leading to $23.3 billion in annual expenditures.[2] Older people who experience a fall often have vestibular dysfunction according to clinical vestibular testing.[3, 4] Vestibular dysfunction has been identified as a critical factor that causes falls in older persons.[5, 6] A large epidemiological study by Agrawal et al.[5] has shown that 49% of adults over 40 years of age reported dizziness and difficulty in balance or falling in the past 12 months with a suggested 35% prevalence rate of vestibular dysfunction in the United States. Thus, early diagnosis and treatment of vestibular disorders might help reduce falls and falls-related costs.[5] However, in real-life circumstances, not only vestibular dysfunction, but also visual impairment, [7] medications,[8] leg extension strength,[9] handgrip strength,[9] and attention[10, 11] have been reported as important factors that may result in falls in older persons.

Vestibular rehabilitation was developed in the early 1940s.[12] At that time investigators began to realize that head and eye movements might affect postural control and dizziness. Several clinical vestibular assessments (i.e. dynamic visual acuity[13-15], the gaze stabilization test[14], the head thrust test[16], the head-shake test[17, 18]) and laboratory tests (caloric test[18], rotational chair[19, 20], vestibular evoked myogenic potenials[21]) have been developed to help clinicians identify functional deficits in persons with vestibular disorders. Although vestibular rehabilitation has been validated,[22-25] clinicians continue to search for technological advances that can help prevent falls and enhance their rehabilitation program.[26]

Auditory feedback has been employed to improve balance control for people with bilateral vestibular hypofunction.[27, 28] Persons with bilateral vestibular loss can utilize an auditory feedback prosthesis to help decrease trunk sway.[27, 28] However, the auditory feedback prostheses in these studies required the user to be familiar with the encoding of the feedback to movement directions.

Wall et al.[29-33] have proposed a new prosthesis, called a vibrotactile feedback prosthesis, that uses sensory substitution technology to replace or augment sensory information in order to provide additional sensory cues for postural control. Recent studies reveal that vibrotactile feedback can improve postural control. Kentala et al.[34] assessed a vibrotactile balance feedback device using computerized dynamic posturography and found that the prosthesis significantly reduced anterior-posterior sway in subjects with vestibular deficits. The investigators also suggested that the prosthesis may be helpful in reducing falls. Vibrotactile feedback has also been shown to improve dynamic walking in healthy elderly adults after a short training protocol.[33]

Dual-task balance paradigms have been used to evaluate the cognitive demands on postural control. Studies have shown that age and disease affect postural control and cognition.[35, 36] Older adults often attend to the postural task more than the cognitive task.[28, 37] Diseases, such as vestibular disorders, also affect the amount of attention required for postural control compared to healthy adults.[38-40] It is not clear if people who use more attentional resources for postural control are able to utilize vibrotactile feedback to control their sway.

Although the vibrotactile feedback device has been validated in small samples for improving postural control,[26, 34, 41-43] the interaction between using vibrotactile feedback information and performing a secondary task in different age groups and people with vestibular disorders is still not clear. Young adults, older adults, and people with unilateral vestibular hypofunction process sensory information in different ways, especially during dual-task conditions.[36, 40, 44, 45] When using the vibrotactile feedback device combined with dual-task conditions, different strategies of balance control may be demonstrated. The purpose of this research is to examine the influence of performing a secondary task while using vibrotactile feedback on postural sway in healthy young and older adults, and people with vestibular disorders. Improving balance control in older people and people with unilateral vestibular hypofunction might help to minimize the risk of falls, their associated secondary complications and hospitalization costs, and improve the quality of life and health of older persons and persons with vestibular disorders.

2.0 BACKGROUND

2.1 AGING, SENSORY FUNCTION AND FALLING

In the United States, 38.6 million people were age 65 or over in 2010.[46] The number of people over the age of 65 is 1.3 times more compared to 1990.[46] More than 2 million people over the age of 65 were injured related to a fall accidents in 2010 and more than 20,000 people over the age of 65 died from a fall related accident in 2009.[47] In 2005, more than 469,000 people over age 65 were hospitalized due to nonfatal unintentional falls. The total medical cost was more than 8 billion dollars and the total work loss cost was more than 5 billion dollars.[47] Falls were ranked the number one nonfatal unintentional injury in 2007.[46] The cost of a fall for an older person is an enormous burden to the individual, society and to the healthcare system. Therefore, fall prevention programs are a critical issue for the health care system and society. In order to develop a falls prevention program, using modern technologies in the elderly may assist in developing a better solution.

Vision, somatosensory and vestibular information are all involved in the maintenance of human postural control.[48, 49] Among the three systems, somatosensation was estimated to contribute 50%~70% of the information in maintaining postural control in older adult and 30%~40% in young adults.[50-52] However, age-related declines affect somatosensory function.[53-55] Vibration perception and tactile sensitivity are affected by aging. [53] Others also reported that the function of plantar mechanoreceptors decreased with aging. [54, 55] Several studies have also suggested that decreasing function in plantar mechanoreceptors is related to increased postural instability[56, 57] and falls.[58] Bergin et al.[56] compared body sway in normal healthy subjects and people with peripheral neuropathies. They found that body sway had a positive correlation with vibration perception. People with peripheral neuropathies demonstrated increased body sway.[56] Others have examined the contribution of foot mechanoreceptive sensation on stability in young and old adults.[57] The vibration perception threshold and tactile sensitivity were tested on young and old adults. Young adults showed lower vibration perception threshold and greater tactile sensitivity than older adults. Foot mechanoreceptive sensation was associated with stability during balance perturbations. Sturnieks et al.[58] investigated physiological risk factors for falls in older adults with lower limb arthritis. They found that lower limb proprioception and muscle strength were related to falling. A comprehensive balance examination should include the examination of distal sensation.[57]

Vestibular function also declines with aging.[59] Age-related declines of vestibular function include inner ear hair cell loss or death[60, 61], neuron fibers degeneration[62, 63], neuronal loss in medial vestibular nucleus[64] and decreased amplitudes of the vestibulo-ocular reflex (VOR)[65]. Declines in vestibular function may lead to dizziness and balance disorders.[5, 66, 67] Agrawal et al.[5] reported that vestibular dysfunction was associated with an increase in the odds ratio of self-reported dizziness and falling. Ishiyama[66] suggested that imbalance and vertigo is related to human aging. In a longitudinal study by Kerber et al.[67], they found that decreasing vestibuloocular reflex (VOR) gain, optokinetic gain, and visual-VOR gain is associated with decreasing Tinetti gait and balance scores. Lin and Bhattacharyya[68] reported that one in five elderly experience problems with dizziness or balance problems based on the

2008 National Health Interview Survey. Others have suggested that early diagnosis and treatment of vestibular disorders might help reduce falls and falls-related costs.[5]

After somatosensory decline, vision becomes the most important sensory feedback for balance control in older adults.[69] Age-related declines of visual function include loss of visual acuity,[70-72] contrast sensitivity,[73-75] and depth perception.[75] Lord and Ward[76] reported that increased reliance for postural control was seen until age 65. However, vision becomes progressively worse after the age of 50.[70] Loss of visual acuity[70-72], contrast sensitivity [75] and reduced depth perception[75] are associated with increased risk of falls in the elderly. Age-related visual impairments, such as macular degeneration, diabetic retinopathy, cataracts, and glaucoma, affect the vision of older adults.[77] Impaired vision with loss of contrast sensitivity, misjudgment of distance, misperceived spatial relationships and multifocal glasses increase the risk of falls.[73, 74, 78] Therefore, good vision management is an effective strategy for reducing falls in elderly.[78]

Using sensory substitution or augmentation as a way to counter these age- and disease-related impairments may help to decrease fall risk in older adults and people with balance impairment. The following section will discuss the development of a sensory substitution prosthesis that is designed to enhance postural control.

2.2 VIBRATION SENSE

Mechanoreceptors in human skin respond to mechanical pressure that transmit the response through the neural afferents to the cerebral cortex.[79] The receptors that respond to vibration are

Merkel disk receptors, Meissner’s corpuscles and Pacinian corpuscles.[80] Merkel disk receptors are classified as slowly adapting receptors and respond to low frequency (5-15 Hz) vibration.[80] Meissner’s corpuscles are classified as rapidly adapting receptors and respond to mid-range frequency (20-50 Hz) vibration.[80] Pacinian corpuscles are also classified as rapidly adapting receptors and respond to high frequency (60-400 Hz) vibration.[80] Humans are most responsive to vibration at frequencies of 200-250 Hz.[81]

The dorsal column-medial lemniscal (DCML) pathway relays vibratory sensation. The neural fibers travel in this pathway from the mechanoreceptors to the dorsal column of the spinal cord. The fibers from the lower extremities travel up the dorsal column to the gracile tract of the spinal column to the gracile nucleus while the fibers from the upper body (6th thoracic vertebrae) travel up lateral to the cuneate tract to the cuneate nucleus. The neurons from the receptors to the gracile or cuneate nucleus are called first order neurons. The neuron fibers then cross to the opposite side of the medulla. At the medulla, the neuron fibers travel in different orientations in the columns and medial lemniscus according to the source of the neuron fibers. The neuron fibers from the lower body travel medial in the columns and more ventral in the medial leminiscus; the neuron fibers from the upper body travel more lateral in the columns and more dorsal in the medial leminiscus. The neuron fibers then ascend the brainstem to terminate in the ventral posterolateral (VPL) nucleus of the thalamus. The neuron fibers from the face terminate in the ventral posteromedial (VPM) nucleus of the thalamus. The neurons from the medulla to the thalamus are called second order neurons. The neuron fibers beginning in the thalamus ascend to the primary somatosensory areas, called third order neurons.(Figure 1)

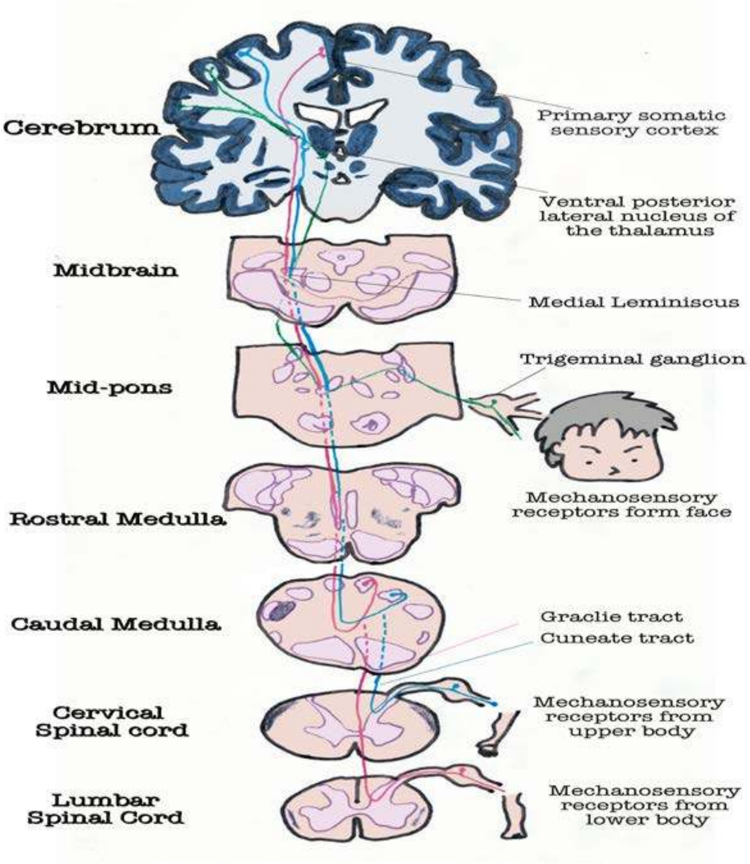


Figure 1. The Dorsal Column-medial Lemniscal Tract Pathway

There are two ways to examine vibration sensation. The tuning fork is most commonly used in clinic to assess the vibration sensation. A guideline from the Michigan Diabetes Research and Training Center, University of Michigan Health System recommends using a 128 Hz tuning fork and testing bilaterally on the boney prominence of the distal interphalangeal (DIP) joint of foot with subjects eyes closed.[82] However, a tuning fork is not sensitive to measure the changes of amplitude threshold of vibration sensation, which may be seen in some diseases, such as diabetic peripheral neuropathy[83] The Biothesiometer (Bio-Mediacl Instrument Company™, OH, USA) is like an electrical tuning fork in which vibration amplitude can be adjusted by changing voltage from 0-50 volts. The Biothesiometer provides semi-quantitative assessment of vibration perception threshold (VPT). VPT of more than 25 V is considered abnormal and be strongly predictive of subsequent foot ulceration.[84] However, Williams et al.[85] have found wide variability in VPT among different sites in people with diabetes. They suggested that the VPT test should be performed bilaterally and tested in different sites to determine the presence of neuropathy.

2.3 VIBROTACTILE FEEDBACK

2.3.1 Basic concept of the vibrotactile feedback

Biofeedback has been commonly used for gait training[86], muscle strength and control training[87] and as a relaxation techniques[88] in rehabilitation. The purpose of using biofeedback is to help people increase the awareness and control of physiological response and learn a technique.[89] As technology advances, there have been changes in the field of rehabilitation as more health professionals embrace biofeedback technology in the care of their patients.

Vibrotactile feedback is one form of biofeedback that has recently been used in rehabilitation of balance and dizziness disorders. Vibrotactile displays were first used by the U.S. Navy to provide pilots with navigational cues from the aircraft avionics.[90, 91] The pilots were trained to use the information from the vibrotactile displays on their abdomen. Rupert et al. have suggested that the information from the vibrotactile displays can help pilots reduce spatial disorientation mistakes[92] and convey aircraft position and motion information.[90] Although using vibrotactile feedback is not a new technology, Wall et al. have extended the concept of vibrotactile feedback to enhance human balance control for the purpose of rehabilitation.[31]

The prototype prosthesis, which included a head- or body- mounted sensor and tactors was proposed by Wall et al. in 2001.[32] At that time, the sensor was composed of one gyroscope and one linear accelerometer and the volume of the sensors was large and not easy to carry. The characteristics of the gyroscope and the linear accelerometer were based on the biophysical model of vestibular function. Human psychophysical experiments have indicated that the minimal thresholds of the human body to detect linear acceleration[93] and angular acceleration are $0.05 m/s^2$ and $1°/s^2$. [94] The effective bandwidth of the semicircular canal and the otolith organs were estimated to be 0.016 to 53Hz[95] and 0 to 40Hz, respectively[96] Wall et al. believed that the prosthesis could substitute for actual vestibular function and enhance one's balance performance. [32]

2.3.2 The design of the vibrotactile feedback system

According to the original design of the vibrotactile feedback system by Wall et al.[32], there were three major elements: an inertial sensor, computer and a vibrotactile array. The inertial sensor was composed of a gyroscope and a linear accelerator. Wall et al.[32] had suggested that the inertial sensor should be able to substitute for vestibular function. The inertial sensor was mounted on the head in the original design[32], but switching to body in the later studies[30]. The signals from the inertial sensor were used to estimate body tilt by calculating the values form gyroscope and the linear accelerator. The signal from the gyroscope and the linear accelerator was used to estimate the angular body tilts and body tilt velocity via a complex mathematic calculation. The vibrotactile display was driven by the body position, angular body tilts and body tilt velocity. The threshold of vibrotactile activation was set at 0.5° head tilt. Computer software was used to process the signal from the inertial sensor using LabView (National Instruments Corporation, Austin, TX).

Various vibrotactile display schemes have been compared with different numbers of tactors and placements on the body. Wall et al.[32] have compared the tactor placement at the shoulder and waist. They concluded that there was no significant difference in root-mean-square (RMS) of center of pressure (COP) between the two locations.[32] Sienko et al.[42, 97] suggested that four columns and two rows of tactors (a total of eight) would be enough for coding tilt magnitude. The columns represent the four directions of body sway (forward, backward, right and left) and two tactors in each column sequentially activate from bottom to top in response to increasing sway in the assistive direction. (Figure 2)

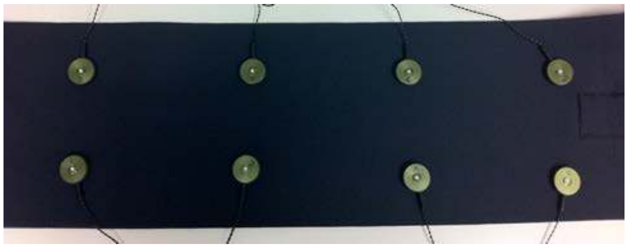


Figure 2. Four Columns and Two Rows of Tactors (4 columns by 2 rows)

Vertiguard®RT and BalanceFreedom (SwayStar™) are commercially available vibrotactile feedback systems on the market. Vertiguard®RT is similar to Wall's device but is simplier (four tactors and a sensor). Vertiguard®RT [98, 99] has been used on different groups with balance deficits, such as people with vestibular disorders and Parkinson's disease. Basta et al.[98] found that Vertiguard®RT vibrotactile feedback training was helpful in reducing trunk and ankle sway and decreasing subjective symptom scores in people with vestibular disorders and Parkinson's disease. BalanceFreedom (SwayStar™)[100, 101] is a device that combines auditory and vibrotactile feedback. It also can be used as an evaluation device for postural sway.[102, 103]

2.3.3 Use of the vibrotactile feedback system for postural control

The effect of the vibrotactile feedback system on controlling postural sway in young healthy subjects and people with vestibular disorders has been validated.[30-34, 41, 97, 104, 105] Wall et al.[32] compared vibrotactile feedback with another balance aid, a light touch cue[106] which was defined as one fingertip lightly placed on a fixed support in front of the subject. Lackner et al[106] had suggested that light touch of the index finger on a stationary surface could reduce postural sway during quiet stance in normal healthy subjects and people with bilateral vestibular loss. The results demonstrated that the vibrotactile feedback system significantly reduced RMS of COP compared to light touch.[32] Kentala et al.[34] compared anterior-posterior (AP) postural sway with and without the vibrotactile feedback prosthesis on six subjects with vestibular deficits based on excessive sway in conditions 5 and 6 of the Sensory Organization Test. Vibrotactile feedback reduced postural sway effectively in the AP direction in the subjects with unilateral or bilateral vestibular hypofunction.[34]

Dozza et al.[41] tested subjects with unilateral vestibular loss to examine the effect of vibrotactile biofeedback during tandem gait. Subjects who experienced a short training period of 5-10 minutes with vibrotactile feedback improved tandem gait performance. Sienko et al.[97]

recruited eight subjects with weakly compensated vestibular loss and noted that the subjects had reduced root-mean-square (RMS) trunk sway when the vibrotactile feedback was applied. They also compared the time which the subjects stayed outside the neutral zone (tactors provided vibrotactile feedback) when the tactors were on versus off. They found that subjects spent less time outside the neutral zone when the tactors were on. Others have used a head-mounted vibrotactile device in persons with bilateral vestibular hypofunction.[105] Postural sway was reduced during computerized dynamic posturography while wearing the head mounted vibrotactile feedback device.[105] Wall et al.[30] also examined the use of VTF on the sensory organization testing condition. The results showed that vibrotactile feedback helped reduce AP sway and improved balance during the sensory organization test condition 5 and 6 when they tested subjects with moderate and severe vestibular deficits.[30] Peterka et al.[104] determined the effectiveness of a vibrotactile balance prosthesis by analyzing subjects' responses to different support surface stimulus perturbations (support surface tilt angle in 1º, 2º, 4º, 8º). The results showed that vibrotactile feedback reduced RMS in healthy adults and people with bilateral vestibular hypofunction for the different support surface stimulus amplitudes, although people with bilateral vestibular hypofunction demonstrated higher RMS postural sway than healthy adults.

By detecting the body position and sway velocity (see section 2.3.2), the vibrotactile feedback system is able to improve postural sway and gait function. Wall et al.[33] examined the effect of vibrotactile feedback on healthy older adults when performing the Dynamic Gait Index (DGI). The results demonstrated that vibrotactile feedback decreased the amount of medial-lateral trunk tilt and improved the DGI scores from a mean of 17.1±0.4 to 20.8±0.3 for subjects at risk for falls. They further analyzed the change of DGI subtest scores and found that vibrotactile feedback helped most in the subtests requiring head turns.[33]

The algorithm to activate Wall et al.'s vibrotactile feedback device is based on combinations of body position and sway velocity. Goodworth et al.[107] examined the various combinations of weighted body position and sway velocity in healthy adults in order to identify the best combination for reducing body sway. However, no specific combination that could reduce postural sway uniformly was found because combinations of feedback that reduce low frequency postural sway (<0.5 Hz) also increased high frequency postural sway (>2Hz) and vice versa.[104, 107] Loughlin et al[108] has proposed a subject-specific design to solve this problem, but only simulation results have been demonstrated so far.

Additional work is needed to validate the vibrotactile feedback devices in other conditions. Most of the studies only demonstrate using vibrotactile feedback under single task conditions, but in real life, standing balance is only one component of functional tasks. Haggerty et al.[109] examined the effect of vibrotactile feedback during a dual-task paradigm. Ten healthy older subjects were recruited in the study. A choice reaction time task was used as a secondary cognitive task (see section 2.4.1). The subjects were asked to respond to the stimuli by pushing buttons or verbally responding. The results demonstrated reduced sway when the vibrotactile feedback was on. The root-mean-square (RMS) of center of pressure was both with and without a secondary cognitive task. Decreased sway also found in the dual-task trials without vibrotactile feedback. The response times in the choice reaction time task were increased in the trials with vibrotactile feedback. They concluded that using vibrotactile feedback is attentionally demanding for older adults.[109]

Attention is a key element in the human's postural control. Using dual-task paradigm can help us to understand the relationship between attention and postural control. How attention affects postural control will be discussed in next section.

2.4 POSTURAL CONTROL AND DUAL-TASK

2.4.1 Dual-task methodology

Postural control was considered an autonomous function in the human body in the early 1900s.[110, 111] However, recent research has suggested that postural control requires certain attentional resources but it varies from condition to condition.[112] The dual-task balance paradigm is a way to investigate the role of cognitive (attentional) demands on postural control. In the dual-task balance paradigm, subjects are asked to perform a concurrent no-postural cognitive task while also performing a balance task.[113] Different approaches to the dual-task paradigm have been studied. Some research focuses on different cognitive tasks to understand the attentional demands on postural control[114, 115] while others change the level of difficulty of the postural task[116-120] to examine the attentional requirements.

Two major cognitive psychology theories have been used to explain posture-cognition outcomes in dual-task paradigms: capacity theory[121] and bottleneck theory.[122] Capacity theory states that cognition and postural control share a limited set of resources so that the competition between the cognitive task and postural task degrade performance on one of the tasks.[123] The bottleneck theory proposes that the nervous system delays operations in one task in order to execute the prioritized task so that there is reduced performance on the non-prioritized task.[123] The bottleneck theory is more apparent in visual information processing than auditory information processing.[124] There are also a few theories that help to explain the posture-cognition outcomes. Automaticity describes performing a task with less effort or without demanding attention.[125, 126] However, a large amount of practice needs to be achieved before automaticity occurs.[127-129]

Several cognitive tasks have been used in the dual-task paradigm. The methods can be ce classified into different categories according to the characteristics of the cognitive task: counting tasks,[130-133] visual reaction time tasks,[118, 134-137] auditory reaction time tasks[36, 116, 138, 139] or the combination of visual and auditory reaction time tasks.[36, 140] In the counting task, counting backward by three or seven is the most common task, starting from a random number or a fixed number. Counting backward has been shown to cause significant degradation in postural stability in healthy subjects.[45, 133, 141] A visual reaction time task usually involves a monitor or cards displaying pictures to the subjects and requires subjects to respond to colors, names or a visual and memory task.[135, 136, 142] The Stroop test[143] can also be used to evaluate cognitive influences on postural control. The Stroop test uses a different color-word display, for example, the word ‘red’ printed in the color blue. The subjects are usually asked to say the ‘color’ of the ink. Auditory reaction time tasks use a tone that may vary in frequency or other characteristic and require the subjects to respond to the tone as quickly as possible by pushing a button. Simple reaction time (RT) tasks, choice RT and inhibition RT tasks[144] are the most common methodologies. In the simple RT task, the subjects respond to a single stimulus as quickly as possible. In the choice RT task, the subjects respond to one of two possible stimuli, for example, by pushing a button when hearing a higher pitched tone with the right hand and a lower pitched tone with the left hand. The inhibition RT task was introduced by Logan et al..[144] The inhibition RT task sometimes mixes the visual and auditory stimuli. The subjects respond to the visual signal as soon as possible and stop the responses if they hear a target tone ("stop" tone) during the trial. The stop signals are presented during 20% of the trials.

Different postural tasks have been used during the dual-task paradigm to examine the attentional requirements. Sitting is considered a lesser a challenge of postural control and usually is assessed as a baseline condition. Postural sway during quiet stance is the baseline condition when measuring the effect of a secondary task on postural sway. The difficulty level of postural tasks can be increased by requiring subjects to stand on a sway-referenced platform or translating platform. The translating platform is considered more difficult than a sway-referenced platform.[36] Walking and stepping are more complex postural tasks and also can be used to examine interference between balance and attention (see section 2.4.4).

Since Kerr et al.[114] published the first study to investigate the influence of attention on standing postural control in young adults, many studies have examined the attentional demands of postural control.[35, 120, 145, 146] Aging and disease may alter the attention demands of postural control. The following section will describe the influence of aging and disease on the dual-task paradigm.

2.4.2 Dual-task performance in young adults

When talking about dual-task performance in aging, the study results from young adults are usually discussed first. In young adults, conflicting results have been noted. Various studies have demonstrating no difference[114, 115], reduced postural sway[137, 147], increased postural sway[133] or variable postural sway depending on the secondary tasks[145] performed.

While studying the effect of a dual-task paradigm on postural control, several confounders that affect the relationship between attention and postural control were found.[115, 145, 147] Kerr et al.[114] examined the attentional demands of standing in young adults. Subjects performed the Brooks spatial and nonspatial memory task while standing. The Brooks spatial memory task involved remembering numbers in imagined matrices. The results demonstrated that there was no significant difference in postural sway due to the type of memory task, but the number of errors increased when the spatial memory task was performed during standing. Others have studied the influence of arousal and attention on the control of postural sway.[115] Young subjects performed four different secondary cognitive tasks during quiet stance. Maki et al.[115] had found that the secondary tasks did not affect postural sway and suggested that the confounding influence of arousal should be controlled when studying attentional effects. The Stroop test has also been used to examine the effect of secondary cognitive tasks on different postural tasks (shoulder width stance, shoulder width stance on a rocker board, tandem stance on a rocker board).[137] The results indicated a decrease in postural sway in the anterior posterior direction when subjects stood with shoulder width stance on a rocker board and performed a secondary cognitive task. Hunter and Hoffman[147] reported that young adults reduced postural sway in medial-lateral COP movements while performing a secondary task requiring mathematical computation. Visual conditions, looking at a stationary or moving digit, were also given in this study. The results showed that the medial-lateral postural sway increased in young adults when their eyes needed to track the moving digit . Pellecchia[133] examined the effect of the difficulties of different cognitive tasks in quiet standing. Three information processing tasks were used as the secondary cognitive tasks: digit reversal, numerical classification and counting backward by three. The digit reversal tasks required the subjects to reverse the order of a pair of digits (e.g. 52 to 25). In the numerical classification task, the subjects needed to categorize that the given number was more than 50 or less than 50 and odd or even. The results showed that postural way increased as the complexities of the cognitive tasks increased. Counting backward by three was the most difficult task and the digit reversal was the easiest task. Although the form of the secondary cognitive task, arousal, and eye movement demonstrated different levels of influences on the postural sway in young adults, it was unknown what confounding factor affected the postural control most in young adults.

Yardley et al.[145] examined the effect of articulatory and secondary cognitive tasks on postural control in young subjects. In this study, subjects performed four secondary tasks while standing on an unstable surface: counting backward aloud (attention + articulation), counting backward silently (attention only), number repetition (articulation only) and no mental task. Three different visual conditions (eyes closed, moving visual images and a static visual image) were also given during the testing. The results indicated that postural sway increased when subjects counted backward aloud and repeated numbers, but not when they counted backward silently. They concluded that articulation might affect postural control more than the cognitive task due to central interference (speech and balance share the same central resources).

Despite different results indicating the influence of a secondary cognitive task on postural sway in young adults, researchers have agreed that postural control is attentionally demanding in young adults, [112, 114, 145] but the effect may be small.[112] In some cases, young adults demonstrate the cognitive first principle in which the postural task has become automatic while performing a secondary cognitive task.[137, 148] However, arousal[115], eye movement[147] and articulation[145] should be controlled while studying the effect of cognitive tasks on postural control as they can all influence the person's postural control.

2.4.3 Dual-task performance in aging

Aging has been associated with increased postural sway in older adults during the dual-task paradigms.[35, 120, 140, 149, 150] Stelmach et al. [35] compared the postural recovery period from a voluntary arm swing task in young and older adults during stable and unstable upright stance with a cognitive (math task) or a motor task (bimanual grip). They found that older adults had increased attentional requirements to recover from postural destabilizing activities. Brown et al.[149] investigated postural recovery in young and older adults using counting backwards by three as a secondary task on a series of unexpected platform displacements. Older adults required more attention than young adults when recovering posture from external perturbations which suggests that older adults might increase their risk of falling because of insufficient attentional resources for postural recovery.[149]

Shumway-Cook & Woollacott[120] used six different sensory conditions to test postural stability in young and older adults during a dual-task paradigm. The secondary task (auditory choice RT) did not affect postural stability in the young group, but the secondary task affected postural sway when visual and somatosensory feedback were removed in the older adults. Rankin et al.[150]. used electromyography (EMG) to investigate the neuromuscular response characteristics on postural muscles (gastrocnemius and tibialis anterior muscles) during stance. The onset latencies of the postural muscle responses did not change under the dual-task condition, but the amplitude of the postural muscle responses were significantly reduced in older adults compared to young adults. They concluded that the reduction in EMG amplitude might be due to less attentional processing capacity for balance control under the dual-task condition.

Redfern et al.[140] studied the influence of attention on sensory integration for postural control in young and older adults by using different postural tasks (fixed platform, sway-referenced floor and sway-referenced visual scene) and different RT tasks (auditory simple RT and inhibition RT). They hypothesized that sensory integration may affect postural sway during dual-task conditions. They suggested that attention is associated with sensory integration and aging might affect the sensory integration, attention and information processing.

Although aging generally is associated with decreasing stability when a secondary cognitive task is performed, some studies have provided different opinions.[134, 146] Redfern et al.[146] examined postural control during surface perturbations in young and older adults with a secondary cognitive task. They asked the subjects to respond to visual and auditory stimuli by pushing a button in one hand for measuring reaction time. The results indicated that the reaction time was longer for the visual stimulus than the auditory stimulus conditions. F However, there was a difference between the young and older group in the COP latency and magnitude. Prado et al.[134] asked subjects to perform a secondary visual task for observing behavior and postural sway between young and older adults. They found that age did not affect the integration of visual information by the postural control system and secondary visual tasks did not necessarily increase postural sway in both groups. Although a secondary cognitive task might not affect postural sway on young or older adults, the older group showed significantly increased response time on the secondary task while performing the balance task.[134, 146]

The level of difficulty of the postural task also affected reaction times during secondary cognitive tasks in older adults.[117-119] Teasdale et al.[117] examined how sensory inputs affect the attentional requirement of postural control in young and older adults. They recorded the responses to a simple RT task as the secondary task in sitting, and standing with different sensory conditions (Eyes open/closed * Surface normal/foam). They found that reaction time was increased from sitting to standing in young and older adult groups and when visual input was reduced, but the reaction time increased more in older adults than younger adults. They concluded that older adults required more attentional capacity as sensory information was reduced. Marsh and Geel[118] studied the attentional requirement of different postural control tasks (seated, standing on hard/foam surface with eyes open/closed) in young and older women with verbal reaction times in response to an auditory stimulus. They determined that older women had slower verbal reaction times than young women and increased verbal reaction time more in standing than sitting. However, they did not find any difference in verbal reaction times as the difficulty of the postural tasks increased. In the study of Lajoie et al.[119] sitting, standing and walking tasks were included to examine the attentional requirements of postural control. An auditory RT task was used as the secondary task. They found that the young group had faster RTs than the older group among the three different postural tasks.

The effect of more complex secondary cognitive tasks on postural control has been examined by Maylor et al..[151] Five different cognitive tasks were used: (1) random digit generation, testing working memory; (2) Brooks' spatial memory task, testing visual-spatial sketch-pad function; (3) backward digit recall, testing phonological loop; (4) silent counting, testing phonological loop; and (5) counting backward in threes, testing the phonological store of the phonological loop. The young group had more stable performance than the older group in the above five conditions. However, the Brooks' spatial memory task and backward digit recall tasks significantly enhanced the age-related difference in postural stability. Maylor et al. suggested that the increasing difference between the young and older group in postural stability in the Brooks' spatial memory task and backward digit recall might be due to the interference of sensory integration.[151]

Since aging shows a significant effect on dual-task performance, the study results indicated that older adults increased the attentional requirements on postural control[35, 117-120, 140, 149, 150]. Woollacott & Shumway-Cook[112] concluded that older adults require more attention when performing a secondary task and have more deleterious effects on postural control compared to young adults. Generally speaking, dual-task performance in aging people demonstrated increasing reaction time and the influence of secondary task on postural sway may depend on the difficulty level of the secondary task. The change in performance on the postural sway may be associated with the sensory integration process. The effect of a dual-task paradigm in walking will be discussed in next section.

2.4.4 Dual-task performance during gait

Besides using dual-task paradigms in static postural control, the dual-task paradigm also has been used with walking to assess the relationship between attention and dynamic postural control. Performing a secondary cognitive task affects young adults more than older adults when walking.[119, 152, 153] These reports showed increased reaction times or slowing of gait speed. However, no gait pattern change was observed.[119, 152, 153] Lajoie et al.[119] reported that although the auditory reaction time task did not affect the gait parameters, older adults required greater attentional resources in standing and walking. Ebersbach et al.[152] examined the effect of dual-task performance on gait in young adults. They found that the secondary task did not necessarily change the gait parameters in young adults. Chen et al.[153] investigated the ability of older adults to avoid obstacles while performing two different secondary cognitive tasks. The results showed that older adults had longer reaction times than young adults and that the error rate increased when they performed a complex cognitive task. The older adults also demonstrated an inability to avoid obstacles and increasing the risk of falling. The relationship between falling and dual-task performance will be discussed in the section 2.4.7.

Most recent studies support the idea that the dual-task performance does not affect gait performance in young and older adults.[154-157] Schrodt et al.[154] examined the influence of a secondary cognitive task on walking and stepping over an obstacle in community-dwelling older adults. They found that gait parameters did not change during dual-task performance. Springer et al.[155] used swing time, gait speed and swing time variability in young, older adults and older adults with a fall history to study the influence of a secondary cognitive task while walking. They found that a dual-task did not affect the swing time during gait, but gait speed was decreased during dual-task performance in all three groups. Srygley et al.[156] used a math task (serial three's and seven subtractions) as the cognitive task to test dual-task performance in young and older adults while walking. The subjects were asked to perform the cognitive task in sitting and walking. They found that older adults had increased reaction times more than young adults while sitting and walking. There was no difference when young and older adults recited the serial three subtractions in sitting and walking; in contrast, serial 7 subtractions demonstrated significant differences between young and older adults. The older adults showed more mistakes than young adults in the all cognitive tasks (serial three's and seven subtractions). Older adults had a decreased ability to perform secondary cognitive tasks, especially when the secondary cognitive task was sufficiently difficult. Motion analysis has been used to investigate the influence of a secondary cognitive task (counting backwards by three) on walking speed and gait parameters of COP displacement, peak lateral force and step width.[157] Cho et al.[157] also used planned sidesteps and unplanned sidesteps at the end of walking task. The results demonstrated that both groups decreased medial-lateral COP displacement and walking speed during the dual-task conditions. Slower gait speed during secondary cognitive tasks was also reported in both groups. However, Dubost et al.[158] reported that dual-tasks increased stride time variability in older healthy adults when a verbal fluency task (enumerating animal names in rhythm) was used as the secondary cognitive task. They concluded that increased stride time variability was related to the verbal fluency task and suggested higher cortical regions were involved when performing a rhythmic secondary cognitive task in older adults. Brach et al.[159] have suggested that increasing gait variability is associated with falls in older persons. A study by Doi et al.[160] used a triaxial accelerometer to measure gait performance under dual-task conditions. Changes of gait parameters associated with performing the dual-task were noted. They further used MRI to study the relationship between brain atrophy and the changes of gait parameters during dual-task performance. The results supported the idea of attentional requirements in gait and also suggested that brain atrophy might be related to the changes of gait performance in dual-task conditions.

The most recent evidence from dual-task studies firmly supports that gait is not simply an automated motor activity, but also involves higher-level cognitive function.[160-162] Executive function (EF) and attention are considered as higher-level cognitive functions. Executive function can be divided into different components: volition, self-awareness, planning, response inhibition, response monitoring and attention/dual-tasking[163-165]. If executive function function is impaired, one's ability to perform dual-tasks in walking will decline remarkably.[156]

Therefore, he/she will experience falls more frequently.[156] The next section will discuss using dual-task paradigms to predict falls.

2.4.5 Dual-tasking and falls prevention

Falling is a common problem in older adults.[166] The decline of dual-task performance has been associated with falls in the elderly.[167-170] Lundin-Olsson et al.[167] observed that some elderly people stop walking when they talk in long term care facilities. They proposed that "stops walking when talking" might be used to predict falls. In their study, they found that the sign of "stops walking when talking" had high specificity (95%), but low sensitivity to predict falls.[167] This was the first study providing the idea of fall predictions based on dual-task performance. Shumway-Cook et al.[168] examined the ability of the Timed Up & Go test to predict falls. They compared the time taken to complete the Timed Up & Go test in single and dual-task conditions. The Timed Up & Go test in single or dual-task conditions was sensitive and specific to identify people who were prone to falls, but performing the secondary task did not enhance the ability of Timed Up & Go test to predict falls. Faulkner et al.[169] investigated the relationship between people with a history a recurrent falls and dual-task performance. Recurrent falls were defined as a history of two or more falls during a 12 month period. They found that higher odds ratios of recurrent falls history was associated with elderly people who performed worse on a secondary visual-spatial decision task while walking. Beauchet et al.[170] designed a twelve-month prospective cohort study to determine the relationship between recurrent falls and dual task-related changes in walking speed. Recurrent falls were defined as two or more falls during a 12 month follow-up period. They recruited 213 subjects from thirteen senior housing facilities and reported that people with recurrent falls had slower walking speed while counting backwards by one. However, several studies found dual-task performance might not be useful to predict falls.[171, 172] A study by Stalenhoef et al.[171] found dual-task performance was not predictive of falls (odds ratio=1.5, 95%CI: 0.7-3.3). Another study by Vaillant et al.[172] found no difference between women who reported a history of falls and no falls while they performed an arithmetic task during the Timed Up & Go test and one-leg-balance test. However, a meta-analysis reported that a change in reaction time while performing secondary task was significantly associated with prediction of falls among older adults (pooled odds ratio =3.5, 95% CI: 3.1-9.1).[173]

Beside older adults, people with cognitive impairment have poor dual-task performance.[174-176] The poor dual-task performance is also associated with increased risk of falls. The next section will discuss dual-task performance in people with cognitive impairment, such as Parkinson's disease and Alzheimer's disease.

2.4.6 Dual-task performance in people with cognitive impairment

People with Parkinson's disease have reported difficulty in tasks with cognitive effort.[174, 177] Several studies have examined dual-task performance in people with Parkinson's disease.[174-176, 178-184] Although different methodologies were used in the studies, consistent results were reported that a secondary task results in deterioration in gait and balance performance. For example, Bloem et al.[181] used The Multiple Tasks Test[185](based on the idea of dual-task paradigm) to examine dual-task performance in walking with young, older adults and people with Parkinson's disease. The results demonstrated that people with Parkinson's disease had more motor errors. They concluded that people with Parkinson's disease had less prioritization of the motor tasks over the cognitive test which suggested a "posture second" strategy in people with Parkinson's disease.[186] Plotnik et al.[187] have reported that dual-task gait performance in people with Parkinson's disease is associated with fall risk.

People with Alzheimer's disease also have cognitive function impairment[188] that is associated with posture and gait disturbance.[189] People with Alzheimer's disease demonstrated decreased ability to perform motor tasks during dual-task conditions.[162, 190, 191] Camicioli et al.[191] reported that walking speed in people with Alzheimer's disease was significantly decreased more than healthy older adults when performing a secondary cognitive task. They suggested that the inability to perform talking while walking contributes to the risk of falls in people with Alzheimer's, which has been confirmed in recent studies.[162, 190]

People with bilateral vestibular disorders also experience falls frequently.[192] People with vestibular disorders also report cognitive problems, such as attention deficit and short-term memory loss.[193] Since the dual-task paradigm is used to examine the relationship between cognition and motor/balance performance, the following section will discuss the interaction between a secondary cognitive task and motor/balance performance in people with vestibular disorders.

2.4.7 Dual-task performance in persons with vestibular disorders

Persons with vestibular disorders usually report fatigue and poor concentration[194, 195] and recent evidence reveals that cognitive-vestibular interaction exists.[193, 196] Smith et al.[196] searched the evidence from MRI, animal studies and dual-task studies and suggested that people with vestibular disorders are more likely to experience cognitive problems. Hanes and McCollum[193] reviewed the evidence from dual-task studies and physiology studies to support this interaction.

Balance problems are a critical issue in people with vestibular disorders. Dual-task studies reveal the interaction between balance control and cognitive function in people with vestibular disorders.[36, 38-40, 197, 198] Andersson et al.[38] studied the influence of a visuospatial cognitive task on healthy control subjects and people with peripheral vestibular dysfunction when performing computerized dynamic posturography in conditions 4 and 5 (condition 4: EO/sway-referenced platform; condition 5: EC/ sway-referenced platform). The results showed that the cognitive task performance was not different between healthy control subjects and people with peripheral vestibular dysfunction. However, cognitive task performance in standing with eyes closed was worse than in sitting in people with peripheral vestibular dysfunction. The balance results demonstrated that people with peripheral vestibular dysfunction had significantly greater postural sway than healthy controls due to cognitive task performance. However, no difference was found between the dual-task and single-task in equilibrium scores. Interestingly, the mean equilibrium scores in people with peripheral vestibular dysfunction were slightly better when performing a secondary cognitive task, but people with peripheral vestibular dysfunction exhibited more falls during balance test conditions. Due to the increasing scores on the mean equilibrium scores in people with peripheral vestibular dysfunction, Andersson et al. suggested that the secondary cognitive task might affect balance in varied ways in people with peripheral vestibular dysfunction. They also suggested that further study should examine the effect of different distracters on postural control in people with peripheral vestibular dysfunction, such as using auditory stimulation or changing the level of difficulty in the secondary cognitive task. Yardley et al.[40] further investigated the influence of different levels of difficulty in a secondary cognitive task on postural control in people with and without vestibular disorders. A simple speed discrimination task was used as the low load cognitive task. In the spatial task, the subjects needed to push the lower or upper button when hearing sounds in a different ear. In the non-spatial task, the subjects needed to push the lower or upper button when hearing different sounds (tone or buzz). Categorization of a numerical stimulus was used as high load cognitive task. This task was further divided into spatial and non-spatial tasks. In the spatial task, the subjects pressed the upper button if they noticed that the time on an analog clock was the same as a set of numbers which represented a time they heard. In the non-spatial task, the subjects pressed the upper button if they heard two even or odd numbers, and the lower button if they heard one even and one odd number. Sitting, standing with eyes closed on a stable platform and a sway-referenced platform were used as balance tasks. The results demonstrated that a low or high load secondary cognitive task did not affect postural sway in both controls and people with vestibular disorders, but it did affect reaction time. When the balancing task became difficult, reaction times increased and accuracy declined. The people with vestibular disorders showed a longer reaction time than controls on the spatial task compared to non-spatial task. Redfern et al.[36] examined the role of attentional processes on people with well-compensated vestibular impairments and healthy controls. Well-compensated was defined as no symptoms of dizziness or definable postural deficits. Simple reaction time, choice reaction time and inhibitory reaction time were used as the secondary cognitive task in different balancing conditions (seated, fixed, sway-referenced, and translating the floor). They found that reaction time and postural sway were increased when the postural task became challenging in both groups, but no significance in postural sway difference was evident between groups. However, people with well-compensated vestibular impairments had slower reaction times than healthy controls under all conditions, especially in choice and inhibitory reaction time tasks. They suggested that the information processing of people with well-compensated vestibular impairments was different compared with the healthy controls. This difference might be at the sensory integration level when the people with compensated vestibular impairments try to orient to multiple sensory signals.

Dual-task interference not only occurs in static balance, but also affects gait in people with vestibular disorders. Nascimbeni et al.[132] had studied dual-task interference during gait in people with unilateral vestibular disorders and healthy controls. Counting backward by three was used as the secondary cognitive task while walking at a self-selected speed. The results showed that there was no difference between gait parameters between the groups in single or dual task performance, but within-subject differences were found. People with unilateral vestibular disorders also demonstrated worse performance on a secondary cognitive task. They concluded that people with unilateral vestibular disorders put the motor task as the first priority which led to the decrease of cognitive performance during gait. Roberts et al.[198] investigated the effect of dual task performance on a linear walking task in subjects with and without vestibular disorders. Four walking conditions and two visual conditions were performed during the test: (1) walking in a straight line (2) a naming task while walking (3) nodding while walking (4) nodding and naming while walking with eyes open or closed. People with vestibular disorders had greater difficulty walking straight compared with healthy subjects and veering increased with the additional cognitive task. The visual condition also influenced the performance in all the testing conditions (eyes closed was worse than eyes open).

Dual-task performance reveals that people with vestibular disorders demonstrate some deficits in components of executive function, such as attention and inhibition. Although people with vestibular disorders may improve their inhibitory function after 6 weeks of vestibular therapy,[199] the evidence indicated that information processing is quite different than normal.[36] Understanding the mechanisms of information processing in people with vestibular disorders will help to improve the care of people with vestibular disorders. However, more research is needed to investigate the relationship of cognition and movement in people with vestibular disorders.

2.4.8 Dual-tasking and clinical applications

The decline of dual-task performance has been associated with falls in the elderly.[169, 170] Thus, improving the ability to perform dual-task conditions may be needed. Several studies have investigated the effect of dual-task training in older adults and older persons with balance impairment.[200-203] Silsupadol et al.[200] conducted a randomized controlled trial in older adults with balance impairment. The participants were divided into three groups: single-task balance training, dual-task balance training with fixed-priority instructions group and dual-task balance training with variable-priority instructions group. Forty-five minute individualized training sessions, three times a week for four weeks were provided to all three groups. Walking speed and Berg Balance Scale scores were improved in all the groups. When the participants were asked to perform a secondary cognitive task in walking, only participants who received dual-task training significantly improved gait speed. However, only the dual-task balance training with the variable-priority instructions group maintained the training effect up to twelve weeks follow-up. They concluded that single-task balance training may not generalize to the dual-task condition and dual-task training with variable-priority instructions helps to maintain the skill during training. Another similar study was conducted by Silsupadol et al.[201] to examine the generalizability of the dual-task balance training effect to the novel dual-task balance condition. Although similar results were shown as the previous study, the dual-task balance training effect did not transfer to a novel dual-task condition. Li et al.[202] studied the effect of cognitive dual-task training (no balance) on balance performance on healthy older adults. Four sessions of cognitive dual-task training (visual tasks) were provided to the experimental group. Reaction time improved and body sway parameters decreased compared to controls were noted. The improvement of executive control might lead to improvements of motor control. Hiyamizu et al.[203] used the chair stand test, functional reach test, the Timed Up and Go test and the Trail Making test to evaluate the effect of dual-task balance training. No differences were found in these tests, but the performance of the Stroop task was improved.

A few studies demonstrated that dual-task balance training improves dual-task performance[200, 201, 203] and postural sway.[202] Although a study by Li et al.[202] showed the transfer effect from the cognitive dual-task (no balance) to motor performance, it is still unclear how the improvement of cognitive performance enhance motor performance.

The literature validated the use of vibrotactile feedback to help balance control in older adults and people with vestibular disorders. [30-33, 97, 105, 203] However, sample sizes were small and sensory integration for balance control was rarely considered in the previous studies. Furthermore, balance control in daily life is not a single task condition. Balance control also needs to compromise other attention attractions. Dual-task paradigms help us to understand the relationship between balance control and attention in more complex circumstances. The literature reviews shows that dual-task performance degraded with aging. [36, 120] People with balance deficits require more attention for postural control.[36, 120] The use of vibrotactile feedback also needs attention in order to use the external information.[109] It is still unknown how the brain integratse the sensory information from external resource (vibrotactile feedback) and inner resource (vision, somatosensory, and vestibular system) to help balance control. Moreover, it is also unclear how the use of vibrotactile feedback information affects secondary cognitive task performance during the sensory integration standing balance conditions. Studies are needed to investigate these questions.

3.0 SPECIFIC AIMS

This dissertation will examine how well vibrotactile feedback can be used to enhance balance control when subjects perform sensory organization balance tasks with a secondary auditory choice reaction time task. The aims of this dissertation will be achieved by comparing healthy young and older adults, and people with unilateral vestibular hypofunction via a two-visit repeated-measures design.

3.1 SPECIFIC AIM 1

3.1.1 Rationale

It has been shown that vibrotactile feedback reduces postural sway during sensory integration tasks, such as in sway-referenced floor conditions and sway-referenced vision and floor conditions. It also been shown that the performance on a secondary information processing task is degraded when the sensory integration task becomes more difficult. Furthermore, there appears to be an aging effect on dual-task performance, such that the choice reaction time is slower in older adults compared with young adults. It is not known whether the ability to use vibrotactile feedback is different between older and young adults, in particular, during the performance of a sensory integration task when sensory feedback may be degraded. Furthermore, the influence of a secondary information processing task on the ability to use VTF has not been assessed in younger adults.

3.1.2 Specific Aim

The first aim of this dissertation is to evaluate the effect of vibrotactile feedback (VTF) use during different sensory integration conditions (Condition: Fixed platform (Fixed)/ Eyes open (EO), Fixed/ Eyes open in the dark (EOD), Sway-referenced platform (SR)/ EO, and SR/EOD) and choice reaction time tasks (CRT: none/auditory choice reaction time task) on postural sway and reaction times in healthy young and older subjects.

3.1.3 Research Question & Hypothesis 1

Question 1.1: Is there an aging effect on the postural sway measure, reaction time and the time in the neutral zone?

Hypothesis 1.1: Older adults will have greater postural sway, increased reaction time and less percentage of time in the neutral zone (within the threshold to activate VTF).

Question 1.2: Do the main effects of VTF, Sensory Conditions and CRT affect postural sway, reaction time and the percentage of time in the neutral zone?

Hypothesis 1.2: There will be greater sway, increased reaction time and less percentage of time in the neutral zone with an absence of VTF, during difficult sensory integration conditions or the presence of the CRT task.

Question 1.3: Is there an interaction between aging and CRT tasks on postural sway magnitude?

Hypothesis 1.3: There will be a significant interaction which will be demonstrated by a greater increase in postural sway in older adults compared with young adults when performing the CRT tasks compared with not performing the CRT tasks.

Question 1.4: Is there an interaction between aging and the presence of VTF on postural sway?

Hypothesis 1.4: There will be a significant interaction which will be demonstrated by a greater decrease in postural sway in young adults compared with older adults when the VTF is used.

Question 1.5: Is there an interaction between aging and VTF on reaction time?

Hypothesis 1.5: There will be a significant interaction which will be demonstrated by a greater increase in reaction time in older adults compared with young adults when VTF is used.

Question 1.6: Is there an interaction between aging and visit on reaction time?

Hypothesis 1.6: There will be a significant interaction which will be demonstrated by a greater decrease in reaction time in young adults compared with older adults on the second visit.

3.2 SPECIFIC AIM 2

3.2.1 Rationale

It has been shown that vibrotactile feedback reduces postural sway during sensory integration tasks in persons with vestibular disorders, such as in sway-referenced floor conditions and sway-referenced vision and floor condition. It also been shown that the performance on a secondary information processing task is degraded when the sensory integration task becomes more difficult. Furthermore, there appears to be a disease effect on the dual-task performance, such that the choice reaction time is slower in people with unilateral vestibular disorder compared with healthy adults. It is not known if people with a vestibular disorder have a different ability to use vibrotactile feedback than healthy adults, in particular during the performance of sensory integration task when sensory feedback may be degraded. Furthermore, the influence of a secondary information processing task on this ability has not been assessed in people with unilateral vestibular disorder.

3.2.2 Specific Aim

The second aim of this dissertation is to evaluate the effect of vibrotactile feedback (VTF) use during different sensory integration conditions (Condition: Fixed/EO, Fixed/EOD, SR/EO, and SR/EOD) and choice reaction time tasks (CRT: none/auditory choice reaction time task) on postural sway and reaction times in people with unilateral vestibular hypofunction and age-matched controls.

3.2.3 Research Question & Hypothesis 2

Question 2.1: Is there a disease effect on the postural sway measure, reaction time and the percentage of time in the neutral zone?

Hypothesis 2.1: People with unilateral vestibular hypofunction will have greater postural sway, increased reaction time and less percentage of time in the neutral zone.

Question 2.2: Do the main effects of VTF, Conditions and CRT affect the postural sway, reaction time and the percentage of time in the neutral zone in people with unilateral vestibular hypofunction?

Hypothesis 2.2: There will be greater sway, increased reaction time and less percentage of time in the neutral zone with the absent of VTF or the present of CRT task, or during difficult sensory integration conditions in people with unilateral vestibular hypofunction.

Question 2.3 Is there an interaction between VTF and sensory integration condition in people with unilateral vestibular hypofunction?

Hypothesis 2.3 There will be a significant interaction which will be demonstrated by a greater decrease in postural sway in people with unilateral vestibular hypofunction in the presence of VTF during difficult sensory integration conditions.

Question 1.5: Is there an interaction between disease group and VTF on reaction time?

Hypothesis 1.5: There will be a significant interaction which will be demonstrated by a greater increase in reaction time in people with unilateral vestibular hypofunction compared with age-matched controls when VTF is used.

4.0 METHODS

4.1 STUDY SUBJECTS

4.1.1 Healthy Subjects

All the procedures, including the screening visit and two experimental visits, were performed at the Eye and Ear Institute, UPMC, Pittsburgh. Each visit lasted one and a half hours to accomplish all the testing procedures.

The inclusion criteria for the healthy subjects were: 18-40 or 65-85 years of age who could stand at least 60 minutes with multiple breaks. The exclusion criteria for healthy subjects included any neurological or orthopedic disorders; known pregnancy; knee or hip replacement; failure on the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS),[204] Dynamic Gait Index scores less than 19,[205] Functional Gait Assessment scores less than 22[206] and impaired sensation with monofilament testing (0.07g)[207], hearing or vision testing; and body types too large/small for our equipment (over 250 pounds; under 5 feet; over 6 feet 3 inches; or >35 Body mass index (BMI)).

Forty healthy subjects (twenty young, twenty older) were recruited by word of mouth, advertisement placement and enrolling subjects from previous studies who had given us permission to contact them. The posters and flyers for this study were distributed to potential subjects according to the procedures established in the approved protocol. In response to the advertisement materials, potential subjects were screened by the phone screening script (Appendix A). During the phone interview the subject was informed of the requirements and the purpose of the study and was asked medical questions regarding their general health condition. Once the subject met the initial criteria for participating in this study, an appointment date and time was set to meet with the principal investigator (PI). In the consent process, the potential subject read the informed consent form and more details about the study procedures were given. No screening procedure was performed before the subject signed the consent form.

The first visit was a screening visit in order to ascertain the subject's qualifications by passing the clinical tests and neuropsychological examination. A brief introduction and practice with the vibrotactile feedback and information processing task was included in the first visit. The second and third visits focused on the experimental procedures that required subjects to perform a standing balance sensory integration task concurrently with an information processing task while utilizing vibrotactile feedback.

4.1.2 Subjects with Unilateral Vestibular Hypofunction

Thirty subjects with unilateral vestibular hypofunction were recruited from the Department Of Otolaryngology, University of Pittsburgh Medical Center, Jordan Center for Balance Disorder. Unilateral vestibular hypofunction was confirmed by caloric, rotational, and vestibular evoked myogenic potential testing.

The inclusion criteria for people with unilateral vestibular hypofunction included persons from 18-40 or 65-85 years of age who could stand at least 60 minutes with breaks and had been diagnosed with unilateral vestibular hypofunction by an otologist or neurotologist. The exclusion criteria for people with vestibular hypofunction included individuals who had a combination of an acute vestibular deficit with another condition, such as benign paroxysmal positional vertigo, an orthopedic or neurological disorder, or body types too big/small for our equipment (over 250 pounds; under 5 feet; over 6 feet 3 inches ;or >35 BMI).

A short interview was done in order to obtain informed consent. The purpose of this study and the brief experimental procedure was explained to the potential subject during the short interview. If the subject agreed, a formal consent process was conducted. In the consent process, the potential subject read the informed consent form and more details about the study procedures were given.

The first visit was a screening visit in order to acquire the subject’s basic data. A brief introduction and practice with the vibrotactile feedback and information processing task was included in the first visit. The second and third visit focused on the experimental procedures that require subjects to perform a standing balance sensory integration task concurrently with an information processing task while utilizing vibrotactile feedback.

4.2 INSTRUMENTATION

4.2.1 Posture Platform

A computerized dynamic posturography platform (Equitest; Neurocom, Inc.) measured center of pressure and also provided sway-referencing about the ankle joint by rotation in the sagittal plane. The posturography platform contained the platform base and computer components. The platform base contained a dual forceplate, force transducers, servomotors, force transducer amplifiers, visual surround servo controls, the platform-computer interface and associated power supplies. The dual forceplate consisted of two 23 x 46 cm footplates connected by a pin joint. The two forceplates are supported by four force transducers. A fifth transducer which is used to measure shear force is located beneath the pin joint. The computer contains software to control the test, acquire and store data, and gave servo commands. The sampling frequency of the center of pressure was 100Hz. The saggittal plane platform rotation to accomplish sway-referencing was modeled using the anterior-posterior center of pressure signal. Sway-referencing outputs an angle of rotation that attempts to keep the ankle angle approximately 90 degrees so that the body is aligned perpendicular to the support surface.

4.2.2 Information Processing Task

A custom program (Labview) provided the simple reaction time task and information processing task (auditory choice reaction time). The auditory simple reaction time (SRT) stimulus consisted of a 980Hz tone played at 80 dB for 250ms and randomly repeated every 2 to 6 seconds during a

2 minute period. The auditory choice reaction time (CRT) stimuli consisted of a 560 Hz and 980Hz tone played at 80dB for 250ms and randomly repeated every 2 to 6 seconds during a 2 minute period. The simple reaction time task and choice reaction time task were transmitted through a set of earplugs (**E·A·R**TONE®). One of two hand-held microswitch buttons was pressed by the subject when they heard the high or low pitch tone. The sampling frequency was 1000 Hz.

4.2.3 The Vibrotactile Feedback System

The vibrotactile feedback system that we use in our laboratory was developed by Dr. Sienko the Mechanical and Biomedical Engineering Departments at the University of Michigan. The design concept is the same as the Wall prototype[32, 97], but small changes were made for financial and technological reasons. The three major components of the modified vibrotactile feedback system are the body tilt sensor component, vibrotactor array component and control unit component (computer and program). The vibrotactile feedback system will be described below.

4.2.3.1 Body Tilt Sensor

The modified vibrotactile feedback system uses a sensor (Xsens Technologies B.V., Enschede, The Netherlands; MTx-28A53G25), consisting of a 3-axis linear accelerometer, a gyroscope and a 3-axis magnetometer and is packaged in a 74.008 cm^3 case (W x L x H: 5.8 x 5.8 x 2.2 cm). Power consumption is 350 mW. The total weight is 50 g. The full scale of the 3-axis linear accelerometer is ±50 m/s^2 over a 0-30 Hz bandwidth. The noise of the 3-axis linear accelerometer is 0.009 m/s^2 in the static condition. The full scale of the rate gyro is 1200 degrees/s over a 0-40 Hz bandwidth. The noise of the rate gyro is 0.006 radius/s in the static condition. The full scale of the magnetometer is 5 a.u. over a 0-10 Hz bandwidth. The noise of the magnetometer is 0.001 arbitrary units (a.u.: means normalized to earth field strength). The orientation of the sensor is computed by a Xsens Kalman Filter (XKF) which used the signals from the 3- axis accelerometer, gyroscope and 3-axis magnetometer for 3 degrees-of-freedom orientation (roll, pitch and yaw), called the XKF-3 algorithm. The measured sensor orientation output yields 0.05 degrees angular resolution over a 0-40 Hz bandwidth. Static accuracy is 0.5 degrees in the direction of roll/pitch. The sensor was placed at the level of L4~L5to mimic the movement of COP.

The XKF-3 algorithm uses the acceleration of gravity to stabilize inclination (i.e. roll and pitch combination, known as "attitude") and the Earth magnetic field to stabilize heading (Yaw) in order to compute the orientation of the sensor. The algorithm assumes the average acceleration of an object is zero so that the gravity acceleration can be used to stabilize the attitude. The local (Earth) magnetic field is used to stabilize heading. However, in different applications, the characteristics of the acceleration or magnetic field are different. Several XKF-3 scenarios are used for different applications to avoid incorrect output of the sensor orientation. (Figure 3) The "**Human**" scenario is used in our study because this scenario deals with the slower movements and the magnetic disturbance taken into account for an indoor environment for the calibration of sensor orientation.

Figure 3. Different Xsens Kalman Filter-3 Scenarios for Various Testing Conditions

In order to test the reliability of the inertial sensor (Xsens Technologies B.V.), a typical session of data collection was simulated, consisting of 20 trials, each lasting for 2 minutes. The sensor reliability was tested by attaching the sensor onto a static tripod, in the same orientation as it would be placed on the subject.(Figure 4) Before running the vibrotactile feedback (VTF) program, the sensor was initialized by starting the Xsens MT management software and selecting the extended Kalman filter (XKF) filtering option in the range of human accelerations (XKF-3 4.10 Human) scenario. Before starting to collect the data, a period of thirty minutes was used for equipment warm-up. Data was collected on two different days, one session on each day, twenty trials for the session, and two minutes for each trial (similar to the experimental design). The VTF software outputs measured pitch and roll position, the measured pitch and roll velocity, and the computed pitch and roll control signals that are used to activate the tactors. In this version of the VTF software, the control signal computation utilizes a digital Butterworth lowpass filter (2nd order, cutoff frequency 2 Hz) to reduce the noise in the measured position and velocity signals. The pitch and roll control signals were defined as position + 0.5 * velocity in pitch and roll direction. Ideally, the sensory should read zero for the control signals. Customized code in Matlab (Matlab® V7.12.0.635 R2001a) was used to analyze the data from the output of vibrotactile feedback program. For each of the six signals of interest (i.e. pitch and roll position, pitch and roll velocity, and control signal), the maximum, minimum, range, and root-mean-square (RMS) were calculated. These values were compared to the threshold of activation for the tactors, which is 1.5 degrees in the anterior direction, 0.5 degrees in the posterior direction, and 0.5 degrees in the both right and left lateral directions.

Figure 4. Sensor Reliability Test Setting

A test of reliability for the sensor was done in two different days. The data of pitch and roll signals summarized in Table 1. Generally, the raw pitch and roll position data were below the threshold setting. However, the range of pitch position in day 1 and day 2 were increasing with trial number. Due to the lowpass filtering of the signals, the computed control signals were below the activation threshold during most of the trials, and the average RMS of the control signals was less than 0.14 deg. However, two trials on day 1 and one trial on day 2 had instances of more than the 0.5 degrees threshold of posterior sway (i.e. minimum pitch control signal). One trial on day 1 and one trial on day 2 had instances of more than the 0.5 degrees threshold of left lateral sway (i.e. minimum roll control signal). The time that the tactors would have been activated during these instances is 0.24, 0.07 and 0.15 seconds in the posterior sway direction, and 0.02 and 1.13 seconds (1.13 = 0.12+0.17+0.03+0.24+0.17+0.23+0.17 separately in one trial) in the left lateral sway direction. The cumulative sum of the tactor activations represents approximately 0.03% of the time that data were collected.

Table 1. Sensor Reliability Test: The values of the pitch and roll signals were recorded in two different days

	RANGE OF MAX	NUMBER OF TRIALS ABOVE THRESHOLD (MAX)	RANGE OF MIN	NUMBER OF TRIALS ABOVE THRESHOLD (MIN)	RANGE OF RMS
PITCH POSITION DAY 1	0.034 ~ 0.407		-0.434 ~ -0.113		0.057 ~ 0.126
PITCH POSITION DAY 2	0.031 ~ 0.426		-0.382 ~ -0.016		0.062 ~ 0.108
ROLL POSITION DAY 1	0.123 ~ 0.386		-0.0454 ~ -0.058		0.055 ~ 0.107
ROLL POSITION DAY 2	0.020 ~ 0.383		-0.388 ~ -0.005		0.065 ~ 0.102
PITCH VELOCITY DAY 1	0.931 ~ 1.369		-1.638 ~ -1.191		0.308 ~0.317
PITCH VELOCITY DAY 2	0.926 ~ 1.144		-1.591 ~ -1.245		0.307 ~ 0.315
ROLL VELOCITY DAY 1	1.124 ~ 1.584		-1.637 ~ -1.324		0.357 ~ 0.369
ROLL VELOCITY DAY 2	1.165 ~ 1.563		-1.754 ~ - 1.333		0.356 ~ 0.365
PITCH CONTROL DAY 1	0.077 ~ 0.359	0	-0.574 ~ -0.257	2	0.070 ~ 0.138
PITCH CONTROL DAY 2	0.093 ~ 0.442	0	-0.530 ~ -0.206	1	0.075 ~ 0.118
ROLL CONTROL DAY 1	0.131 ~ 0.439	0	-0.503 ~ -0.104	1	0.075 ~ 0.123
ROLL CONTROL DAY 2	0.048 ~ 0.437	0	-0.612 ~ -0.228	1	0.082 ~ 0.116

Range of Max: the range of maximum values in twenty trials. Range of Min: the range of minimum values in twenty trials. RMS: root-mean-square. Threshold is set as 1.5 degrees in the anterior direction (Max pitch), 0.5 degrees in the posterior direction (Min pitch), and 0.5 degrees in the both right and left lateral directions (Max and Min Roll).

Our results suggest that the tactors in the posterior and left lateral direction might be activated due to sensor noise in a small portion of trials. However, the accuracy and precision of the sensor during dynamic test is not calibrated here. Moreover, considering the duration of time that the signals were over the threshold, it does not affect the results of our study.

4.2.3.2 Vibrotactor Array

The C-2 tactor (Engineering Acoustics, Inc, FL, USA) is used to provide the vibration feedback. The C-2 tactor can provide a strong, point like sensation. It has a primary response in the 200-300 Hz range that corresponds to the peak sensitivity of the Pacinian corpuscle (40-250

Hz).[208, 209] The tactor output is 350mA RMS (max) at 250 Hz. The C-2 tactor is 3cm diameter by 0.8cm in height with total weight of 17 grams. The tactors are arranged in pairs (1 pair anterior, 1 pair posterior, 1 pair left and 1 pair right) in a vertical orientation, two-by-four arrays. A wide elastic fabric belt (Neoprene, Alpha Medical L.L.C.) is used to fix the tactors around the waist. The anterior pair was placed 5 cm above and below the umbilicus. The posterior pair was placed 5 cm above and below the L5 spinal process. The right and left pairs were placed 5 cm above and below the right and left iliac crest.

4.2.3.3 Control Unit (Computer and program)

There are two parts of the control unit. One is the tactor control system (Engineering Acoustics, Inc, FL) (Figure 6) and another part is a custom-made software program. The tactor control system is capable of operating up to eight C-2 tactors. This tactor control system is connected to the computer via USB for communicating with the custom-made program.

Figure 5. The Tactor Control Unit

The custom-made program was coded in Visual C++ 6.0 (Microsoft). The program collects the processed data (sensor orientation) from the sensor and computes the sway position and velocity to determine the direction, location and activation of the C-2 tactors.

The C++ program collects quaternion data (output definition: DATA = (q_0,q_1,q_2,q_3)) from the sensor and converts it to Euler-angles orientation data by using the following equations:

Roll: $\phi_{GS} = \tan^{-1}\left(\dfrac{2q_2q_3 + 2q_0q_1}{2q_0^{\ 2} + 2q_3^{\ 2} - 1}\right)$ radians

Pitch: $\theta_{GS} = \ \sin^{-1}(2q_1q_3 - 2q_0q_2)$ radians

Yaw: $\varphi_{GS} = \tan^{-1}\left(\dfrac{2q_1q_2 + 2q_0q_3}{2q_0^{\ 2} + 2q_1^{\ 2} - 1}\right)$radians

Anterior-posterior trunk sway position and velocity were determined from the pitch values and medial-lateral trunk sway position and velocity were determined from the roll values. A 2nd order Butterworth low-pass filter with a cutoff frequency of 10 Hz was used to filter position and velocity values to eliminate the high frequency noise.[97] The thresholds for activation of the tactors was set to1.5 degrees anterior, 0.5 degrees posterior, 0.5 degrees mediolateral in the bottom row and 3 degrees anterior, 1.5 degrees posterior, 1.5 degrees mediolateral in the top row. Two methods were used to determine the activation of a tactor: anterior-posterior trunk angular position only or trunk angular position plus velocity. In the position only mode, the tactors were activated by the pitch and roll values. For example, if a subject is tilting forward more than 1.5 degrees, the tactor in the bottom front row will vibrate. In the position plus velocity mode, the activation of tactors is produced by the sum of the position value plus 0.5 times the velocity. It means that the bottom row of tactors may vibrate even if the body tilt angle is less than the threshold values (1.5 degrees anterior, 0.5 degrees left, right and posterior). The tactor will stop vibrating after the trunk position and velocity return back below the threshold (dead zone). After the program decides to activate a tactor, a signal will be sent to the tactor controller and the tactor will vibrate to provide the feedback. (Figure 6) The body position + body movement velocity mode was used to activate of a tactor in this study. The tactor only activated one column at a time by using the nearest tactor activation algorithm.

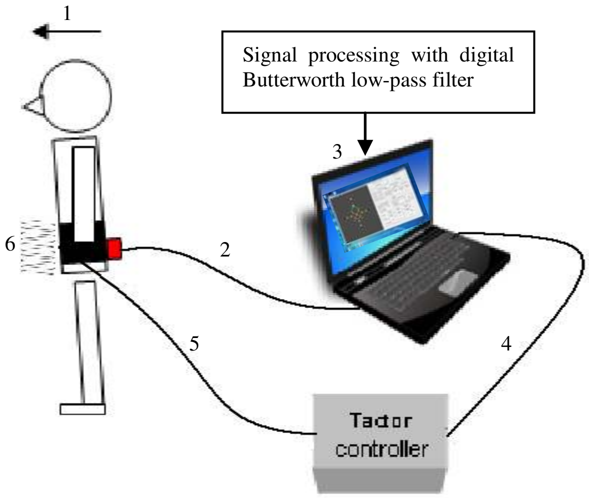


Figure 6. Diagram of the Vibrotactile Feedback System

1. Body tilt forward 2. Signals from sensor transmit to the computer 3. Signal processing by the computer 4. Control signals sending information to then tactor controller 5. Controller sending signals to activate a tactor 6. Tactor vibration

4.3 PROCEDURES

4.3.1 Screening visit

The screening procedures were performed by a physical therapist and a research technician. The screening tests included the RBANS, DGI and FGA, visual acuity, monofilament testing, and an audiogram. The RBANS is a standardized battery of short tasks that examine five neuropsychological domains including language, attention, visuospatial abilities, immediate and delayed memory domains.[204] The DGI and FGA were used to evaluate a subject's dynamic balance. Visual acuity was tested with standard eye charts. Semmes-Weinstein monofilament testing was conducted using a series of small plastic filaments of different diameter applied to the bottom of the foot to assess tactile sensitivity. An audiogram with a standard pure-tone hearing test was used to rule out hearing deficits. After the subject completed all the screening tests, the PI will confirm the subject's eligibility for participating in this study. After the subject's qualification was determined, the purpose of using the vibrotactile feedback device and a short period of practice using the vibrotactile feedback was performed.

During the first visit, the information processing task was practiced. The information processing task consisted of two tests: a simple reaction time (SRT) test and choice reaction time (CRT) test. The simple reaction time test required the subject to respond to a single tone and press the button on his/her dominant hand as quickly as possible. The choice reaction time test required the subject to discriminate between a high (980Hz) or low pitch (560Hz) tone as quickly as possible and press the corresponding button. If the subject heard a high pitch tone, he/she needed to press a button that was held in the dominant hand. If they heard a low pitch tone, he/she needed to press a button being held in the non-dominant hand. Pink noise was played in the background in all the trials. The sound was delivered by insert earplugs. Two trials of each test were performed.

After the practice of the information processing tasks, the vibrotactile feedback tactors and inertial sensor were placed around the subject's waist using a 22cm wide elastic belt (Alpha Medical L.L.C.). The subject was asked to lean his/her body into four directions: forward, backward, leftward and rightward. The subject felt a vibrating sensation on the same side of the lean direction. The subject needed to move to the opposite direction once he/she felt the vibration in order to stop the vibration. The subject was instructed to keep the vibrotactile tactor quiet so that they learned how to use the vibration information to maintain their balance. Five conditions which were combinations of the information processing task, balance task and vibrotactile feedback were practiced at the end of first visit. Each condition was two minutes long. (Appendix A: training protocol flow chart)

4.3.2 Experimental visit (2nd and 3rd visit)

The subject wore a polyester T-shirt (Patagonia®) so that every subject had a consistent garment under the tactors. Baseline reaction times including SRT and CRT were determined in the sitting position. Three trials of each type were performed. The first trial was a practice trial. Pink noise was played in the background in either the second or third trial in SRT and CRT tasks. The tones of SRT or CRT were delivered once every three to five seconds during a two minute period. After completing the baseline measures, the subject stood on a posture platform with the vibrotactile feedback system around his/her waist. The tactor placement was described in section 4.2.3.2. The subject wore a harness for safety and protection. Practice using the vibrotactile feedback occurred like in the first visit practice, but the duration of each condition was reduced to one minute in order to prevent early onset fatigue of the subjects. The subjects performed the CRT task and pressed the corresponding button in response to a high or low pitch tone while he/she performed the balance task in the last practice trial. Experimental trials consisted of different combinations of conditions including vibrotactile feedback (on or off), information processing task (on or off), and the sensory conditions (Fixed platform (Fixed) / Eyes open in the light (EO), Fixed/Eyes open in the dark (EOD), Sway-referenced platform (SR)/EO and SR/EOD). The order of the combinations was randomized for each subject. Testing consisted of a total of sixteen, 2-minute standing trials. The sixteen conditions are shown in Appendix B. The third visit repeated the same testing as the second visit within 1-2 weeks to assess the repeatability of the data. The experimental trials were in different random order for the two study visit.

4.3.3 Data analysis

The dependent variables were postural sway including root-mean square (RMS) trunk tilt and RMS center of pressure, reaction time, the percentage of time in the neutral zone. Postural sway was recorded in the anterior-posterior (AP) and the medial-lateral (ML) directions at a sampling rate of 100Hz. However, we only use AP direction for the analysis because the sway-referencing platform only occurs in AP direction. In order to estimate the magnitude of trunk tilt and COP movement in the AP movement, the RMS was computed from the trunk tilt and COP data in the AP direction as follows:

$$RMS = \sqrt{(1/N)\sum_{i=1}^{N}(COP_i - COP_{avg})^2}$$

Reaction times were calculated from the trials having the information processing task. Eight trials in each visit contained the RTs. Twenty-five to twenty-nine RTs were in each trial. The median of the RTs was calculated when the responses were correct. The first RT response was not included in the calculation because the subject usually responded with increased latency.

The percentage of time in the neutral zone indicated how long that the composite sway variable was inside of the threshold that we set for this study.

In order to investigate within-trial performance, we divided the 120 seconds of data into four periods (Period 1: 1-30 second; Period 2: 31-60 second; Period 3: 61-90 second; Period 4: 91-120 second). The data in different visit (Visit) was also compared. The analyses of aims are performed using repeated measure analysis of variance for all the dependent variables. A significance level of $\alpha = 0.05$ is used throughout the analysis.

4.3.3.1 Statistical analysis (Aim 1)

Aim 1: To evaluate the effect of using vibrotactile feedback during different visit, period and sensory integration conditions (Condition: Fixed/EO, Fixed/EOD, SR/EO and SR/EOD) and information processing tasks (CRT: none/auditory choice reaction time task) in healthy young and older subjects.

A Mixed-model repeated measures ANOVA with Age group as the between-subjects independent variable and VTF, CRT, Condition, Visit and Period as the within-subjects independent variable will be used to test the hypotheses of Aim 1. Normality will be tested using the Shapiro-Wilk test. If the assumption of normality is violated, a logarithm transformation will be used used to normalize the data. The dependent variables are: postural sway measures (RMS COP and RMS trunk tilt), reaction time and the percentage of time in the neutral zone.

In order to test Hypothesis 1.1, The main effect and between-subjects and within-subjects factors on postural sway, reaction time and the percentage of time in the neutral zone.

Hypothesis 1.2: The main effect of aging on postural sway, reaction time and the percentage of time in the neutral zone.

Dependent variable (DV): postural sway, reaction times and the percentage of time in the neutral zone

Between-subject variable: aging group

Hypothesis 1.3: The main effect of VTF, Condition and CRT affect the postural sway, reaction time and the percentage of time in the neutral zone.

Dependent variable (DV): postural sway, reaction times and the percentage of time in the neutral zone

Within-subject variables (IV): VTF, Condition, and CRT

Hypothesis 1.4 The interaction between aging and CRT.

Hypothesis 1.4 The interaction between aging and VTF.

Dependent variable (DV): postural sway, reaction times and the percentage of time in the neutral zone

*Within-subject variable*s: VTF, Condition, and CRT

4.3.3.2 Statistical analysis (Aim 2)

Aim 3: To evaluate the effect of VTF under different sensory integration condition, CRT, Period, and Visit in people with unilateral vestibular hypofunction and age-matched controls.

A Mixed-model repeated measures ANOVA with disease group as between-subject independent variable and VTF, CRT, Period and Visit as the within-subject independent variable was used to test the hypothesis of Aim 2. Normality was test using the Shapiro-Wilk test. If the assumption of normality was violated, logarithm transformation was used to format the data. Dependent variables are: postural sway measures (RMS trunk tilt and RMS COP), reaction time and the percentage of time in the neutral zone.

In order to test Hypothesis 2.1 The main effect and between-subjects and within-subjects factors on postural sway, reaction time and the percentage of time in the neutral zone.

Hypothesis 2.2: The main effect of disease on postural sway, reaction time and the percentage of time in the neutral zone.

Dependent variable (DV): postural sway, reaction times and the percentage of time in the neutral zone

Between-subject variable (IV): disease group

Hypothesis 2.3: The main effect of VTF, Condition and CRT affect the postural sway, reaction time and the percentage of time in the neutral zone.

Dependent variable (DV): postural sway, reaction times and the percentage of time in the neutral zone

Within-subject variables (IV): VTF, Condition, and CRT

Hypothesis 2.4 The interaction between aging and CRT.

Hypothesis 2.4 The interaction between aging and VTF.

Dependent variable (DV): postural sway, reaction times and the percentage of time in the neutral zone

Within-subject variables: VTF, Condition, and CRT

5.0 THE USE OF VIBROTACTILE FEEDBACK DURING DUAL-TASK STANDING BALANCE IN OLDER AND YOUNG ADULTS

5.1 INTRODUCTION

Postural control is a perceptual-motor process involving the collection and processing of sensory information and the execution of appropriate motor responses [210]. Sensory information from the visual, somatosensory and vestibular systems contribute to the maintenance of human postural control [48, 49]. Age-related declines in visual, somatosensory and vestibular function may contribute to an increase in the risk of falling in older adults [6, 56, 75]. Falls in older adults not only impact personal health but also affect the person socially and economically [1, 2].

Various sensory substitution or augmentation devices have been proposed to counter age-related impairments and to decrease the risk of falls in older adults and people with balance deficits [28, 34]. Vibrotactile feedback (VTF) is a type of sensory augmentation that has been developed to help people with balance problems [32]. An inertial measurement unit, which is used to detect body motion, a processor and a haptic display are typically included in a VTF system. Vibration cues are provided as feedback when a person's trunk or head exceeds a pre-defined motion-based threshold. Several studies have validated the effect of VTF applied to the trunk on reducing postural sway in young healthy subjects and people with vestibular deficits [30, 32-34, 41, 42, 97, 99, 211-213].

Dual-task paradigms have been used to study the relationship between attention, postural control and aging effect. Recent studies have suggested that postural control requires attention, and is affected by age-related changes in attention[120, 146]. Older adults demonstrated slower reaction times compared to younger adults on a secondary cognitive task during dual-task conditions, which indicates an increase in attentional demands in older adults versus young adults [120, 134, 140, 146, 149, 150].

The use of VTF requires attention [109]. Haggerty et al. have examined the use of VTF during dual-task conditions in older adults [109]. An auditory choice reaction time task was used as the secondary cognitive task and various foot stances were used as postural tasks. Reaction times increased during use of VTF while performing a secondary task compared with not using VTF, but the VTF was still able to reduce RMS sway [109]. However, how the age-related changes in attention would affect the use of a sensory augmentation device such as VTF was not studied in Haggerty et al.'s study. Moreover, given the interaction between sensory integration and attention, it is not clear how much additional attention is required to process the VTF signal during the sensory integration condition.

An unresolved issue is the duration of time over which VTF is effective at reducing sway. It has been proposed that people with balance problems will wear vibrotactile feedback systems for the purpose of balance training or as a balance aid. However, there are no studies that examine the effect of duration in using VTF. In many of the previous research studies, the duration of using VTF was less than a minute [26, 32, 34, 97, 213]. The short duration of the testing conditions is not representative of how VTF would be used clinically.

The purposes of this study were to investigate: 1) balance performance in a dual-task paradigm under various sensory conditions while using VTF in different age groups, 2) the dual-task performance under different sensory conditions while using VTF in different age groups, and 3) the effect of experience on VTF use. We hypothesized that older adults would have more difficulty using the feedback for the VTF during dual-task conditions than younger adults and that greater experience with VTF would improve postural sway.

5.2 METHODS

5.2.1 Subjects

Twenty healthy young adults (mean age: 24.6, SD 2.4; age range: 19-29 years; 8 males, 12 female) and twenty healthy older adults (mean age: 75.4 SD 6.0; age range: 65-84 years 10 males, 10 female) participated. Each subject completed three study visits including one screening/training visit plus two experimental visits. The average number of days between the two experimental visits for the young group was 6 (SD 3) days and for the older group was 6 (SD 4) days. Subjects were excluded during screening if they had neurologic or orthopedic disorders, or were pregnant. During the screening visit, subjects were excluded if they failed the Repeatable Battery for the Assessment of Neuropsychological Status (RBANS) [204], had Dynamic Gait Index scores less than 19 [205] or Functional Gait Assessment scores that were less than 22 [206]. In addition, those who had impaired sensation with the Semmes-Weinstein monofilament test (0.07g) [207], had abnormal age corrected audiometric function, or had binocular visual acuity with corrective lenses worse than 20/40 were excluded. The Institutional Review Board at the University of Pittsburgh approved the protocol.

5.2.2 Instrumentation

The VTF system consisted of a belt, an inertial measurement unit (IMU, Xsense Technologies B.V., Enschede, The Netherlands), eight vibrating tactors (C-2, Engineering Acoustics Inc., Casselberry, FL, USA), and a laptop computer. The belt was wrapped around the subject's waist and two tactors were placed within the belt vertically separated by 5 cm in each of the following locations: midline front, midline back, right and left side of the body. The IMU was attached to the posterior of the belt at the level of the fourth lumbar vertebra. The IMU detected and recorded the subject's sway position (angular deviation from vertical) and sway velocity (angular velocity) in the anterior-posterior (AP) and medial-lateral (ML) directions. Vibrotactile feedback was provided when the feedback control signal, equal to the sway position value plus 0.5 times the sway velocity [107] exceeded the following thresholds. The threshold of the lower row tactors was set to 1.5 anteriorly, 0.5 posteriorly, and 0.5 to the right and left. The threshold of the upper row tactors was set to 3 anteriorly, 1.5 posteriorly and 1.5 to right and left. The limits of stability are larger in the anterior direction compared to the posterior direction so a larger threshold for anterior postural sway was set [97]. "The nearest neighbor" principle was used in the feedback algorithm which activated only one tactor at a time by determining which direction had the greatest control signal value [97]. Tactor vibrations were at 250 Hz. The subject was instructed to stay in the neutral zone (area below threshold for vibration) as much as possible. Subjects were barefoot and wore a thin standard shirt so that the tactors could be sensed easily.

A computerized dynamic posturography platform (EquiTest^{TM}; Neurocom, Inc.) was used to record the center of pressure (COP). The EquiTest also provided sway-referencing in the sagittal plane about the ankle joints by estimating the body pitch from the AP COP.

A secondary attention task was delivered by a customized program (Labview, National Instruments) providing an auditory choice reaction time task (CRT). The auditory CRT stimuli consisted of 560 Hz and 980 Hz tones transmitted through a set of earphones (**E·A·R**TONE®). The tones were played at 80 dB for 250 millisecond (ms) and repeated every 2 to 6 seconds during a 2 minute period. Using one microswitch button in each hand, the subject pressed the button in the dominant hand for a high pitch tone and the non-dominant hand for a low pitch tone. Twenty-five to twenty-nine stimuli were presented in each trial. The onset of the switch activation relative to the stimulus was recorded with a temporal resolution of 1 ms.

5.2.3 Experimental procedure

The first visit was used for screening and training the subject. The subject was briefly trained to perform the CRT tasks, and how to use the VTF. The VTF training conditions included standing on a fixed platform with eyes open in light (Fixed/EO), standing on a fixed platform with eyes open in dark (Fixed/EOD), standing on a sway-referenced platform with eyes open with light (SR/EO), standing on a sway-referenced platform with eyes open in dark (SR/EOD), and standing on a sway-referenced platform with EO while performing the CRT tasks. The subjects were instructed to stand comfortably, to move away from vibration and to stay in the neutral zone as much as they could. Darkened goggles were used during the EOD condition to minimize visual reference cues. Each training condition lasted for 120 seconds. During the experimental visits 1 and 2, a short training trial was held before the experimental test. The one-minute training trials included one trial of the CRT task and five different sensory balance conditions. Then, a total of sixteen two-minute experimental tests were performed, including all combinations of VTF on/off, CRT task on/off, and the sensory conditions (Fixed/EO, Fixed/EOD, SR/EO and SR/EOD). The subjects performed the experimental conditions in random order during both of the two experimental visits.

5.2.4 Outcome measures

The trunk tilt was recorded by the IMU in the AP and ML direction. The COP was also recorded by the forceplate in the AP and ML directions. In order to investigate within-trial performance, we divided the 120 seconds of data into four periods (Period 1: 1-30 second; Period 2: 31-60 second; Period 3: 61-90 second; Period 4: 91-120 second) [214, 215]. The root-mean square (RMS) of trunk tilt and RMS COP were computed from the IMU data and forceplate data after subtracting the mean value, via a custom Matlab (The MathWorks, Natick, MA) program. However, because the sway-referenced platform only moved in the AP direction, ML trunk tilt and COP were not included in the data analysis. The IMU data was only recorded during the trials with VTF so that the trunk tilt was only recorded in eight out of sixteen trials. The COP was recorded during all sixteen trials.

The percentage of time in the neutral zone was calculated from the IMU data. The 120 second-trial was divided into four periods. The percentage of time in the neutral zone was calculated from the IMU data so that it was calculated only during trails when VTF was used.

Median reaction times (RTs) were calculated for each of the eight trials with the CRT task. The first RT response was not included in the median calculation because the subjects usually responded with an increased latency. The median of the RTs was used to assess the influence of VTF, sensory condition and between-visit factors on attention in the young and older groups.

5.2.5 Statistical Analysis

A repeated measures analysis of variance (ANOVA) was conducted to investigate the aims. A secondary analysis showed that while there was an interaction between platform condition and vision conditions on the RMS COP, this effect did not appear in any other higher order interactions with any of the other factors. Consequently, we used a simpler model using sensory condition (Condition) with four levels (fixed/SR platform x EO/EOD) instead of using the platform and vision factors. The effect of Age, Period, Visit, CRT and Condition were tested with the RMS trunk tilt data and the percentage of time in the neutral zone. The Age, Period, visit, VTF, CRT and Condition were tested with the RMS COP. The postural sway data (RMS trunk tilt and RMS COP) were logarithmically transformed to meet the assumption of normality of a repeated measures ANOVA. A Bonferroni correction was applied if post-hoc analysis was needed for the Condition and Period variables. The highest order interactions considered were three-way interactions. Similarly, we investigated the effect of Age, Visit, VTF and Condition on the median reaction time (RT). All statistical analyses were performed using IBM® SPSS® Statistics, Release Version 19 (IBM, Armonk, NY). A significance level of $\alpha = 0.05$ was used.

5.3 RESULTS

5.3.1 Postural Sway

The repeated measures ANOVA revealed numerous significant main effects and interactions on RMS COP (Table 2) and RMS trunk tilt (Table 3). Significant main effects included Age, Condition, Period and Visit on RMS COP and RMS trunk tilt. Our baseline showed that older adults had approximately 34% greater RMS COP than younger adults while VTF was off ($p \leq 0.001$), and 38% greater RMS COP than younger adults while CRT was off ($p \leq 0.001$). Over all conditions, older adults had approximately 33% greater RMS COP and 58% greater RMS trunk tilt than younger adults ($p \leq 0.001$). The sensory condition had a dramatic effect on the magnitude of RMS COP and RMS trunk tilt, increasing by more than a factor of three from the Fixed/EO condition to the SR/EOD condition. A significant Period effect was observed, which was due to greater RMS COP in the initial 30 seconds compared to the final 90 seconds and greater RMS trunk tilt in the last 30 seconds compared to the middle 60 seconds. There was a modest, but significant Visit effect, with reduced RMS COP and RMS trunk tilt during experimental visit 2 compared with experimental visit 1. There was not a significant main effect of VTF on RMS COP, due to interactions between VTF and other factors (as described below). The effect of the secondary CRT task on postural sway measures was minor overall, as there was not a significant main effect. Furthermore, CRT did not appear in any higher order interactions.

Significant higher order interactions were found in RMS COP data. The interactions could be divided into three groupings based on the three-way interactions (Table 2). The first grouping involved the effects of VTF, Age, and Condition. As mentioned previously, we did not find a significant main effect of VTF; however, this unexpected finding can be explained by the three-way interaction of VTF*Condition*Age (Figure 7). Specifically, during the fixed platform conditions (7a and 7b), VTF elicited greater RMS COP only in older adults ($p < 0.001$), while there was no change in RMS COP due to VTF in younger adults ($p > 0.13$). In contrast, during the SR platform conditions (7c and 7d), application of VTF reduced RMS COP in both older and younger adults ($p < 0.022$). Thus the increase in RMS COP in older adults during VTF on the fixed platform trials counteracted the reduction in RMS COP during VTF on the sway-referenced trials, so that overall, the average effect of VTF was not significant. The plots of the three-way interaction also help to demonstrate the significant two-way interactions between VTF*Condition and VTF*Age.

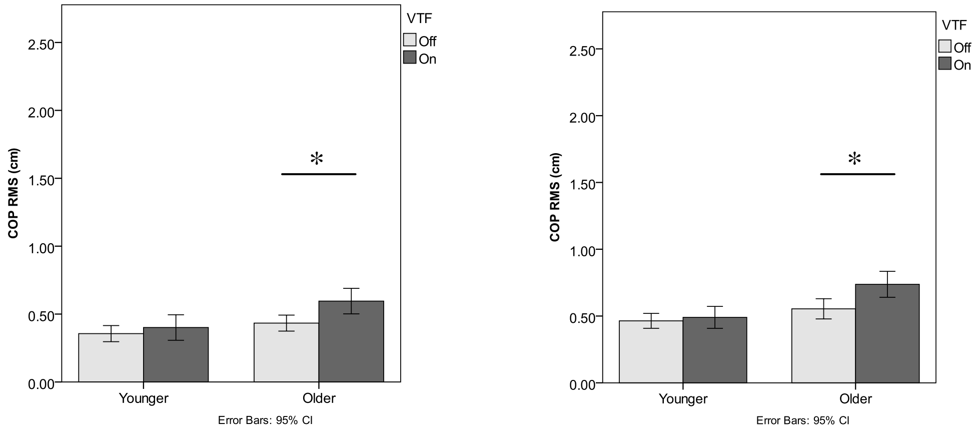
Table 2. Effects of age, sensory condition, vibrotactile feedback (VTF), performance of auditory choice reaction time (CRT) tasks, period and visit on the root-mean-square of the anterior-posterior center of pressure (RMS COP)

Main Effects	RMS COP (mean ± SD)	F and P values	Interaction(s)	F and P values
Age	Younger: 0.76 ± 0.20 Older: 1.05 ± 0.24	$F_{1, 38} = 19.6$, $p < 0.001$	VTF*Age*Condition VTF*Age VTF*Condition	$F_{2.1, 80.0} = 7.5$, $p < 0.001$ $F_{1, 38} = 5.5$, $p = 0.02$ $F_{2.1, 80.0} = 60.6$, $p < 0.001$
Condition[a]	Fixed/EO: 0.45 ± 0.16 Fixed/EOD: 0.56 ± 0.18 SR/EO: 1.03 ± 0.42 SR/EOD: 1.57 ± 0.39	$F_{1.9, 71.2} = 564.1$, $p < 0.001$		
VTF	Off: 0.93 ± 0.27 On: 0.87 ± 0.27	$F_{1, 38} = 0.4$, $p = 0.55$	Period*VTF*Condition Period*VTF Period*Condition	$F_{9, 342} = 2.2$, $p = 0.02$ $F_{3, 114} = 11.6$, $p < 0.001$ $F_{6.3, 240.0} = 4.4$, $p < 0.001$
CRT	Off: 0.92 ± 0.27 On: 0.89 ± 0.25	$F_{1, 38} = 3.8$, $p = 0.058$		
Period[b]	1: 0.98 ± 0.28 2: 0.86 ± 0.25 3: 0.86 ± 0.26 4: 0.89 ± 0.27	$F_{2.3, 88.2} = 26.2$, $p < 0.001$	VTF*Age*Visit VTF*Age VTF*Visit	$F_{1, 38} = 6.1$, $p = 0.018$ $F_{1, 38} = 5.5$, $p = 0.02$ $F_{1, 38} = 14.1$, $p = 0.001$
Visit	1st : 0.92 ± 0.25 2nd: 0.88 ± 0.28	$F_{1, 38} = 8.8$, $p = 0.005$		

- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- [a]Post-hoc test for Condition: all conditions were significantly different, $p < 0.001$
- [b]Post-hoc test for Period: Period 1 significantly greater than Periods 2, 3 and 4, $p < 0.001$

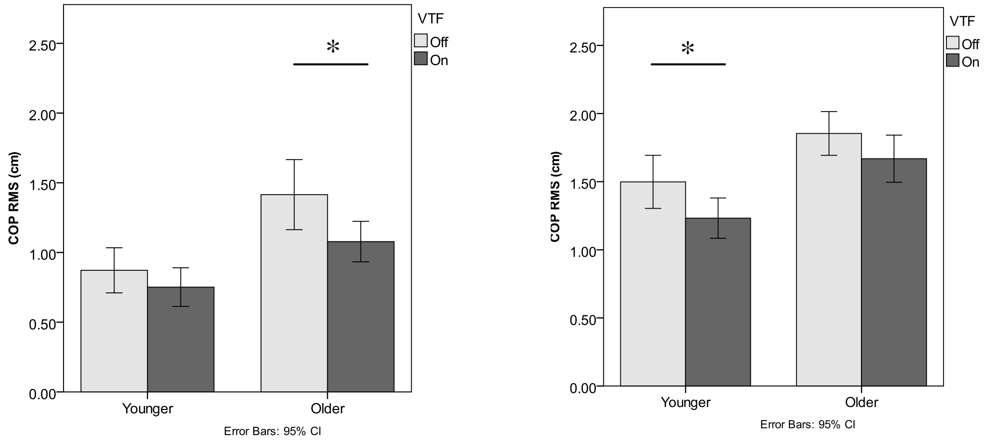
a. Fixed/EO

b. Fixed/EOD



c. SR/EO

d. SR/EOD



- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- VTF: Vibrotactile feedback.
- *: $p < 0.05$.

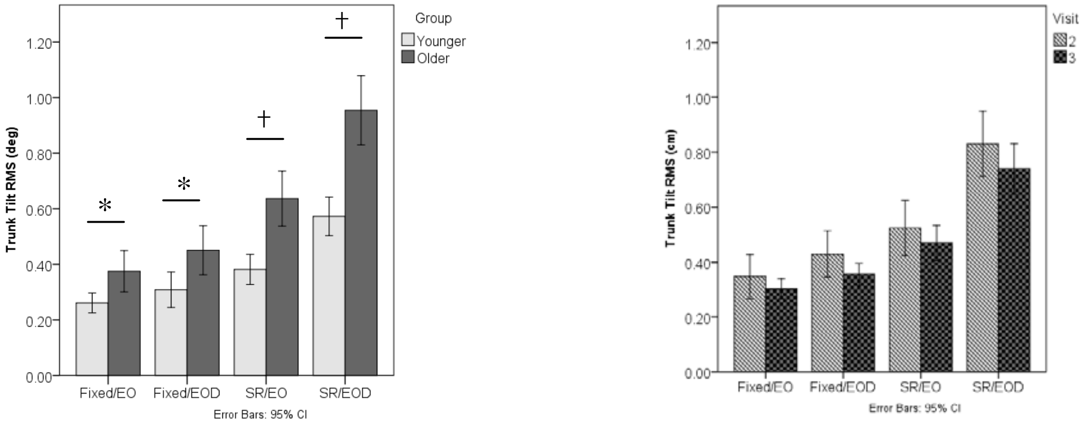
Figure 7. Effect of VTF*Age*Condition interaction on the root-mean-square of the anterior-posterior center of pressure (RMS COP)

Significant interactions between the factors were found for the RMS trunk tilt when VTF was used (Table 3). The Age*Condition (*p* = 0.028) interaction demonstrated that older adults had a greater increase in RMS trunk tilt compared with younger adults as the sensory conditions changed amongst the Fixed/EO, Fixed/EOD, SR/EO to the SR/EOD conditions (Figure 8a). Although the Condition*Visit interaction (*p* = 0.049) was found, the post-hoc analysis did not reveal any statistical difference between different visit among all conditions. The Condition*Period interaction (*p* = 0.021) illustrated that in the Fixed/EOD condition, there was a decrease in RMS trunk tilt in Period 3, then an increase in Period 4. In the SR/EO condition, Period 4 had the largest RMS trunk tilt. In the SR/EOD condition, there was a decrease in RMS trunk tilt from Period 1 to Period 2, then an increase from Period 2 to 4 (Figure 8c).

Table 3. Effects of age, sensory condition, performance of auditory choice reaction time (CRT) task, period and visit on the root-mean-square of the anterior-posterior trunk tilt (RMS trunk tilt)

Main Effects	RMS trunk tilt (deg) (mean ± SD)	F and P values	Interaction(s)	F and P values
Age	Younger: 0.38 ± 0.10 Older: 0.60 ± 0.18	$F_{1,38} = 14.5$, $p < 0.001$	Condition*Age Condition*Visit Condition*Period	$F_{2.4,85.2} = 3.5$, $p = 0.028$ $F_{3,108} = 2.7$, $p = 0.049$ $F_{5.9,213.0} = 2.6$, $p = 0.021$
Condition[a,b]	Fixed/EO: 0.32 ± 0.14 Fixed/EOD: 0.37 ± 0.17 SR/EO: 0.51 ± 0.21 SR/EOD: 0.76 ±0.28	$F_{2.4,85.2} = 284.2$, $p < 0.001$		
CRT	Off: 0.49 ±0.20 On: 0.49 ± 0.18	$F_{1,36} = 0.2$, $p = 0.68$		
Period	1: 0.50 ± 0.20 2: 0.48 ± 0.19 3: 0.48 ± 0.20 4: 0.53 ± 0.20	$F_{2.1,75.1} = 8.3$, $p < 0.001$		
Visit	1st : 0.53 ±0.24 2nd : 0.45 ± 0.14	$F_{1,36} = 10.6$, $p = 0.002$		

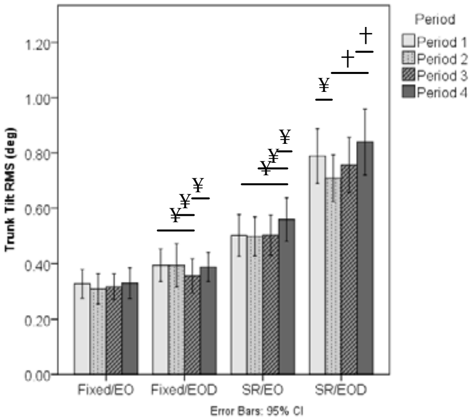
- [a] Post-hoc test for Condition: all conditions were significantly different, $p < 0.001$.
- [b] Post-hoc test for Period: Period 4 significantly greater than Periods 2 and 3, $p < 0.001$.



a. **Age*Condition interaction**

b. Condition*Visit interaction

c. Condition*Period interaction

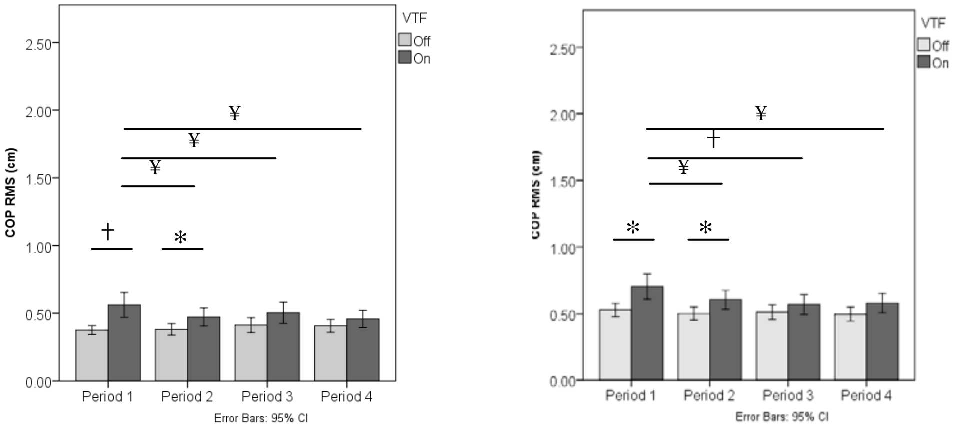


- *:$p < 0.05$; $^{¥}$ $p < 0.017$; † $p < 0.001$.

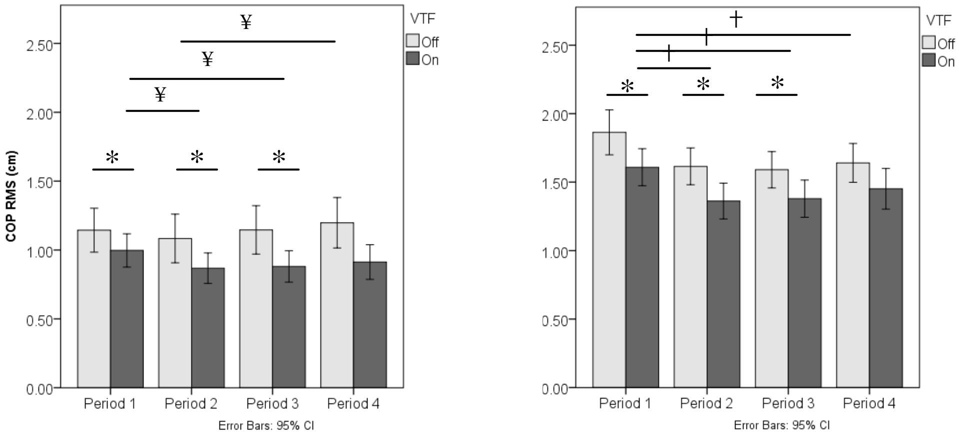
Figure 8. Age*Condition, Condition*Visit and Condition*Period interaction on the root-mean-square of the anterior-posterior trunk tilt (RMS trunk tilt) when VTF was applied

The second interaction grouping consisted of the factors Period, VTF, and Condition (Figure 9). The three-way interaction illustrates that during the Fixed/EO condition (9a), RMS COP was relatively level across all four periods when there was no VTF. On the other hand when VTF was available, RMS COP was increased in period 1 compared with periods 2, 3 and 4 ($p < 0.007$). During the SR/EO condition (9c), the RMS COP was relatively stable across all periods, both with and without VTF. Lastly, during the SR/EOD condition, there was a reduction in RMS COP in periods 2, 3, and 4 compared with period 1 when VTF was on or off ($p < 0.001$).

The final interaction grouping contained the VTF, Age and Visit factors (Figure 10). Whereas the reduction in RMS COP with VTF on was consistent across visits in younger adults ($p = 0.46$), older adults had no improvement in RMS COP with VTF on visit 1, but a significant improvement in sway with VTF on visit 2 ($p = 0.003$).


a. Fixed/EO

b. Fixed/EOD

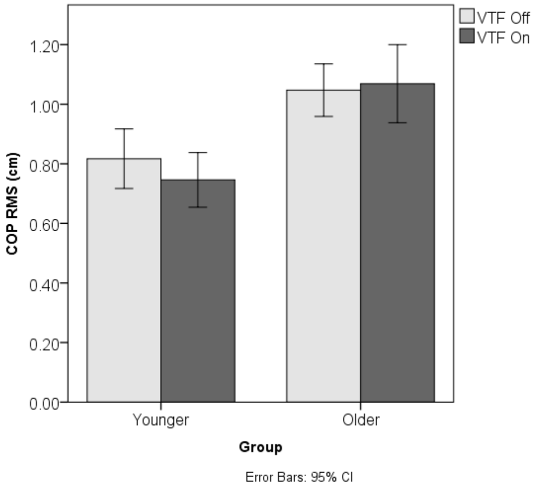

c. SR/EO

d. SR/EOD

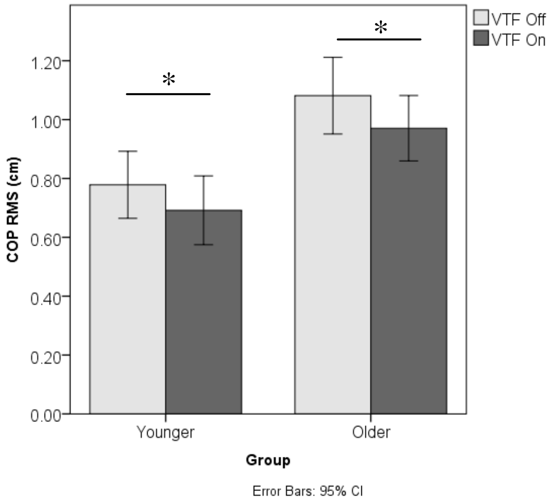
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- VTF: Vibrotactile feedback.
- Period 1: 1-30 s; Period 2: 31-60 s; Period 3: 61-90 s; Period 4: 91-120 s
- $^{+} p < 0.001$; $^{*} p < 0.05$; $^{¥} p < 0.017$

Figure 9. Effect of Period*VTF*Condition interaction on the root-mean-square of the anterior-posterior center of pressure (RMS COP)

a. Experimental Visit 1



b. Experimental Visit 2



- VTF: Vibrotactile feedback.
- * $p < 0.05$

Figure 10. Effect of VTF*Age*Visit interaction on the root-mean-square of the anterior-posterior center of pressure (RMS COP)

5.3.2 Percentage time in the neutral zone

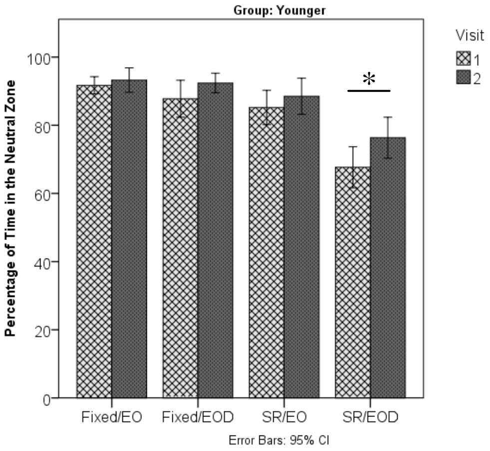
The effect of Age, CRT, Period, Condition and Visit with RMS trunk tilt was examined. The repeated measures ANOVA of the percentage time in the neutral zone showed significant main effects of Age, Condition, Period and Visit (Table 4). Younger adults demonstrated higher percentage of time in the neutral zone compared to older adults. The sensory condition had a significant effect on the percentage of time in the neutral zone, decreasing the percentage of time in the neutral zone from the Fixed/EO, Fixed/EOD, SR/EO to the SR/EOD conditions. In Period 1, subjects had greater percentage of time in the neutral zone compared to periods 2, 3 and 4. During the second visit, subjects had a greater percentage of time in the neutral zone compared with first visit. There was no significant main effect or interactions for CRT. Interactions were found in the percentage of time in the neutral zone data. The significant interactions were divided into two groupings. The first grouping involved Condition, Age and Visit. In the experimental visit 1, there was a significant reduction in the percentage of time in the neutral zone form the beginning of the trial to the end during the Fixed/EOD and SR/EO conditions. On the other hand, there was no significant change in the percentage of time in the neutral zone across period 1 to 4 (Figure 11). The Condition*Age interactions illustrated that the older adults had less time in the neutral zone as the sensory conditions were from the Fixed/EO, Fixed/EOD, SR/EO to the SR/EOD conditions compared with younger adults. The Period*Condition*Visit interactions demonstrated that Period 1 had the larger percentage of time in the neutral zone among all conditions during experimental visit 1, but Period 4 had the larger percentage of time in the neutral zone in the Fixed/EO condition during experimental visit 2 (Figure 12). The Period*Age interaction showed that the older adults had reduced the percentage of time in the neutral zone from period 1 to 4 compared with no change in percentage of time in the neutral zone across periods in younger adults.

Table 4. Effects of age, sensory condition, performance of auditory choice reaction time (CRT) task, period and visit on the percentage of time in the neutral zone

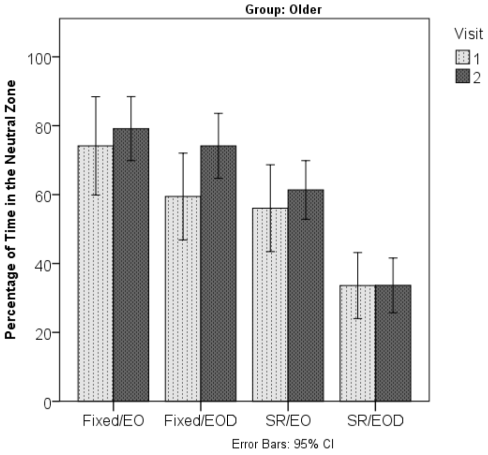
Main Effects	Percentage of Time in the neutral Zone (%) (mean ± SD)	F and P values	Interaction(s)	F and P values
Age	Younger: 85 ± 8 Older: 59 ± 18	$F_{1,36} = 21.3$, $p < 0.001$	Condition*Age*Visit Condition*Age	$F_{3,108} = 3.9$, $p = 0.015$ $F_{3,108} = 12.7$, $p < 0.001$
Condition[a,b]	Fixed/EO: 84 ± 19 Fixed/EOD: 78 ± 20 SR/EO: 73 ± 21 SR/EOD: 52 ± 24	$F_{3,108} = 106.3$, $p < 0.001$	Period*Condition*Visit Period*Visit	$F_{6.1,218.3} = 2.2$, $p = 0.046$ $F_{2.2,77.5} = 3.1$, $p = 0.049$
CRT	Off: 73 ± 20 On: 70 ± 20	$F_{1,36} = 2.1$, $p = 0.15$	Period*Age	$F_{1.8,63.5} = 4.0$, $p = 0.028$
Period[b]	1: 74 ± 17 2: 71 ± 20 3: 71 ± 21 4: 70 ± 21	$F_{1.8, 63.5} = 7.7$, $p = 0.002$		
Visit	1st : 69 ± 23 2nd : 75 ± 18	$F_{1,36} = 8.3$, $p = 0.007$		

- [a]Post-hoc test for Condition: all conditions were significantly different, $p \leq 0.006$.
- [b]Post-hoc test for Period: Period 1 significantly greater than Periods 2, 3 and 4, $p < 0.05$.

a. Younger group



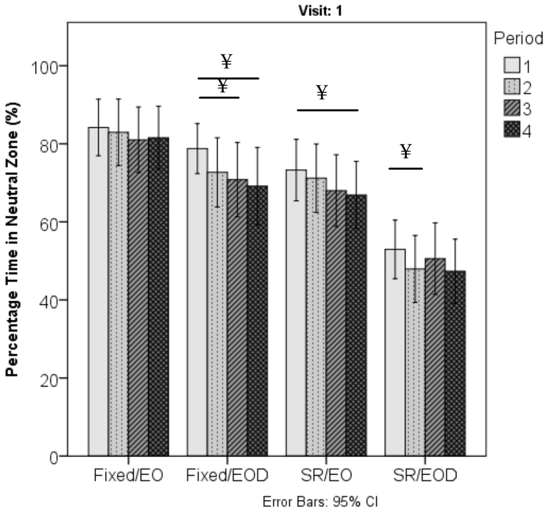
b. Older group



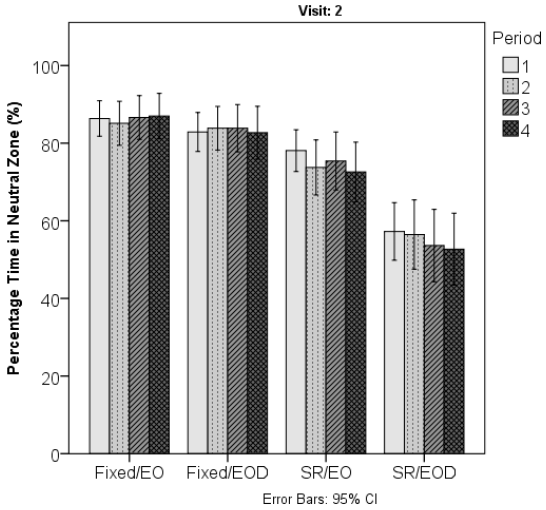
- $^{+}p < 0.001$; * $p < 0.05$.
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- Younger group showed increase percentage time in the neutral zone on SR/EOD condition.

Figure 11. Condition*Age*Visit interaction on the percentage of time in the neutral zone

a. Experimental Visit 1



b. Experimental Visit 2



- ¥ $p < 0.017$
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).

Figure 12. Period*Condition*Visit interaction on the percentage of time in the neutral zone

5.3.3 Reaction Time

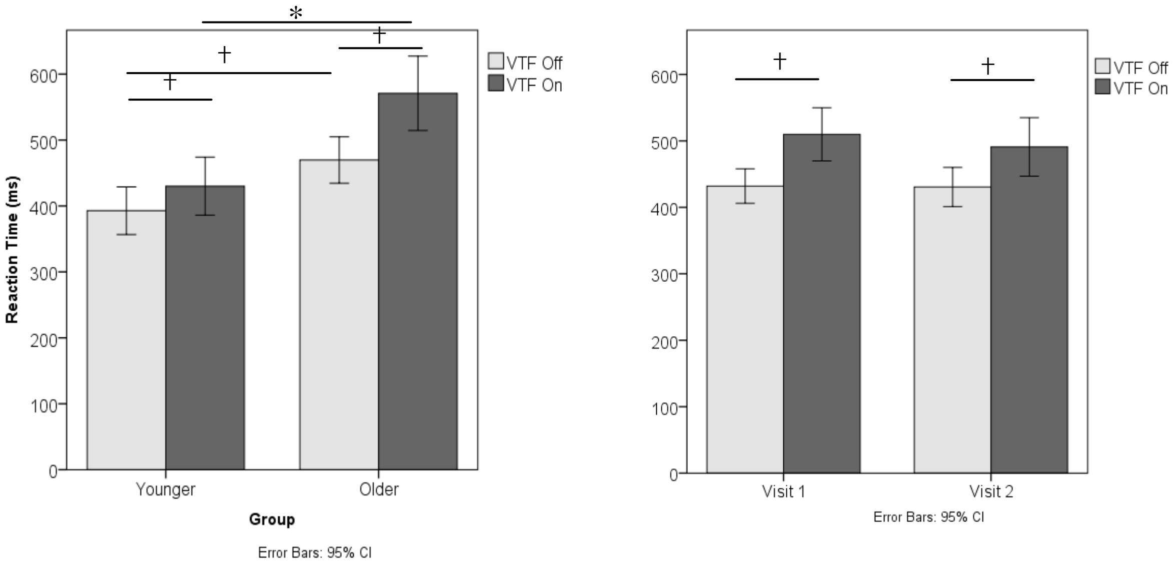
In order to explore how the different factors influenced the attention demands of the postural task, a secondary auditory choice reaction time task was performed. A repeated measures ANOVA of the median reaction time (RT) from each trial demonstrated significant main effects of Age, Condition, and VTF (Table 5). The RTs of older adults were slower than younger adults by 109 ms. RTs increased as the challenge of the sensory condition increased. In particular, the SR/EOD condition produced RTs significantly greater than all the other conditions, and the SR/EO condition resulted in greater RTs compared with the Fixed/EO condition. When VTF was used, the RTs increased about 69 ms compared with when VTF was not used.

In addition, there were three significant two-way interactions, as shown in Figure 13. The VTF*Age interaction (13a) demonstrated that the increase in RTs due to VTF was greater in older adults compared with younger adults (101 ms v. 37 ms, $p < 0.001$). The VTF*Visit interaction (13b) showed that the increase in RTs due to use of VTF was greater in the first versus the second visit (78 ms v. 60 ms, $p = 0.01$). Finally, the Age*Visit interaction (13c) indicated that younger adults had faster RTs on second experimental visit while the RTs of the older group was essentially the same on both experimental visits (-26 ms v. +6 ms, $p = 0.018$).

Table 5. Effects of age, sensory condition, vibrotactile feedback (VTF), and visit on the median reaction time during performance of an auditory choice reaction time task

Main Effects	Reaction Time (ms) (mean ± SD)	F and P values	Interaction(s)	F and P values
Age	Younger: 411 ± 84 Older: 520 ± 96	$F_{1,38} = 14.5$, $p < 0.001$	VTF*Age VTF*Visit Age*Visit	$F_{1,38} = 17.1$, $p < 0.001$ $F_{1,38} = 7.1$, $p = 0.009$ $F_{1,38} = 6.1$, $p = 0.018$
Condition[a,b]	Fixed/EO: 447 ± 104 Fixed/EOD: 454 ± 106 SR/EO: 465 ± 104 SR/EOD: 497 ± 114	$F_{3,114} = 29.1$, $p < 0.001$		
VTF	Off: 431 ± 85 On: 500 ± 128	$F_{1,38} = 80.2$, $p < 0.001$		
Visit	1st : 471 ± 101 2nd : 461 ± 113	$F_{1,38} = 2.4$, $p = 0.13$		

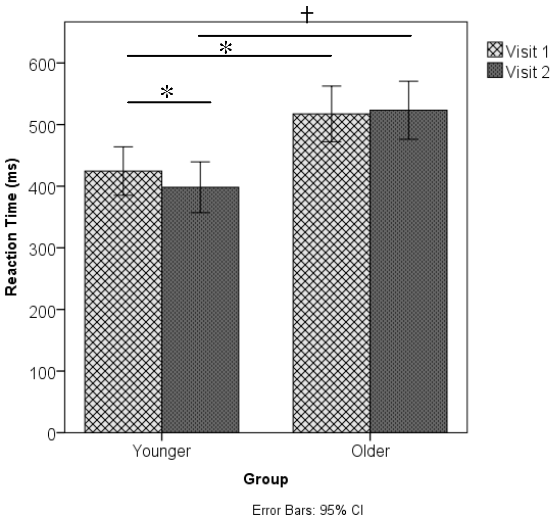
- Platform conditions: Fixed platform (Fixed) and Sway-referenced platform (SR).
- Light conditions: Eyes open (EO) and Eyes open in the dark (EOD).
- [a]Post-hoc test for Condition: SR/EOD significantly greater than Fixed/EO, Fixed/EOD and SR/EO, $p < 0.001$.
- [b]Post-hoc test for Condition: SR/EO significantly greater than Fixed/EO, $p = 0.006$.



a. VTF*Age interaction

b. VTF*Visit interaction

c. Age*Visit interaction



- VTF: Vibrotactile feedback.
- $^{\dagger} p < 0.001$; * $p < 0.05$

Figure 13. Effect of a. VTF*Age interaction, b. VTF*Visit interaction and c. Age*Visit interaction on median reaction time

5.4 DISCUSSION

The purpose of the study was to examine the effect of using VTF on postural sway and reaction times during dual-task standing balance. The results of the postural sway data demonstrated that younger and older adults utilized VTF differently. Vibrotactile feedback resulted in elevated sway in older adults during fixed platform conditions, but helped to reduce sway in both older and younger adults in sway-referenced platform conditions. Also, older adults required more experience to take advantage of the VTF for reducing sway. It was found that greater than 30 s was needed to reach a steady state in postural sway when VTF was being integrated with other sensory information. Reaction times were higher while VTF was on suggesting that additional attentional resources are used to process VTF information.

Our findings extend the research of Haggerty et al., who also studied the use of VTF during dual-task conditions [109] by comparing two different age groups. In their study, community-dwelling older adults stood upright using different bases of support with eyes open or closed to compare the effect of VTF while performing an auditory CRT. Moreover, in Haggerty's study, the subjects performed 30-second trials within one visit. However, in our study, we compared the performance in both younger and older adults while using VTF during a dual-task condition. Furthermore, a longer trial and a second visit were provided to investigate the effect of time while using VTF. Sensory conditions (Fixed or SR platform) were also taken into consideration in order to realize how the VTF information integrated with inner body sensory information.

Vibrotactile feedback has been shown to reduce RMS trunk tilt [26, 30, 34, 97, 213], COP displacement RMS [32, 34] and increase the percentage of time in the neutral zone [97]. Our data did not compare the RMS trunk tilt and the percentage of time in the neutral zone with and without VTF, but we used the RMS trunk tilt and the percentage of time in the neutral zone to corroborate the result of the RMS COP.

Our data demonstrated that younger and older subjects responded differently to VTF under various sensory integration tasks in RMS COP. When the platform was fixed, VTF increased RMS COP in older adults. However, when the platform was sway-referenced, VTF decreased RMS COP similarly in both younger and older adults. One possible explanation for the increased sway in older adults during fixed platform conditions is that they overcorrected in the opposite direction when they perceived the VTF. Furthermore, it is possible that with additional training, the increased sway effect at the beginning may disappear, given the finding of a reduction of sway in the second visit compared with the first visit. Our results of a reduction in sway on the SR platform are consistent with several previous studies [30, 32, 34, 42, 97].

Younger subjects showed greater percentage of time in the neutral zone than older adult while using VTF. This finding suggests that younger people have better ability to maintain their trunk stability within the pre-defined motion-based threshold while using VTF. Postural control studies have demonstrated that younger people have better ability to control body stability than older adults [216, 217]. The ability to spend more time in the neutral zone may also indicate that ageing influences the ability to use VTF.

Generally speaking, our results demonstrated that the CRT task was not an essential factor that affected the postural sway. This result corresponds to the study by Redfern et al. [146], which found that postural sway was unchanged by the presence of the reaction time task, although RT performance was affected. In our experiment, the “posture first” principle may explain the negligible effect of the secondary cognitive task on sway [218, 219].

The secondary cognitive task resulted in longer RTs in older adults compared with younger adults, consistent with previous studies [120, 146, 218]. Furthermore, the use of VTF required additional attention during the sensory integration conditions, confirming the results of Haggerty et al [109]. However, our data also suggested that the attention requirement in utilizing VTF was greater in older adults than younger adults. Specifically, RTs increased by 101 ms in older adults and 37 ms in younger adults when VTF was present. The increase in reaction time is significant and suggests that more attentional resources are needed [220]. The increase in attention needed to use VTF indicates that some older adults who have executive dysfunction may not be good candidates for using VTF.

The effect of sensory conflict on the ability of VTF to reduce sway is unclear. Several studies have applied VTF during the sensory organization test (SOT) condition 5 (Eyes closed / Sway-referenced (SR) platform) and condition 6 (SR visual surround/ SR platform) [26, 30, 34]. The results showed that VTF improved balance performance in both SOT conditions 5 and 6. Moreover, Kentala et al. reported that the benefit from VTF was greater in SOT condition 5 than condition 6 and they suggested that visual conflict might interfere with the use of VTF information [34]. To complement these studies, we investigated the use of VTF in the light and dark, and also on a fixed and SR platform in order to examine the effect of sensory integration. However, the visual conflict condition was not studied in our study design.

Our results showed that the length of time also affects postural sway while using VTF. The Period*VTF interaction was found in the Fixed/EO, Fixed/EOD and Fixed/SR conditions. The data demonstrated that the RMS COP decreased after Period 1(30 seconds) when VTF was used. The decrease in RMS COP in Period 2 and after suggests that dynamic reweighting of the sensory feedback occurred. With additional experience using VTF, sway was reduced in experimental Visit 2 compared with Visit 1. The decrease in the postural sway during Period 2 suggests that with additional training, the optimal beneficial effect of using VTF might be achieved.

5.5 CONCLUSION

Our data suggest that younger and older adults use VTF differently, depending on the underlying sensory integration balance task. Although the use of VTF required more attention, older adults were able to use VTF to reduce sway in SR platform conditions. The length of time and visit also affected postural sway performance while VTF was applied. Designing a training protocol for VTF should take these factors into consideration.

6.0 THE USE OF VIBROTACTILE FEEDBACK DURING DUAL-TASK STANDING BALANCE IN PEOPLE WITH UNILATERAL VESTIBULAR HYPOFUNCTION

6.1 INTRODUCTION

Vestibular dysfunction is a common disorder seen in the US. It is estimated that 35.4% of US adults over 40 have a vestibular problem.[5] People with vestibular deficits have an increased risk of falling.[5, 192] Preventing falls in people with vestibular problems may decrease the cost of medical expenditures and improve the quality of life for people with vestibular dysfunction.[5]

Vibrotactile feedback (VTF) have been proposed to enhance balance ability in people with balance problems.[32] Studies have shown that VTF decreased postural sway in people with vestibular deficits while standing on a sway-referenced (SR) platform with eye closed and visual sway-referenced conditions.[30, 34] However, how the platform and eye conditions (sensory integration) affect the use of VTF were not considered in the previous studies.[30, 34]

Dual-task paradigms have been used to test the allocation of attention shift between balance tasks and cognitive tasks.[114] Studies have demonstrated that people with vestibular problems require more attention for balance compared to healthy controls, as demonstrated by increased auditory choice reaction times.[36] Redfern et al.[36] also suggested that the increase in attentional demand was due to the increased attentional requirement in the sensory selection process before responding to the balance tasks. Vibrotactile feedback provides extra sensory information to the brain.[32] Moreover, Haggerty et al. have indicated that using VTF requires attention.[109]. It is unclear if vibrotactile feedback information affects the sensory selection process and requires more attention in people with vestibular disorders.

The purpose of this study was to investigate the effect of performing dual-task conditions under different sensory integration conditions while using VTF on postural sway in people with unilateral vestibular hypofunction (UVH) and age-matched controls. We hypothesized that people with UVH will have a poor ability to use VTF compared with age-matched controls during dual-task conditions, resulting in increasing postural sway and slower reaction time.

6.2 METHODS

6.2.1 Subjects

Ten people with unilateral vestibular hypofunction and seven aged-matched controls were enrolled in this study. Three of the participants with unilateral vestibular disorders did not complete the study. Table 6 summarizes the basic characteristics for the seven subjects with UVH and age-matched controls.(Table 6) People with UVH were referred by a clinic doctor or physical therapists after the diagnosis was confirmed. Exclusion criteria consisted of a diagnosis of a neurologic or orthopedic disorder, known pregnancy, binocular visual acuity with corrective lenses worse than 20/40, or impaired sensation with the Semmes-Weinstein monofilament test (0.07g)[207]. Additional excludsion criteria for the control group were scores less than 19 on the Dynamic Gait Index [205], scores of less than 22 on the Functional Gait Assessment [206], or abnormal age-corrected audiometric function.

The Institutional Review Board at the University of Pittsburgh approved the protocol.

6.2.2 Instrumentation

The VTF system consisted of a belt, an inertial measurement unit (IMU, Xsense Technologies B.V., Enschede, The Netherlands), eight vibrating tactors (C-2, Engineering Acoustics Inc., Casselberry, FL, USA), and a laptop computer. Two tactors were placed vertically within the belt wrapping around the subject's waist in midline front, midline back, right and left side directions. The IMU, which detected the subject's sway position and sway velocity in the anteroposterior (AP) and mediolateral (ML) directions, was attached to the posterior of the belt at the level of the fourth lumbar vertebra. The IMU also measured the trunk tilt from vertical while the VTF was activated. Vibrotactile feedback was provided when the control signal value, equal to sway position plus 0.5 times the sway velocity, exceeded threshold.[107] The threshold of the lower tactors was 1.5 anteriorly, 0.5 posteriorly, and 0.5 right and left. The threshold of the upper tactors was 3 anteriorly, 1.5 posteriorly, and 1.5 right and left. We set a larger threshold for the anterior direction because the limits of stability are larger in the anterior direction compared with the posterior direction.[97] "The nearest neighbor" principle was used in the feedback algorithm which activated only one tactor at a time by determining which direction had the greatest control signal value.[97] The subject was instructed to stay in the neutral zone (area without any VTF given) as much as possible and move away from the vibration site. Subjects were wore thin foot coverings and wore a thin shirt so that the tactors could be sensed easily.

A computerized dynamic posturography platform (Smart EquiTest^{TM}; Neurocom, Inc.) was used to record the center of pressure (COP). The Smart EquiTest also provided sway-referencing in the sagittal plane about the ankle joints by estimating the body pitch from the AP COP.

A secondary auditory choice reaction time task (CRT) was delivered by a customized program (Labview, National Instruments). The auditory CRT stimuli consisted of 560 Hz and 980Hz tones transmitted through a set of earphones (**E·A·R**TONE®).The tones were played at 80dB for 250ms and repeated every 2 to 6 seconds during a 2 minute period. Using one microswitch button in each hand, the subject pressed a button in one hand for a high pitch tone and the other hand for a low pitch tone. Twenty-five to twenty-nine auditory stimuli were presented in each trial. The onset of the switch activation relative to the stimulus was recorded with a temporal resolution of 1 millisecond.

6.2.3 Experimental procedure

A screening and training visit was required prior to the two experimental visits. During the screening and training visit, the subject was briefly introduced and trained to perform the CRT tasks, and how to use the VTF. The training conditions included four sensory integration conditions (Eyes open (EO)/Eyes open in the dark (EOD) x Fixed/Sway-referenced platform (SR)) and one dual-task condition on EO/SR platform. The subjects were instructed to stand comfortably, to move away from vibration and to stay in the neutral zone as much as they could. Darkened goggles were used during the EOD condition to avoid the light interference from the computer screen. Each training condition lasted for 120 seconds. During the two experimental visits, a short training period was held before the experimental test, which repeated the VTF training conditions, but with a less duration to avoid fatigue and for warm-up. A total of sixteen two-minute trials were performed, including all combinations of VTF on/off, CRT task on/off, and sensory conditions (Fixed/EO, Fixed/EOD, SR/EO and SR/EOD). The subjects performed the experimental conditions in random order during both of the two different experimental visits.

6.2.4 Outcome measures

The trunk tilt was recorded by the IMU in the anterior-posterior (AP) and medial-lateral (ML) directions during the eight conditions when the VTF was activated. The COP was also recorded in the AP and ML direction for all trials. However, only AP direction of trunk tilt and COP data were used because the sway-referencing platform only occurred in the AP direction. The root-mean square (RMS) of trunk tilt and COP were calculated via a customized Matlab (The MathWorks, Natick, MA) program. We divided the 120 second data into four periods (Period 1: 0-30s; Period 2: 30-60s; Period 3: 60-90s; Period 4: 90-120s) to investigate within-trial performance.[214, 215] The percentage of time in the neutral zone was also calculated from the IMU data. The median reaction times (RTs) were calculated from each of the eight conditions with CRT task. Prior to extracting the median reaction time in each CRT condition, the first RT response was excluded due to the increase in latency on the first response.

6.2.5 Statistical Analysis

All data was examined for normality via the Shapiro-Wilk test. Independent t-tests or the Mann-Whitney test was used to examine group difference in age, gait speed, DGI and FGA. A Chi-square test was used for subject gender difference. A repeated measures analysis of variance (ANOVA) was conducted to examine the study aims. The effect of group, Period, CRT, Condition and Visit on trunk tilt RMS and the percentage of time in the neutral zone were tested in order to assess control of trunk movements while having VTF available. The effects of group, Period, VTF, CRT, Condition and Visit on COP RMS were also tested in order to examine control of center of mass during all conditions. However, two out of seven people with UVH were not able to perform the balance task during SR/EOD condition so that we only used three levels of sensory integration conditions (Fixed/EO, Fixed/EOD and SR/EO) in our model. Because we were interested in the interactions between Group and the repeated factors, we used repeated measures ANOVA. In addition, because of the small sample size, we also performed an analysis of the Group effect using the Mann-Whitney test. The postural sway data (trunk tilt RMS and COP RMS) was logarithmically transformed to meet the assumption of a repeated measure ANOVA. A Bonferroni correction was applied if post-hoc analysis was needed for the Condition and Period variable. Similarly, we investigated the effect of group, VTF, Condition and Visit on reaction times. All statistical analyses were performed using IBM® SPSS® Statistics, Release Version 19 (IBM, Armonk, NY). A significance level of $\alpha = 0.05$ was used.

6.3 RESULTS

The sample consisted of six females and one male in the UVH group and 5 females and 2 males in the age-matched control group (*p* = 0.53). There was no statistically significant difference between the two groups in age (*p* =0.90). Significant differences between UVH and controls were found in gait speed (*p* = 0.01), DGI (*p* = 0.01) and FGA (*p* = 0.01). (Table 6) We confirmed the results for the main group effect in the ANOVA by performing a Mann-Whitney Test, a group difference was only found for reaction time (p = 0.03), but not COP RMS (p = 0.81), trunk tilt RMS (p=0.26) or the percentage time in the neutral zone (p = 0.47).

Table 6. Basic information for subjects with unilateral vestibular hypofunction and normal control subjects

Group	ID	Age	Gender	Lesion Side	Duration (wks)	Dizziness Rating*	Gait Speed	DGI	FGA
UVH	1	65	F	L	1	7	0.91	19	19
	3	56	F	R	28	2	1.07	20	21
	5	55	F	L	265	2	0.86	18	16
	6	59	F	L	282	0	1.04	21	22
	7	64	M	L	5	5	0.84	12	12
	9	52	F	L	260	1	1.23	21	24
	10	60	F	L	7	1	1.12	22	27
Mean		59 ± 4					1.01 ± 0.15	19± 3	20 ± 5
Controls	1	65	F				1.03	23	28
	2	55	F				1.38	23	28
	3	58	F				1.41	24	28
	4	59	F				1.15	22	27
	5	64	M				1.19	24	28
	6	50	F				1.21	24	23
	7	64	M				1.63	24	28
Mean		59 ± 5					1.29 ± 0.20	23 ± 1	27± 2
p value		$p = 0.90$[b]	$p = 0.53$[c]				$p = 0.01$[a]	$p = 0.01$[b]	$p = 0.01$[b]

- [a]Independent t-test; [b]Mann-Whitney test; [c]Chi-square test
- *Dizziness rating: 0 to 10 scale, 10 is the maximum intensity of dizziness; averaged from two visits

6.3.1 Postural Sway

The repeated measures ANOVA showed that there was no significant group difference between people with UVH and age-matched controls on COP RMS ($p = 0.692$, effect size = 0.25) (Table 7) and trunk tilt RMS ($p = 0.399$, effect size = 0.29) (Table 8) and

Significant main effects included Condition ($p < 0.001$) and VTF ($p = 0.014$) for COP RMS (Table 7), and Condition ($p < 0.001$) and Period ($p = 0.002$) for trunk tilt RMS (Table 8). The magnitude of COP RMS and trunk tilt RMS increased across the sensory conditions: Fixed/EO, Fixed/EOD to the SR/EO condition. A significant effect of Period was only observed for trunk tilt RMS, which was due to the greater trunk tilt RMS in the last 30 seconds compared to the second period of 30 seconds. A significant VTF effect was found for COP RMS, which showed that COP RMS was higher during the use of VTF. There were no main effects of Visit or CRT for COP RMS and trunk tilt RMS.

There were no significant interactions among group, Condition, CRT, Period, and Visit for trunk tilt RMS while using VTF. However, several significant interactions were found for COP RMS. The Group*CRT*Visit interaction demonstrated that during experimental visit 1, people with UVH had greater COP RMS while performing secondary CRT tasks compared with no dual task, but not during experimental visit 2. Control subjects did not have significant changes in COP RMS due to CRT or Visit.(Figure 14) Several two-way interactions were present.(Figure 15) The VTF*Period interaction showed that COP RMS was not different across period while VTF was off, but was significantly less in Period 2 than Period 1 and 4.(Figure 15a) The VTF*Condition interaction revealed that there was an increase in COP RMS when VTF was on during fixed platform conditions, but a slight decrease during the sway-referenced platform condition.(Figure 15b) The Period*Condition interaction demonstrated that COP RMS was decreased in Period 3 and 4 compared to Period 1during the fixed/EOD condition, and COP RMS was decreased in Period 2 compared to Period 3 and 4 during the SR/EO condition.(Figure 15c)

Table 7. Effects of group, sensory condition, vibrotactile feedback (VTF), performance of auditory choice reaction time (CRT) tasks, period and visit on the root-mean-square of the anterior-posterior center of pressure (RMS COP)

Main Effects	RMS COP (mean ± SD)	F and P values	Interaction(s)	F and P values
Group	Control: 0.73 ± 0.15 UVH: 0.85 ± 0.33	$F_{1, 12} = 0.2$, $p = 0.692$	Period*VTF Period*Condition VTF*Condition	$F_{3, 36} = 6.1$, $p = 0.002$ $F_{6, 72} = 4.6$, $p < 0.001$ $F_{2, 24} = 11.9$, $p < 0.001$
Condition[a]	Fixed/EO: 0.50 ± 0.16 Fixed/EOD: 0.64 ± 0.20 SR/EO: 1.24 ± 0.59	$F_{1.2, 13.4} = 63.2$, $p < 0.001$		
VTF	Off: 0.78 ± 0.27 On: 0.80 ± 0.25	$F_{1, 12} = 8.3$, $p = 0.014$	Group*CRT*Visit	$F_{1, 12} = 6.4$, $p = 0.027$
CRT	Off: 0.81 ± 0.30 On: 0.78 ± 0.23	$F_{1, 12} = 0.1$, $p = 0.772$		
Period	1: 0.81 ± 0.24 2: 0.76 ± 0.25 3: 0.79 ± 0.27 4: 0.81 ± 0.29	$F_{3, 36} = 1.8$, $p = 0.158$	VTF*Condition*Visit*Group	$F_{2, 24} = 5.7$, $p = 0.009$
Visit	1st : 0.79 ± 0.25 2nd: 0.80 ± 0.29	$F_{1, 12} = 0.2$, $p = 0.644$		

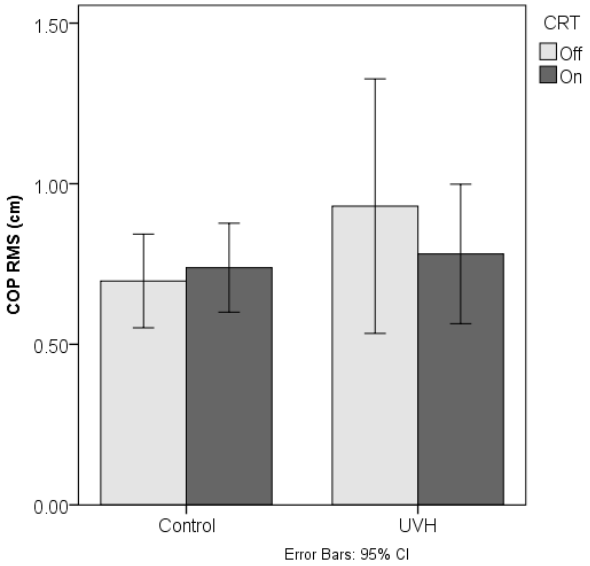
- Fixed: Fixed platform; SR: Sway-referenced platform; EO: Eye open; EOD: Eye open in the dark; VTF: Vibrotactile feedback; CRT: auditory choice reaction time; COP: center of pressure; RMS: root-mean square
- [a]Post-hoc test for Condition: all conditions were significantly different, $p < 0.01$

Table 8. . Effects of group, sensory conditions (Condition), performance of auditory choice reaction time (CRT) task, period and visit on the root-mean-square of the anterior-posterior trunk tilt (RMS trunk tilt)

Main Effects	RMS trunk tilt (mean ± SD)	F and P values	Interaction(s)	F and P values
Group	Control: 0.44 ± 0.12 UVH: 0.52 ± 0.14	$F_{1, 12} = 0.8$, $p = 0.399$	None	None
Condition[a]	Fixed/EO: 0.38 ± 0.13 Fixed/EOD: 0.44 ± 0.11 SR/EO: 0.62 ± 0.24	$F_{2, 24} = 23.7$, $p < 0.001$		
CRT	Off: 0.47 ± 0.14 On: 0.49 ± 0.14	$F_{1, 12} = 1.7$, $p = 0.221$		
Period[b]	1: 0.49 ± 0.14 2: 0.45 ± 0.13 3: 0.46 ± 0.14 4: 0.51 ± 0.15	$F_{3, 36} = 5.9$, $p = 0.002$		
Visit	1st : 0.51 ± 0.15 2nd: 0.45 ± 0.13	$F_{1, 12} = 4.1$, $p = 0.066$		

- Fixed: Fixed platform; SR: Sway-referenced platform; EO: Eye open; EOD: Eye open in the dark; VTF: Vibrotactile feedback; CRT: auditory choice reaction time; RMS: root-mean square
- [a]Fixed/EO vs Fixed/EOD, $p = 0.013$; Fixed/EO vs SR/EO, $p < 0.001$; SR/EO vs Fixed/EOD, $p = 0.006$
- [b]2 vs 4, $p = 0.001$

A. Experimental Visit 1



B. Experimental Visit 2

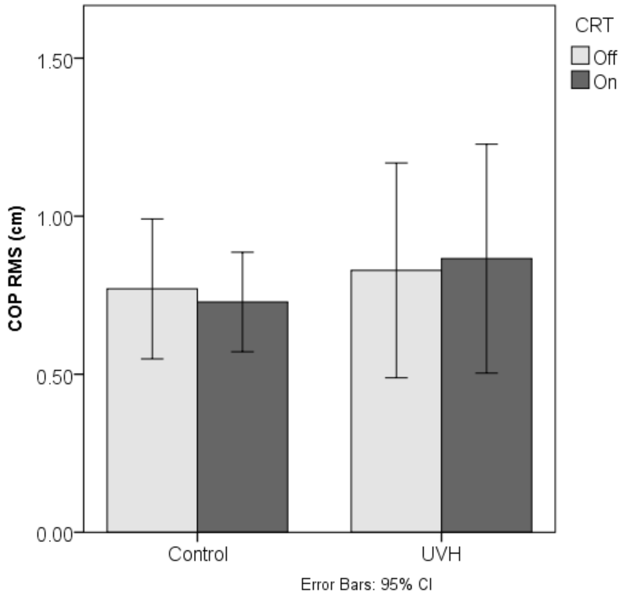
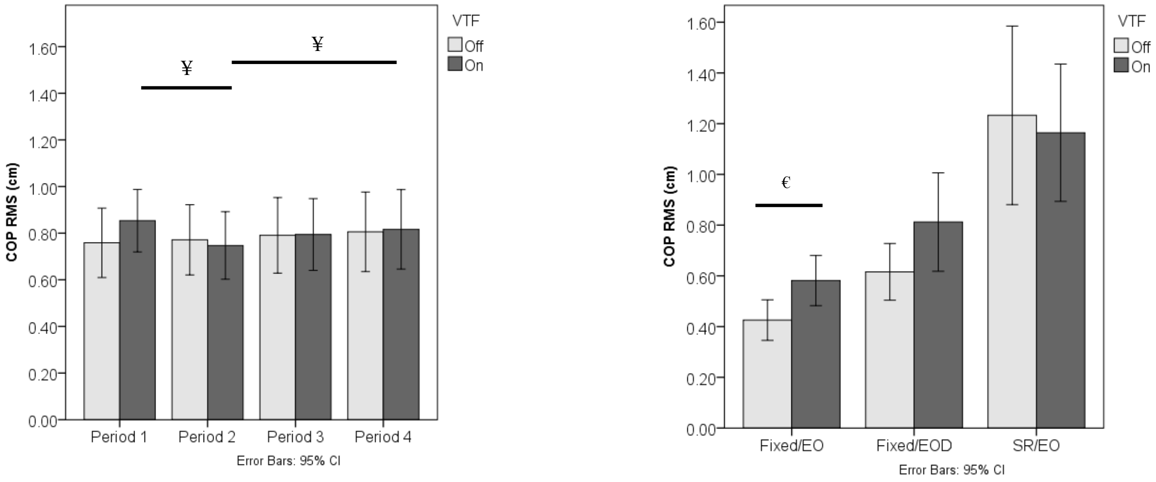


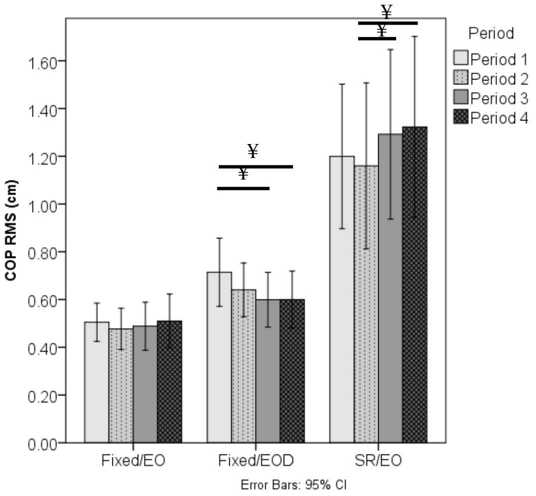
Figure 14. Group*CRT*Visit interaction on the root-mean-square of the anterior-posterior center of Pressure (RMS COP)



a. VTF*Period interaction

b. VTF*Condition interaction[1]

c. Period*Condition interaction



- COP: center of pressure; RMS: root-mean square
- [1]RMS COP was significant difference among the three sensory conditions, $p < 0.025$
- $^{¥}p < 0.017$; $^{€}p < 0.025$

Figure 15. VTF*Period interaction on sway-referenced platform and Eye open condition: RMS COP reduced in Period while VTF was on compared to RMS COP increased with time while VTF was off

6.3.2 Percentage of Time in the Neutral Zone

No significant group effect was found in the percentage of Time in the Neutral Zone ($p = 0.426$, effect size = 0.18) The repeated measures ANOVA revealed significant main effects of Condition ($p < 0.001$) and Period ($p < 0.001$).(Table 9) The post-hoc analysis showed that the percentage of time in the neutral zone during the Fixed/EO condition was greater than the SR/EO condition. People with UVH and age-matched controls had a larger percentage of time in the neutral zone during Period 1 compared to Period 4. There were no main effects of Group, CRT, Visit and no interactions among the factors.

Table 9. Effects of group, sensory condition, performance of auditory choice reaction time (CRT) task, period and visit on the percentage of time in the neutral zone

Main Effects	Percentage of Time in the neutral Zone (%) (mean ± SD)	F and P values	Interaction(s)	F and P values
Group	Control: 0.76 ± 0.14 UVH: 0.71 ± 0.12	$F_{1,12} = 0.7$, $p = 0.426$	None	None
Condition[a]	Fixed/EO: 0.82 ± 0.13 Fixed/EOD: 0.75 ± 11 SR/EO: 0.64 ± 0.19	$F_{3,24} = 11.0$, $p < 0.001$		
CRT	Off: 0.75 ± 0.12 On: 0.72 ± 0.14	$F_{1,36} = 2.3$, $p = 0.156$		
Period [b]	1: 0.78 ± 0.10 2: 0.74 ± 0.14 3: 0.73 ± 0.14 4: 0.70 ± 0.15	$F_{3, 36}= 10.0$, $p < 0.001$		
Visit	1st : 0.69 ± 0.19 2nd : 0.78 ± 0.11	$F_{1,12} = 2.6$, $p = 0.134$		

- [a] Post-hoc test for Condition: Fixed/EO vs SR/EO, $p = 0.003$.
- [b] Post-hoc test for Period: Period 1 significantly greater than Periods 4, $p < 0.017$.

6.3.3 Reaction Time

Reaction Time was used to examine the attention demands of the postural task. A repeated measures ANOVA of the median reaction time (RT) demonstrated significant main effects of Group ($p = 0.027$) and VTF ($p< 0.001$).(Table 10) The RTs of people with UVH were slower than the age-matched controls by 67 milliseconds. When VTF was used, the RT increased approximately 77 milliseconds in people with UVH and 63 milliseconds in controls compared with when VTF was not used. No interaction was found.

Table 10. Effects of group, sensory condition, vibrotactile feedback (VTF), and visit on the median reaction time during performance of an auditory choice reaction time task

Main Effects	Reaction Time (ms) (mean ± SD)	F and P values	Interaction(s)	F and P values
Group	Control: 475 ± 54 UVH: 542 ± 44	$F_{1,12} = 6.3$, $p < 0.027$	None	None
Condition	Fixed/EO: 500 ± 63 Fixed/EOD: 513 ± 63 SR/EO: 510 ± 59	$F_{2,24} = 1.2$, $p = 0.333$		
VTF	Off: 474 ± 51 On: 543 ± 70	$F_{1,12} = 51.9$, $p < 0.001$		
Visit	1st : 518 ± 58 2nd : 499 ± 69	$F_{1,12} = 2.0$, $p = 0.187$		

- The presence of VTF affected the reaction time significantly.
- Fixed: Fixed platform; SR: Sway-referenced platform; EO: Eye open; EOD: Eye open in the dark; VTF: Vibrotactile feedback; CRT: auditory choice reaction time.

6.4 DISCUSSION

The purpose of this study was to examine if individuals with UVH had different postural performance and reaction time on dual-task conditions when using VTF compared with controls. We did not detect a difference between subjects with UVH and controls on the magnitude of postural sway while using VTF during dual-task and different sensory integration conditions. However, people with UVH had slower RTs than age-matched controls, which suggested that people with UVH required additional attention to perform the balance tasks.

The postural sway parameters during dual-task conditions were not different between the two groups in our study. Our results for COP RMS confirmed previous findings of Redfern et al and Yardley et al.[36, 40] Redfern et al. found no group differences for postural sway when people with well-compensated vestibular lesions were compared with age-matched controls while they performed different cognitive tasks during balancing.[36] Yardley et al. also compared the COP RMS between people with uncompensated vestibular disorders and healthy controls and found no difference for COP RMS on a stable or sway-referenced platform while they performed secondary mental tasks.[40] However, lower equilibrium scores were found in people with vestibular disorders in Yardley et al.'s study while performing secondary mental tasks on posturography.[40]

Slower RTs of 67 ms were found in people with UVH compared to the age-matched controls while performing a secondary cognitive task, averaged across all tasks. This magnitude of difference in RTs was consistent with previous studies that demonstrated a 40 ms difference between well compensated individuals with UVH and controls [36], and a 75 ms difference between poorly compensated subjects with UVH and controls.[40] Our study subjects were uncompensated, as 6 out of 7 reported dizziness, and all demonstrated clinically impairments during the DGI and FGA test.

It is interesting that the Group*CRT*Visit interaction was found in our study. The people with UVH had less COP RMS when performing the CRT during the first experimental visit. Andersson et al have proposed that performance of a mathematical mental task may help to control body sway.[39] The results in their study showed decreased postural sway while a mental task was performed. Yardley et al. also found improvement in equilibrium scores while performing an auditory choice reaction time task as a secondary mental task.[40] A previous section that compared younger and older adults found an effect of Visit during dual-task paradigms.(see section 5) Similar to the current study, we found that COP RMS was reduced on the second experimental visit.

Vibrotactile feedback has been shown to reduce trunk tilt RMS [26, 30, 34, 97, 213] and COP RMS. [32, 34] Our results showed that the effect of using VTF on COP RMS depended on other experimental factors. The VTF*Condition interaction indicated that when the platform was fixed, VTF induced greater COP RMS. However, when the platform was sway-referenced, VTF decreased COP RMS, but the effect was small. Similar results have been shown in our previous study in which younger and older adults demonstrated increased COP RMS during fixed platform conditions and decreased COP RMS during sway-referenced condition. It is suggested that the increased sway when VTF was active in the fixed platform conditions is due to over-correction of sway in the opposite direction.

In this study, we also examined how sensory integration affected dual-task performance while using VTF. Our results illustrated that there was no difference in reaction times during Fixed/EO, Fixed/EOD and SR/EO conditions. The results of Redfern et al. suggested that sway-referencing significantly increases reaction times.[36] Surprisingly, our results showed there was no main effect of Condition on reaction time or any interactions, which has been shown in our previous study.(See section 5) In our previous study, subjects increased RTs greatly in SR/EOD compared to other sensory integration condition. However, SR/EOD condition was not included in the analysis in this study because the subjects with UVH could not complete the task. The lack of main effect of Condition on reaction time may be also due to the small sample size in our study.

A group difference was not found for the trunk tilt RMS and COP RMS. The study was limited by a small sample size. According to the effect size in this study, it was estimated that a total of 78 subjects (39 in each group) would be needed in order to show significant between-group differences for trunk tilt RMS and a total of 108 subjects (54 in each group) would be needed for the COP RMS. Considering the time and financial issues, it was not realistic to recruit all the UVH subjects needed to demonstrate differences in postural performance. Nonetheless, between-group differences in reaction time performance was observed with this sample size.

6.5 CONCLUSION

Our data indicated that no difference was found between the people with UVH and age-matched controls on postural sway parameters while using VTF under dual-task conditions. However, people with UVH require more attentional resources to perform secondary cognitive tasks while using VTF.

7.0 DISCUSSION

The purpose of this dissertation was to examine the effect of using VTF on postural sway and reaction times during dual-task conditions in younger and older adults, and in people with unilateral vestibular hypofunction and age-matched controls. Similar findings were seen in both studies, including the VTF*Condition interaction, Period*VTF interaction, and Period*Condition interaction. These findings suggest that sensory integration conditions and experience significantly affected the ability to utilize VTF. Moreover, reaction time increased while the VTF was applied in both studies. Although there are different degrees of delay in reaction times among the different study groups, VTF significantly increased the reaction time, which suggests that there was additional attentional requirements while using VTF.

In our study, the instruction given to the subjects for responding to VTF was "stand comfortably, respond to the vibration when you feel it and push different buttons when you hear the different tones." Compared to other studies using VTF, the common instruction was "stand still and respond to vibration."[97, 109] Our different instructions might have influenced the study results. Our idea was to ask subjects to respond like they might need to respond during real-life conditions. No warning was given during the testing conditions. Therefore, we expected the subjects would have greater RMS COP during the first thirty seconds because the subjects adjusted their postural control over time. Study also suggested that nonstationary properties of postural sway within the first twenty seconds.[214] We also observed increase postural sway after ninety seconds. This increasing postural sway might be due to muscle fatigue in the lower extremities.

Our results were not able to find difference in RMS trunk tilt and RMS COP between people with unilateral vestibular hypofunction and age-matched controls, which was limited by a small sample size. However, according to the effect size that was calculated from our data, a total of 78 subjects would be needed for the RMS trunk tilt and 108 subjects for the RMS COP to demonstrate significance. In our clinical setting, it was not realistic for us to recruit such a large number of patients.

8.0 STUDY LIMITATIONS/OBSERVATIONS

In our study design, we randomized the testing conditions for two different study visits in order to eliminate the order effect because of fatigue. In the results, we found testing conditions (different sensory integration conditions) and VTF interaction in both studies. VTF with a fixed platform induced greater RMS COP and with a sway-referenced platform reduced RMS COP. The increase in RMS COP may have been due to an overcorrection in the opposite direction. However, the randomized testing conditions could not help us assure that the increased RMS COP was due to the overcorrection in fixed platform condition. A solution to confirm the effect of VTF during different platform conditions should control the sequence of platform condition. Controlling the sequence of the sensory integration conditions may help to see the effect of fixed platform versus sway-referenced platform while using VTF. For example, subjects would perform all the fixed platform conditions first and then the sway-referenced platform conditions during the study visit.

Besides the testing conditions, the pre-defined threshold for VTF that we used in this dissertation may affect the postural sway in older adults. We set the threshold of 0.5 degree in the posterior direction for all the subjects. However, during the experiment, we observed that older adults tended to lean backward when we started the testing, even if we asked the subjects try to stand comfortably at the start of each condition. The tactor in the back was vibrating because the subjects leaned backward, and forced the subjects to correct their posture, even if the subjects felt steady, especially during fixed platform conditions. This corrective movement may have caused more body movements because of overcorrection. Moreover, in some subjects, hip strategy was also observed while they responded to the VTF. Using hip strategy to respond VTF was not optimal because large hip movements cause the tactors to vibrate more frequently. A wider pre-defined threshold or subject-specific threshold for VTF should be considered for older people and people with vestibular hypofunction.

The total mean length of time to complete one visit was one hour and forty-five minutes. Older subjects and people with unilateral vestibular function required more time to finish the protocol because of frequent rests required by the subjects. The long time for testing might have caused fatigue and decrease performance. Further studies should consider a shorter test protocol.

9.0 FUTURE WORK

Applying VTF during postural control activities is ongoing in our lab. Most previous studies focused on static balance.[26, 30-32, 42, 109, 213] The ultimate goal for us is to apply VTF during vestibular rehabilitation exercises and during functional movement. We believe that our efforts in these studies will enhance the experience of using VTF and help us to reach the ultimate goal of improving balance in people with balance deficits and people with vestibular disorders.

An unsolved question in this dissertation is why RMS COP increased during fixed platform conditions while using VTF. Further studies may apply EMG to the lower legs to determine the muscle responses while using VTF in single and dual-task conditions and different platform conditions. The EMG may help us understand the pattern of muscles responses in order to further explain the increase postural sway during fixed platform condition or the mechanism of reducing postural sway while using VTF. A fixed order of testing conditions may also warrant further study to control the order effect in a small sample size.

Examination of the learning curve for using VTF during standing balance tasks in different age groups and people with vestibular disorders in order to maximize the effect of VTF for training purposes might also be worthy of future study. There is no literature that demonstrates the optimal “dosage” of VTF training and formalization. Knowing the learning curve could help the people to expect the benefit from using VTF after period of time of training.

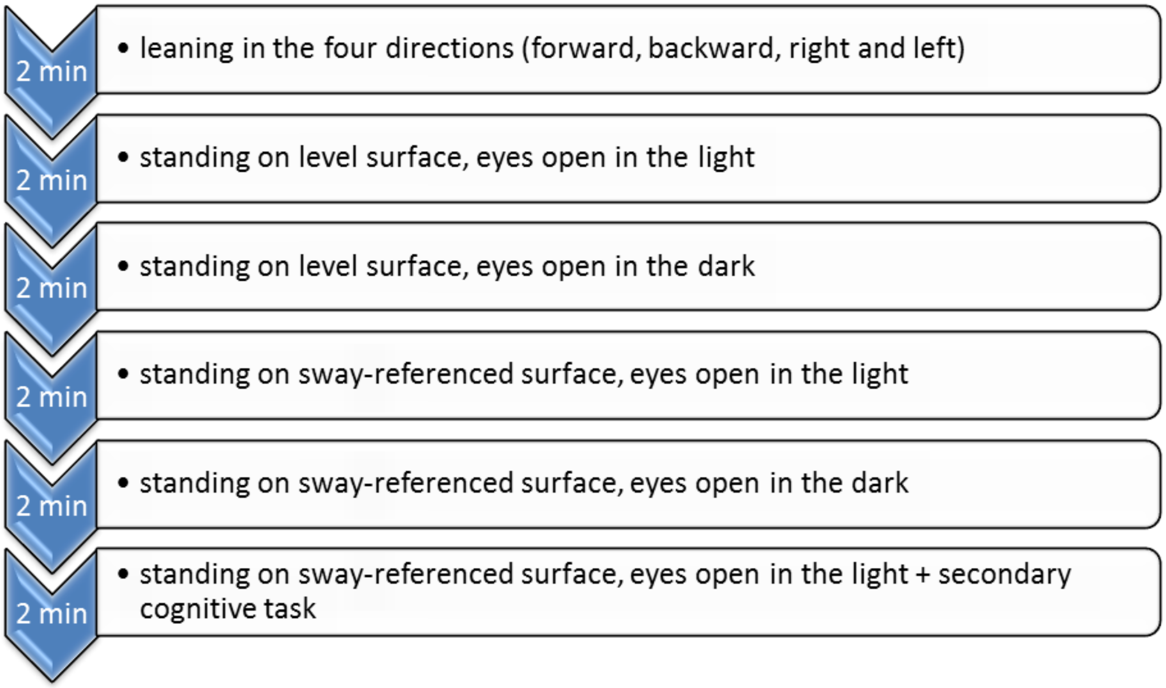
Future investigation could also determine the effectiveness of VTF during vestibular rehabilitation exercises. However, it may be beneficial to customize the VTF thresholds by determining appropriate levels for each subject for each exercise, prior to subjects performing the different exercises.

10.0 CONCLUSION

The ability to utilize VTF to reduce postural sway was not affected by secondary cognitive tasks in younger and older adults, and people with unilateral hypofunction. However, the use of VTF delayed the responses for the secondary cognitive tasks, which implies that more attention is required while using VTF in younger and older adults, and people with vestibular hypofunction. In our study, postural sway differences were only seen between the younger and older groups during dual-task conditions while using VTF, but not between people with vestibular hypofunction and the age-matched groups. Several factors were found that affect the use of VTF to control postural sway. Sensory condition and experience affect postural sway while using VTF. When developing a training protocol for VTF, age, sensory integration condition and the length of time using VTF should be taken into consideration to maximize the effect of VTF. Future study designs should utilize VTF in vestibular rehabilitation programs to examine the effectiveness of VTF to aid recovery in people with vestibular disorders.

APPENDIX A

TRAINING PROTOCOL FLOW CHART



APPENDIX B

SIXTEEN TEST CONDITIONS

Condition	Vibrotactile feedback	Information processing task	Visual feedback	Somatosensory feedback
1	On	On	On	On
2	On	On	On	Off
3	On	On	Off	On
4	On	On	Off	Off
5	On	Off	On	On
6	On	Off	On	Off
7	On	Off	Off	On
8	On	Off	Off	Off
9	Off	On	On	On
10	Off	On	On	Off
11	Off	On	Off	On
12	Off	On	Off	Off
13	Off	Off	On	On
14	Off	Off	On	Off
15	Off	Off	Off	On
16	Off	Off	Off	Off

Visual feedback on: eyes open in the light; Visual feedback off: eyes open in the dark; Somatosensory feedback on: Sway-referenced platform; Somatosensory feedback off: fixed platform

BIBLIOGRAPHY

1. Stevens, J.A., et al., *Self-reported falls and fall-related injuries among persons aged>or=65 years--United States, 2006.* Journal of Safety Research, 2008. **39**(3): p. 345-9.
2. Davis, J.C., et al., *International comparison of cost of falls in older adults living in the community: a systematic review.* Osteoporosis International, 2010. **21**(8): p. 1295-306.
3. Kruschinski, C., et al., *Fracture risk of patients suffering from dizziness: a retrospective cohort study.* Eur J Gen Pract, 2010. **16**(4): p. 229-35.
4. Murray, K.J., et al., *A pilot study of falls risk and vestibular dysfunction in older fallers presenting to hospital emergency departments.* Disability and Rehabilitation, 2005. **27**(9): p. 499-506.
5. Agrawal, Y., et al., *Disorders of balance and vestibular function in US adults: data from the National Health and Nutrition Examination Survey, 2001-2004.* Archives of Internal Medicine, 2009. **169**(10): p. 938-44.
6. Agrawal, Y., et al., *Diabetes, vestibular dysfunction, and falls: analyses from the National Health and Nutrition Examination Survey.* Otology and Neurotology, 2010. **31**(9): p. 1445-50.
7. Ganz, D.A., et al., *Will my patient fall?* JAMA, 2007. **297**(1): p. 77-86.
8. Gerdhem, P., et al., *Clinical history and biologic age predicted falls better than objective functional tests.* Journal of Clinical Epidemiology, 2005. **58**(3): p. 226-32.
9. Stel, V.S., et al., *A classification tree for predicting recurrent falling in community-dwelling older persons.* Journal of the American Geriatrics Society, 2003. **51**(10): p. 1356-64.
10. Di Fabio, R.P., et al., *Influence of elderly executive cognitive function on attention in the lower visual field during step initiation.* Gerontology, 2005. **51**(2): p. 94-107.
11. Greany, J.F. and R.P. Di Fabio, *Saccade to stepping delays in elders at high risk for falling.* Aging Clinical and Experimental Research, 2008. **20**(5): p. 428-33.
12. Cooksey, F.S., *Rehabilitation in vestibular injuries.* Proceedings of the Royal Society of London. Series B: Biological Sciences, 1946. **39**: p. 273-8.
13. Dannenbaum, E., et al., *Clinical evaluation of dynamic visual acuity in subjects with unilateral vestibular hypofunction.* Otology and Neurotology, 2009. **30**(3): p. 368-72.
14. Mohammad, M.T., et al., *The reliability and response stability of dynamic testing of the vestibulo-ocular reflex in patients with vestibular disease.* Journal of Vestibular Research, 2011. **21**(5): p. 277-88.

15. Longridge, N.S. and A.I. Mallinson, *The Dynamic Illegible E-test: A Technique for Assessing the Vestibulo-ocular Reflex.* Acta Otolaryngol, 1987. **103**(5-6): p. 273-9.
16. Schubert, M.C., et al., *Optimizing the sensitivity of the head thrust test for identifying vestibular hypofunction.* Physical Therapy, 2004. **84**(2): p. 151-8.
17. Goebel, J.A., et al., *Head-shake vestibulo-ocular reflex testing: comparison of results with rotational chair testing.* Otolaryngology - Head and Neck Surgery, 1995. **112**(2): p. 203-9.
18. Vicini, C., A. Casani, and P. Ghilardi, *Assessment of head shaking test in neuro-otological practice.* ORL; Journal of Oto-Rhino-Laryngology and Its Related Specialties, 1989. **51**(1): p. 8-13.
19. Gianoli, G.J. and J.S. Soileau, *Chronic suppurative otitis media, caloric testing, and rotational chair testing.* Otology and Neurotology, 2008. **29**(1): p. 13-5.
20. Arriaga, M.A., D.A. Chen, and K.A. Cenci, *Rotational chair (ROTO) instead of electronystagmography (ENG) as the primary vestibular test.* Otolaryngology - Head and Neck Surgery, 2005. **133**(3): p. 329-33.
21. Chiarovano, E., et al., *Ocular and cervical VEMPs: a study of 74 patients suffering from peripheral vestibular disorders.* Clinical Neurophysiology, 2011. **122**(8): p. 1650-9.
22. Whitney, S.L. and M.M. Rossi, *Efficacy of vestibular rehabilitation.* Otolaryngologic Clinics of North America, 2000. **33**(3): p. 659-72.
23. Macias, J.D., S. Massingale, and R.D. Gerkin, *Efficacy of vestibular rehabilitation therapy in reducing falls.* Otolaryngology - Head and Neck Surgery, 2005. **133**(3): p. 323-5.
24. Topuz, O., et al., *Efficacy of vestibular rehabilitation on chronic unilateral vestibular dysfunction.* Clinical Rehabilitation, 2004. **18**(1): p. 76-83.
25. Hillier, S.L. and M. McDonnell, *Vestibular rehabilitation for unilateral peripheral vestibular dysfunction.* Clinical Otolaryngology, 2011. **36**(3): p. 248-9.
26. Wall, C., 3rd, *Application of vibrotactile feedback of body motion to improve rehabilitation in individuals with imbalance.* Journal of Neurologic Physical Therapy, 2010. **34**(2): p. 98-104.
27. Hegeman, J., et al., *The balance control of bilateral peripheral vestibular loss subjects and its improvement with auditory prosthetic feedback.* Journal of Vestibular Research, 2005. **15**(2): p. 109-17.
28. Dozza, M., L. Chiari, and F.B. Horak, *Audio-biofeedback improves balance in patients with bilateral vestibular loss.* Archives of Physical Medicine and Rehabilitation, 2005. **86**(7): p. 1401-3.
29. Wall, C., 3rd, et al., *Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt.* IEEE Transactions on Bio-medical Engineering, 2001. **48**(10): p. 1153-61.
30. Wall, C., 3rd and E. Kentala, *Control of sway using vibrotactile feedback of body tilt in patients with moderate and severe postural control deficits.* Journal of Vestibular Research, 2005. **15**(5-6): p. 313-25.
31. Wall, C., 3rd, et al., *Applications of vibrotactile display of body tilt for rehabilitation.* Conference Proceedings, Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2004. **7**: p. 4763-5.

32. Wall, C., 3rd, et al., *Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt.* IEEE Trans Biomed Eng, 2001. **48**(10): p. 1153-61.
33. Wall, C., 3rd, D.M. Wrisley, and K.D. Statler, *Vibrotactile tilt feedback improves dynamic gait index: a fall risk indicator in older adults.* Gait and Posture, 2009. **30**(1): p. 16-21.
34. Kentala, E., J. Vivas, and C. Wall, 3rd, *Reduction of postural sway by use of a vibrotactile balance prosthesis prototype in subjects with vestibular deficits.* Annals of Otology, Rhinology and Laryngology, 2003. **112**(5): p. 404-9.
35. Stelmach, G.E., H.N. Zelaznik, and D. Lowe, *The influence of aging and attentional demands on recovery from postural instability.* Aging, 1990. **2**(2): p. 155-61.
36. Redfern, M.S., et al., *Cognitive influences in postural control of patients with unilateral vestibular loss.* Gait and Posture, 2004. **19**(2): p. 105-14.
37. Bernard-Demanze, L., et al., *Age-related changes in posture control are differentially affected by postural and cognitive task complexity.* Curr Aging Sci, 2009. **2**(2): p. 139-49.
38. Andersson, G., L. Yardley, and L. Luxon, *A dual-task study of interference between mental activity and control of balance.* American Journal of Otology, 1998. **19**(5): p. 632-7.
39. Andersson, G., et al., *Dual-task study of cognitive and postural interference in patients with vestibular disorders.* Otology and Neurotology, 2003. **24**(2): p. 289-93.
40. Yardley, L., et al., *Interference between postural control and mental task performance in patients with vestibular disorder and healthy controls.* Journal of Neurology, Neurosurgery and Psychiatry, 2001. **71**(1): p. 48-52.
41. Dozza, M., et al., *Effects of practicing tandem gait with and without vibrotactile biofeedback in subjects with unilateral vestibular loss.* Journal of Vestibular Research, 2007. **17**(4): p. 195-204.
42. Sienko, K.H., et al., *Assessment of vibrotactile feedback on postural stability during pseudorandom multidirectional platform motion.* IEEE Transactions on Bio-medical Engineering, 2010. **57**(4): p. 944-52.
43. Horak, F.B., et al., *Vibrotactile biofeedback improves tandem gait in patients with unilateral vestibular loss.* Annals of the New York Academy of Sciences, 2009. **1164**: p. 279-81.
44. Mendelson, D.N., et al., *Inhibitory processes relate differently to balance/reaction time dual tasks in young and older adults.* Neuropsychology, Development, and Cognition. Section B, Aging, Neuropsychology and Cognition, 2010. **17**(1): p. 1-18.
45. Jamet, M., et al., *Age-related part taken by attentional cognitive processes in standing postural control in a dual-task context.* Gait and Posture, 2007. **25**(2): p. 179-84.
46. US Bureau of the Census. *2012 census data.* 2012; Available from: http://www.census.gov/compendia/statab/cats/population.html.
47. National Center for Injury Prevention and Control. *Web-based injury statistics query and reporting system (WISQARS).* Available from: http://www.cdc.gov/injury/wisqars/index.html.
48. Horak, F.B., L.M. Nashner, and H.C. Diener, *Postural strategies associated with somatosensory and vestibular loss.* Experimental Brain Research, 1990. **82**(1): p. 167-77.
49. Dichgans, J. and H.C. Diener, *The contribution of vestibulo-spinal mechanisms to the maintenance of human upright posture.* Acta Otolaryngol, 1989. **107**(5-6): p. 338-45.

50. Horak, F.B., et al., *Vestibular and somatosensory contributions to responses to head and body displacements in stance.* Experimental Brain Research, 1994. **100**(1): p. 93-106.
51. Simoneau, G.G., et al., *Role of somatosensory input in the control of human posture.* Gait and Posture, 1995. **3**(3): p. 115-112.
52. Faraldo-Garcia, A., et al., *Influence of age and gender in the sensory analysis of balance control.* European Archives of Oto-Rhino-Laryngology, 2012. **269**(2): p. 673-7.
53. Perry, S.D., W.E. McIlroy, and B.E. Maki, *The role of plantar cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation.* Brain Research, 2000. **877**(2): p. 401-6.
54. Verrillo, R.T., S.J. Bolanowski, and G.A. Gescheider, *Effect of aging on the subjective magnitude of vibration.* Somatosensory and Motor Research, 2002. **19**(3): p. 238-44.
55. Shaffer, S.W. and A.L. Harrison, *Aging of the somatosensory system: a translational perspective.* Physical Therapy, 2007. **87**(2): p. 193-207.
56. Bergin, P.S., et al., *Body sway and vibration perception thresholds in normal aging and in patients with polyneuropathy.* Journal of Neurology, Neurosurgery and Psychiatry, 1995. **58**(3): p. 335-40.
57. Patel, M., et al., *The contribution of mechanoreceptive sensation on stability and adaptation in the young and elderly.* European Journal of Applied Physiology, 2009. **105**(2): p. 167-73.
58. Sturnieks, D.L., et al., *Physiological risk factors for falls in older people with lower limb arthritis.* Journal of Rheumatology, 2004. **31**(11): p. 2272-9.
59. Park, J.J., et al., *Age-related change in the number of neurons in the human vestibular ganglion.* Journal of Comparative Neurology, 2001. **431**(4): p. 437-43.
60. Park, J.C., S.B. Hubel, and A.D. Woods, *Morphometric analysis and fine structure of the vestibular epithelium of aged C57BL/6NNia mice.* Hearing Research, 1987. **28**(1): p. 87-96.
61. Rosenhall, U. and W. Rubin, *Degenerative changes in the human vestibular sensory epithelia.* Acta Otolaryngol, 1975. **79**(1-2): p. 67-80.
62. Makary, C.A., et al., *Age-related primary cochlear neuronal degeneration in human temporal bones.* Journal of the Association for Research in Otolaryngology, 2011. **12**(6): p. 711-7.
63. Richter, E., *Quantitative study of human Scarpa's ganglion and vestibular sensory epithelia.* Acta Otolaryngol, 1980. **90**(3-4): p. 199-208.
64. Alvarez, J.C., et al., *Neuronal loss in human medial vestibular nucleus.* Anatomical Record, 1998. **251**(4): p. 431-8.
65. Peterka, R.J., F.O. Black, and M.B. Schoenhoff, *Age-related changes in human vestibulo-ocular and optokinetic reflexes: pseudorandom rotation tests.* Journal of Vestibular Research, 1990. **1**(1): p. 61-71.
66. Ishiyama, G., *Imbalance and vertigo: the aging human vestibular periphery.* Seminars in Neurology, 2009. **29**(5): p. 491-9.
67. Kerber, K.A., G.P. Ishiyama, and R.W. Baloh, *A longitudinal study of oculomotor function in normal older people.* Neurobiology of Aging, 2006. **27**(9): p. 1346-53.
68. Lin, H.W. and N. Bhattacharyya, *Balance disorders in the elderly: Epidemiology and functional impact.* Laryngoscope, 2012.
69. Hytonen, M., et al., *Postural control and age.* Acta Otolaryngol, 1993. **113**(2): p. 119-22.

70. Gittings, N.S. and J.L. Fozard, *Age related changes in visual acuity.* Experimental Gerontology, 1986. **21**(4-5): p. 423-33.
71. Kaido, M., et al., *Age-related changes in functional visual acuity in healthy individuals.* Japanese Journal of Ophthalmology, 2011. **55**(3): p. 183-9.
72. Clark, R.D., S.R. Lord, and I.W. Webster, *Clinical parameters associated with falls in an elderly population.* Gerontology, 1993. **39**(2): p. 117-23.
73. Owsley, C., R. Sekuler, and D. Siemsen, *Contrast sensitivity throughout adulthood.* Vision Research, 1983. **23**(7): p. 689-99.
74. Owsley, C., *Aging and vision.* Vision Research, 2011. **51**(13): p. 1610-22.
75. Lord, S.R., D. McLean, and G. Stathers, *Physiological factors associated with injurious falls in older people living in the community.* Gerontology, 1992. **38**(6): p. 338-46.
76. Lord, S.R. and J.A. Ward, *Age-associated differences in sensori-motor function and balance in community dwelling women.* Age and Ageing, 1994. **23**(6): p. 452-60.
77. Whiteside, M.M., M.I. Wallhagen, and E. Pettengill, *Sensory impairment in older adults: part 2: Vision loss.* American Journal of Nursing, 2006. **106**(11): p. 52-61; quiz 61-2.
78. Lord, S.R., *Visual risk factors for falls in older people.* Age and Ageing, 2006. **35 Suppl 2**: p. ii42-ii45.
79. Gilman, S., *Joint position sense and vibration sense: anatomical organisation and assessment.* Journal of Neurology, Neurosurgery and Psychiatry, 2002. **73**(5): p. 473-7.
80. Kandel, E.R., J.H. Schwartz, and T.M. Jessell, *Principles of neural science*. 4th ed. 2000, New York: McGraw-Hill, Health Professions Division. xli, 1414 p.
81. Gardner, E.P., J.H. Martin, and T.M. Jessell, *The bodily senses*, E.R. Kandel, J.H. Schwartz, and T.M. Jessell, Editors. 2000, New York: McGraw-Hill. p. 430-50.
82. Michigan Diabetes Research and Training Center, U.o.M.H.S. *How to use the Michigan Neuropathy Screening Instrument.* 2009; Available from: www.med.umich.edu/mdrtc/profs/documents/svi/MNSI_howto.pdf.
83. Bloom, S., et al., *Use of a biothesiometer to measure individual vibration thresholds and their variation in 519 non-diabetic subjects.* British Medical Journal (Clinical Research Edition), 1984. **288**(6433): p. 1793-5.
84. Young, M.J., et al., *The prediction of diabetic neuropathic foot ulceration using vibration perception thresholds. A prospective study.* Diabetes Care, 1994. **17**(6): p. 557-60.
85. Williams, G., et al., *Variability in vibration perception threshold among sites: a potential source of error in biothesiometry.* British Medical Journal (Clinical Research Edition), 1988. **296**(6617): p. 233-5.
86. Redd, C.B. and S.J. Bamberg, *A wireless sensory feedback system for real-time gait modification.* Conference Proceedings, Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2011. **2011**: p. 1507-10.
87. Lepley, A.S., P.A. Gribble, and B.G. Pietrosimone, *Effects of electromyographic biofeedback on quadriceps strength: a systematic review.* Journal of Strength and Conditioning Research, 2012. **26**(3): p. 873-82.
88. Jensen, M.P., et al., *Effects of self-hypnosis training and EMG biofeedback relaxation training on chronic pain in persons with spinal-cord injury.* International Journal of Clinical and Experimental Hypnosis, 2009. **57**(3): p. 239-68.
89. Bartlett, L., et al., *Biofeedback therapy for symptoms of bowel dysfunction following surgery for colorectal cancer.* Tech Coloproctol, 2011. **15**(3): p. 319-26.

90. Rupert, A.H., F.E. Guedry, and M.F. Reschke, *The use of tactile interfaces to convey position and motion perceptions.* Advisory Group for Aerospace Research and Development CP541 20 1, 1994: p. 20-75.
91. Rupert, A.H., et al, *Tactile interface to improve situation awareness*, in *Aerospace Medical Assoication*. 1996: Washington, DC.
92. Rupert, A.H., *An instrumentation solution for reducing spatial disorientation mishaps.* IEEE Engineering in Medicine and Biology Magazine, 2000. **19**(2): p. 71-80.
93. Jones, G.M. and L.R. Young, *Subjective detection of vertical acceleration: a velocity-dependent response?* Acta Oto-laryngologica, 1978. **85**(1-2): p. 45-53.
94. Benson, A.J., *Effect of spaceflight on thresholds of perception of angular and linear motion.* Arch Otorhinolaryngol, 1987. **244**(3): p. 147-54.
95. Jones, G.M. and J.H. Milsum, *Spatial and dynamic aspects of visual fixation.* IEEE Transactions on Bio-medical Engineering, 1965. **12**(2): p. 54-62.
96. De Vries, H., *The mechanics of the labyrinth otoliths.* Acta Otolaryngol, 1951. **38**(3): p. 262-73.
97. Sienko, K.H., et al., *Effects of multi-directional vibrotactile feedback on vestibular-deficient postural performance during continuous multi-directional support surface perturbations.* Journal of Vestibular Research, 2008. **18**(5-6): p. 273-85.
98. Basta, D., et al., *Efficacy of a vibrotactile neurofeedback training in stance and gait conditions for the treatment of balance deficits: a double-blind, placebo-controlled multicenter study.* Otology and Neurotology, 2011. **32**(9): p. 1492-9.
99. Basta, D. and A. Ernst, *[Vibrotactile neurofeedback training with the Vertiguard(R)-RT-system. A placebo-controlled double-blinded pilot study on vestibular rehabilitation].* HNO, 2011. **59**(10): p. 1005-11.
100. Allum, J.H. and A.L. Adkin, *Improvements in trunk sway observed for stance and gait tasks during recovery from an acute unilateral peripheral vestibular deficit.* Audiology and Neuro-Otology, 2003. **8**(5): p. 286-302.
101. Basta, D., et al., *Vestibular rehabilitation by auditory feedback in otolith disorders.* Gait and Posture, 2008. **28**(3): p. 397-404.
102. Allum, J.H., et al., *Trunk sway measures of postural stability during clinical balance tests: effects of a unilateral vestibular deficit.* Gait and Posture, 2001. **14**(3): p. 227-37.
103. Horlings, C.G., et al., *Trunk sway analysis to quantify the warm-up phenomenon in myotonia congenita patients.* Journal of Neurology, Neurosurgery and Psychiatry, 2009. **80**(2): p. 207-12.
104. Peterka, R.J., C. Wall, 3rd, and E. Kentala, *Determining the effectiveness of a vibrotactile balance prosthesis.* Journal of Vestibular Research, 2006. **16**(1-2): p. 45-56.
105. Goebel, J.A., et al., *Effectiveness of head-mounted vibrotactile stimulation in subjects with bilateral vestibular loss: a phase 1 clinical trial.* Otology and Neurotology, 2009. **30**(2): p. 210-6.
106. Lackner, J.R., et al., *Precision contact of the fingertip reduces postural sway of individuals with bilateral vestibular loss.* Experimental Brain Research, 1999. **126**(4): p. 459-66.
107. Goodworth, A.D., C. Wall, 3rd, and R.J. Peterka, *Influence of feedback parameters on performance of a vibrotactile balance prosthesis.* IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2009. **17**(4): p. 397-408.

108. Loughlin, P., A. Mahboobin, and J. Furman, *Designing vibrotactile balance feedback for desired body sway reductions.* Conference Proceedings, Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2011. **2011**: p. 1310-3.
109. Haggerty, S., et al., *Effects of biofeedback on secondary-task response time and postural stability in older adults.* Gait and Posture, 2012. **35**(4): p. 523-8.
110. Keshner, E.A., *Reevaluating the theoretical model underlying the neurodevelopmental theory. A literature review.* Physical Therapy, 1981. **61**(7): p. 1035-40.
111. Shumway-Cook, A. and M.H. Woollacott, *Motor control : theory and practical applications*. 2nd ed. 2001, Philadelphia: Lippincott Williams & Wilkins. x, 614 p.
112. Woollacott, M. and A. Shumway-Cook, *Attention and the control of posture and gait: a review of an emerging area of research.* Gait and Posture, 2002. **16**(1): p. 1-14.
113. Abernethy, B., *Dual-task methodology and motor skill research: some methodological constraints.* . Journal of human movement studies, 1988. **14**: p. 101-32.
114. Kerr, B., S.M. Condon, and L.A. McDonald, *Cognitive spatial processing and the regulation of posture.* Journal of Experimental Psychology: Human Perception and Performance, 1985. **11**(5): p. 617-22.
115. Maki, B.E. and W.E. McIlroy, *Influence of arousal and attention on the control of postural sway.* Journal of Vestibular Research, 1996. **6**(1): p. 53-9.
116. Akram, S.B. and J.S. Frank, *Cognitive demands of postural control during continuous rotational perturbations of the support surface.* Gait and Posture, 2009. **29**(1): p. 86-90.
117. Teasdale, N., et al., *On the cognitive penetrability of posture control.* Experimental Aging Research, 1993. **19**(1): p. 1-13.
118. Marsh, A.P. and S.E. Geel, *The effect of age on the attentional demands of postural control.* Gait and Posture, 2000. **12**(2): p. 105-13.
119. Lajoie, Y., et al., *Upright standing and gait: are there changes in attentional requirements related to normal aging?* Experimental Aging Research, 1996. **22**(2): p. 185-98.
120. Shumway-Cook, A. and M. Woollacott, *Attentional demands and postural control: the effect of sensory context.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 2000. **55**(1): p. M10-6.
121. Kahneman, D., *Attention and effort*. Prentice-Hall series in experimental psychology. 1973, Englewood Cliffs, N.J.,: Prentice-Hall. x, 246 p.
122. Broadbent, D.E., *Perception and communication*. 1958, New York,: Pergamon Press. 338 p.
123. Fraizer, E.V. and S. Mitra, *Methodological and interpretive issues in posture-cognition dual-tasking in upright stance.* Gait and Posture, 2008. **27**(2): p. 271-9.
124. Anderson, J.R., *Cognitive psychology and its implications / John R. Anderson*. 6th ed. 2005, New York: Worth Publishers. xv, 519 p.
125. Schneider, W. and R.M. Shiffrin, *Controlled and automatic human information processing. I. Detection, search and attention.* Psychological Review 1977. **84**: p. 1-66.
126. Shiffrin, R.M. and W. Schneider, *Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory.* Psychological Review, 1977. **84**: p. 127-190.
127. Stefanidis, D., et al., *Redefining simulator proficiency using automaticity theory.* American Journal of Surgery, 2007. **193**(4): p. 502-6.

128. Kuczynski, M., M. Szymanska, and E. Biec, *Dual-task effect on postural control in high-level competitive dancers.* Journal of Sports Sciences, 2011. **29**(5): p. 539-45.
129. Stins, J.F., et al., *Sway regularity reflects attentional involvement in postural control: effects of expertise, vision and cognition.* Gait and Posture, 2009. **30**(1): p. 106-9.
130. Uemura, K., et al., *Fear of falling is associated with prolonged anticipatory postural adjustment during gait initiation under dual-task conditions in older adults.* Gait and Posture, 2011.
131. Swanenburg, J., et al., *The reliability of postural balance measures in single and dual tasking in elderly fallers and non-fallers.* BMC Musculoskelet Disord, 2008. **9**: p. 162.
132. Nascimbeni, A., et al., *Dual task interference during gait in patients with unilateral vestibular disorders.* Journal of Neuroengineering Rehabilitation, 2010. **7**: p. 47.
133. Pellecchia, G.L., *Postural sway increases with attentional demands of concurrent cognitive task.* Gait and Posture, 2003. **18**(1): p. 29-34.
134. Prado, J.M., T.A. Stoffregen, and M. Duarte, *Postural sway during dual tasks in young and elderly adults.* Gerontology, 2007. **53**(5): p. 274-81.
135. Reilly, D.S., et al., *Interaction between the development of postural control and the executive function of attention.* J Mot Behav, 2008. **40**(2): p. 90-102.
136. Olivier, I., et al., *Age-related differences in cognitive and postural dual-task performance.* Gait and Posture, 2010. **32**(4): p. 494-9.
137. Dault, M.C., et al., *Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations.* Gait and Posture, 2001. **14**(3): p. 248-55.
138. Mahboobin, A., P.J. Loughlin, and M.S. Redfern, *A model-based approach to attention and sensory integration in postural control of older adults.* Neuroscience Letters, 2007. **429**(2-3): p. 147-51.
139. Kelly, V.E., A.A. Janke, and A. Shumway-Cook, *Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults.* Experimental Brain Research, 2010. **207**(1-2): p. 65-73.
140. Redfern, M.S., et al., *Attention influences sensory integration for postural control in older adults.* Gait and Posture, 2001. **14**(3): p. 211-6.
141. Le Clair, K. and C. Riach, *Postural stability measures: what to measure and for how long.* Clinical Biomechanics, 1996. **11**(3): p. 176-178.
142. Vogel, E.K., G.F. Woodman, and S.J. Luck, *Storage of features, conjunctions and objects in visual working memory.* Journal of Experimental Psychology: Human Perception and Performance, 2001. **27**(1): p. 92-114.
143. Stroop, J.R., *Studies of interference in serial verbal reactions. .* Journal of Experimental Psychology, 1935. **18**(6): p. 643-662.
144. Logan, G., R.J. Schachar, and R. Tannock, *Impulsivity and inhibition control.* Psychological Science, 1997. **8**(1): p. 60-64.
145. Yardley, L., et al., *Effect of articulatory and mental tasks on postural control.* Neuroreport, 1999. **10**(2): p. 215-9.
146. Redfern, M.S., et al., *Attentional dynamics in postural control during perturbations in young and older adults.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 2002. **57**(8): p. B298-303.

147. Hunter, M.C. and M.A. Hoffman, *Postural control: visual and cognitive manipulations.* Gait and Posture, 2001. **13**(1): p. 41-8.
148. Berger, L. and L. Bernard-Demanze, *Age-related effects of a memorizing spatial task in the adults and elderly postural control.* Gait and Posture, 2011. **33**(2): p. 300-2.
149. Brown, L.A., A. Shumway-Cook, and M.H. Woollacott, *Attentional demands and postural recovery: the effects of aging.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 1999. **54**(4): p. M165-71.
150. Rankin, J.K., et al., *Cognitive influence on postural stability: a neuromuscular analysis in young and older adults.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 2000. **55**(3): p. M112-9.
151. Maylor, E.A. and A.M. Wing, *Age differences in postural stability are increased by additional cognitive demands.* Journals of Gerontology. Series B, Psychological Sciences and Social Sciences, 1996. **51**(3): p. P143-54.
152. Ebersbach, G., M.R. Dimitrijevic, and W. Poewe, *Influence of concurrent tasks on gait: a dual-task approach.* Perceptual and Motor Skills, 1995. **81**(1): p. 107-13.
153. Chen, H.C., et al., *Stepping over obstacles: dividing attention impairs performance of old more than young adults.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 1996. **51**(3): p. M116-22.
154. Schrodt, L.A., et al., *Characteristics of stepping over an obstacle in community dwelling older adults under dual-task conditions.* Gait and Posture, 2004. **19**(3): p. 279-87.
155. Springer, S., et al., *Dual-tasking effects on gait variability: the role of aging, falls, and executive function.* Movement Disorders, 2006. **21**(7): p. 950-7.
156. Srygley, J.M., et al., *When does walking alter thinking? Age and task associated findings.* Brain Research, 2009. **1253**: p. 92-9.
157. Cho, C.Y., L. Gilchrist, and S. White, *A Comparison between young and old adults in their ability to rapidly sidestep during gait when attention is divided.* Gerontology, 2008. **54**(2): p. 120-7.
158. Dubost, V., et al., *Relationships between dual-task related changes in stride velocity and stride time variability in healthy older adults.* Hum Mov Sci, 2006. **25**(3): p. 372-82.
159. Brach, J.S., et al., *Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed.* J Neuroeng Rehabil, 2005. **2**: p. 21.
160. Doi, T., et al., *Brain Atrophy and Trunk Stability During Dual-Task Walking Among Older Adults.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 2011.
161. Yogev-Seligmann, G., J.M. Hausdorff, and N. Giladi, *The role of executive function and attention in gait.* Movement Disorders, 2008. **23**(3): p. 329-42; quiz 472.
162. Sheridan, P.L. and J.M. Hausdorff, *The role of higher-level cognitive function in gait: executive dysfunction contributes to fall risk in Alzheimer's disease.* Dementia and Geriatric Cognitive Disorders, 2007. **24**(2): p. 125-37.
163. Lezak, M.D., *Neuropsychological assessment.* 3rd ed. 1995, New York: Oxford University Press. xviii, 1026 p.
164. Goethals, I., et al., *The prefrontal cortex: insights from functional neuroimaging using cognitive activation tasks.* European Journal of Nuclear Medicine and Molecular Imaging, 2004. **31**(3): p. 408-16.

165. Stuss, D.T. and B. Levine, *Adult clinical neuropsychology: lessons from studies of the frontal lobes.* Annual Review of Psychology, 2002. **53**: p. 401-33.
166. Gill, T., A.W. Taylor, and A. Pengelly, *A population-based survey of factors relating to the prevalence of falls in older people.* Gerontology, 2005. **51**(5): p. 340-5.
167. Lundin-Olsson, L., L. Nyberg, and Y. Gustafson, *"Stops walking when talking" as a predictor of falls in elderly people.* Lancet, 1997. **349**(9052): p. 617.
168. Shumway-Cook, A., S. Brauer, and M. Woollacott, *Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test.* Physical Therapy, 2000. **80**(9): p. 896-903.
169. Faulkner, K.A., et al., *Multitasking: association between poorer performance and a history of recurrent falls.* Journal of the American Geriatrics Society, 2007. **55**(4): p. 570-6.
170. Beauchet, O., et al., *Dual task-related changes in gait performance in older adults: a new way of predicting recurrent falls?* Journal of the American Geriatrics Society, 2008. **56**(1): p. 181-2.
171. Stalenhoef, P.A., et al., *A risk model for the prediction of recurrent falls in community-dwelling elderly: a prospective cohort study.* Journal of Clinical Epidemiology, 2002. **55**(11): p. 1088-94.
172. Vaillant, J., et al., *[Prediction of falls with performance on Timed "Up-and-Go" and one-leg-balance tests and additional cognitive tasks].* Ann Readapt Med Phys, 2006. **49**(1): p. 1-7.
173. Beauchet, O., et al., *Stops walking when talking: a predictor of falls in older adults?* European Journal of Neurology, 2009. **16**(7): p. 786-95.
174. Brown, R.G. and C.D. Marsden, *Dual task performance and processing resources in normal subjects and patients with Parkinson's disease.* Brain, 1991. **114 (Pt 1A)**: p. 215-31.
175. Camicioli, R., et al., *Verbal fluency task affects gait in Parkinson's disease with motor freezing.* Journal of Geriatric Psychiatry and Neurology, 1998. **11**(4): p. 181-5.
176. Holmes, J.D., et al., *Dual-task interference: the effects of verbal cognitive tasks on upright postural stability in Parkinson's disease.* Parkinsons Dis, 2010. **2010**: p. 696492.
177. Dalrymple-Alford, J.C., et al., *A central executive deficit in patients with Parkinson's disease.* Journal of Neurology, Neurosurgery and Psychiatry, 1994. **57**(3): p. 360-7.
178. Bond, J.M. and M. Morris, *Goal-directed secondary motor tasks: their effects on gait in subjects with Parkinson disease.* Archives of Physical Medicine and Rehabilitation, 2000. **81**(1): p. 110-6.
179. Morris, M., et al., *Postural instability in Parkinson's disease: a comparison with and without a concurrent task.* Gait and Posture, 2000. **12**(3): p. 205-16.
180. Ashburn, A., et al., *A community-dwelling sample of people with Parkinson's disease: characteristics of fallers and non-fallers.* Age and Ageing, 2001. **30**(1): p. 47-52.
181. Bloem, B.R., et al., *The multiple tasks test. Strategies in Parkinson's disease.* Experimental Brain Research, 2001. **137**(3-4): p. 478-86.
182. O'Shea, S., M.E. Morris, and R. Iansek, *Dual task interference during gait in people with Parkinson disease: effects of motor versus cognitive secondary tasks.* Physical Therapy, 2002. **82**(9): p. 888-97.

183. Hausdorff, J.M., J. Balash, and N. Giladi, *Effects of cognitive challenge on gait variability in patients with Parkinson's disease.* Journal of Geriatric Psychiatry and Neurology, 2003. **16**(1): p. 53-8.
184. Rochester, L., et al., *Attending to the task: interference effects of functional tasks on walking in Parkinson's disease and the roles of cognition, depression, fatigue, and balance.* Archives of Physical Medicine and Rehabilitation, 2004. **85**(10): p. 1578-85.
185. Bloem, B.R., et al., *The Multiple Tasks Test: development and normal strategies.* Gait and Posture, 2001. **14**(3): p. 191-202.
186. Bloem, B.R., et al., *The "posture second" strategy: a review of wrong priorities in Parkinson's disease.* Journal of the Neurological Sciences, 2006. **248**(1-2): p. 196-204.
187. Plotnik, M., et al., *Postural instability and fall risk in Parkinson's disease: impaired dual tasking, pacing, and bilateral coordination of gait during the "ON" medication state.* Experimental Brain Research, 2011. **210**(3-4): p. 529-38.
188. McKhann, G., et al., *Clinical diagnosis of Alzheimer's disease: report of the NINCDS-ADRDA Work Group under the auspices of Department of Health and Human Services Task Force on Alzheimer's Disease.* Neurology, 1984. **34**(7): p. 939-44.
189. Scarmeas, N., et al., *Motor signs during the course of Alzheimer disease.* Neurology, 2004. **63**(6): p. 975-82.
190. Manckoundia, P., et al., *Impact of cognitive task on the posture of elderly subjects with Alzheimer's disease compared to healthy elderly subjects.* Movement Disorders, 2006. **21**(2): p. 236-41.
191. Camicioli, R., et al., *Talking while walking: the effect of a dual task in aging and Alzheimer's disease.* Neurology, 1997. **48**(4): p. 955-8.
192. Herdman, S.J., et al., *Falls in patients with vestibular deficits.* American Journal of Otology, 2000. **21**(6): p. 847-51.
193. Hanes, D.A. and G. McCollum, *Cognitive-vestibular interactions: a review of patient difficulties and possible mechanisms.* Journal of Vestibular Research, 2006. **16**(3): p. 75-91.
194. Yardley, L., et al., *Neuro-otological and psychiatric abnormalities in a community sample of people with dizziness: a blind, controlled investigation.* Journal of Neurology, Neurosurgery and Psychiatry, 1998. **65**(5): p. 679-84.
195. Godemann, F., et al., *A prospective study on the course of anxiety after vestibular neuronitis.* Journal of Psychosomatic Research, 2004. **56**(3): p. 351-4.
196. Smith, P.F., et al., *Does vestibular damage cause cognitive dysfunction in humans?* Journal of Vestibular Research, 2005. **15**(1): p. 1-9.
197. Nascimbeni, A., et al., *Dual task interference during gait in patients with unilateral vestibular disorders.* Journal of Neuroengineering Rehabilitation, 2010. **7**: p. 47.
198. Roberts, J.C., H.S. Cohen, and H. Sangi-Haghpeykar, *Vestibular disorders and dual task performance: impairment when walking a straight path.* Journal of Vestibular Research, 2011. **21**(3): p. 167-74.
199. Mohammad, M.T., et al., *Perceptual and motor inhibition in individuals with vestibular disorders.* Journal of Neurologic Physical Therapy, 2010. **34**(2): p. 76-81.
200. Silsupadol, P., et al., *Effects of single-task versus dual-task training on balance performance in older adults: a double-blind, randomized controlled trial.* Archives of Physical Medicine and Rehabilitation, 2009. **90**(3): p. 381-7.

201. Silsupadol, P., et al., *Training-related changes in dual-task walking performance of elderly persons with balance impairment: a double-blind, randomized controlled trial.* Gait and Posture, 2009. **29**(4): p. 634-9.

202. Li, K.Z., et al., *Benefits of cognitive dual-task training on balance performance in healthy older adults.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 2010. **65**(12): p. 1344-52.

203. Hiyamizu, M., et al., *Effects of dual task balance training on dual task performance in elderly people: a randomized controlled trial.* Clinical Rehabilitation, 2012. **26**(1): p. 58-67.

204. Wilk, C.M., et al., *Test-retest stability of the Repeatable Battery for the Assessment of Neuropsychological Status in schizophrenia.* American Journal of Psychiatry, 2002. **159**(5): p. 838-44.

205. Whitney, S.L., et al., *The sensitivity and specificity of the Timed "Up & Go" and the Dynamic Gait Index for self-reported falls in persons with vestibular disorders.* Journal of Vestibular Research, 2004. **14**(5): p. 397-409.

206. Wrisley, D.M., et al., *Reliability, internal consistency, and validity of data obtained with the functional gait assessment.* Physical Therapy, 2004. **84**(10): p. 906-18.

207. Bell-Krotoski, J.A., et al., *Threshold detection and Semmes-Weinstein monofilaments.* Journal of Hand Therapy, 1995. **8**(2): p. 155-62.

208. Talbot, W.H., et al., *The sense of flutter-vibration: comparison of the human capacity with response patterns of mechanoreceptive afferents from the monkey hand.* Journal of Neurophysiology, 1968. **31**(2): p. 301-34.

209. Mountcastle, V.B., R.H. LaMotte, and G. Carli, *Detection thresholds for stimuli in humans and monkeys: comparison with threshold events in mechanoreceptive afferent nerve fibers innervating the monkey hand.* Journal of Neurophysiology, 1972. **35**(1): p. 122-36.

210. Schmidt, R.A., *A schema theory of discrete motor skill learning.* Psychol Rev 1975. **82**: p. 225-60.

211. Lee, B.C., et al., *Cell phone based balance trainer.* J Neuroeng Rehabil, 2012. **9**: p. 10.

212. Bechly, K.E., et al., *Determining the preferred modality for real-time biofeedback during balance training.* Gait and Posture, 2013. **37**(3): p. 391-6.

213. Sienko, K.H., M.D. Balkwill, and C. Wall, 3rd, *Biofeedback improves postural control recovery from multi-axis discrete perturbations.* J Neuroeng Rehabil, 2012. **9**: p. 53.

214. Carroll, J.P. and W. Freedman, *Nonstationary properties of postural sway.* Journal of Biomechanics, 1993. **26**(4-5): p. 409-16.

215. O'Connor, K.W., et al., *Postural adaptations to repeated optic flow stimulation in older adults.* Gait and Posture, 2008. **28**(3): p. 385-91.

216. Huang, M.H. and S.H. Brown, *Age differences in the control of postural stability during reaching tasks.* Gait and Posture, 2013. **38**(4): p. 837-42.

217. Woollacott, M.H. and A. Shumway-Cook, *Changes in posture control across the life span--a systems approach.* Physical Therapy, 1990. **70**(12): p. 799-807.

218. Shumway-Cook, A., et al., *The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls.* Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 1997. **52**(4): p. M232-40.

219. Lajoie, Y., et al., *Attentional demands for static and dynamic equilibrium.* Experimental Brain Research, 1993. **97**(1): p. 139-44.

220. Pashler, H.E., *Attention*. Studies in cognition series. 1998, Hove, East Sussex, UK: Psychology Press. viii, 407 p.