Journal of Vestibular Research 27 (2017) 63–76
DOI:10.3233/VES-170606
IOS Press

The role of sensory augmentation for people with vestibular deficits: Real-time balance aid and/or rehabilitation device?

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Received 28 April 2016
Accepted 28 November 2016

Abstract. This narrative review highlights findings from the sensory augmentation field for people with vestibular deficits and addresses the outstanding questions that are critical to the translation of this technology into clinical and/or personal use. Prior research has demonstrated that the real-time use of visual, vibrotactile, auditory, and multimodal sensory augmentation technologies can improve balance during static and dynamic stance tasks within a laboratory setting. However, its application in improving gait requires additional investigation, as does its efficacy as a rehabilitation device for people with vestibular deficits. In some locomotor studies involving sensory augmentation, gait velocity decreased and secondary task performance worsened, and subjects negatively altered their segmental control strategies when cues were provided following short training sessions. A further question is whether the retention and/or carry-over effects of training with a sensory augmentation technology exceed the retention and/or carry-over effects of training alone, thereby supporting its use as a rehabilitation device. Preliminary results suggest that there are short-term improvements in balance performance following a small number of training sessions with a sensory augmentation device. Long-term clinical and home-based controlled training studies are needed. It is hypothesized that sensory augmentation provides people with vestibular deficits with additional sensory input to promote central compensation during a specific exercise/activity; however, research is needed to substantiate this theory. Major obstacles standing in the way of its use for these critical applications include determining exercise/activity specific feedback parameters and dosage strategies. This paper summarizes the reported findings that support sensory augmentation as a balance aid and rehabilitation device, but does not critically examine efficacy or the quality of the research methods used in the reviewed studies.

Keywords: Sensory augmentation, sensory substitution, feedback, biofeedback, vibrotactile, balance, gait, vestibular

1. Vestibular disorders

Vestibular and balance disorders are burdensome to society, limiting participation in work [72], exercise [64], driving [23] and social contexts, as well as resulting in increased health care costs [2, 73]. Vestibular disorders are primarily characterized by vertigo, dizziness, visual complaints, or unsteadiness [16], which often lead to secondary physical and psychological impairments [69]. A recent initiative by the Classification Committee of the Barany

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ISSN 0957-4271/17/$35.00

Society (CCBS) recommended that the International Classification of Vestibular Disorders (ICVD) be organized into four layers: (1) symptoms and signs, (2) syndromes, (3) disorders and diseases, and (4) mechanisms, in order to accommodate the breadth of clinical and research applications [16]. A few examples of specific types of vestibular disorders include: vestibular neuritis, bilateral vestibulopathy – distinguished by lack of vertigo but presence of notable imbalance, and central vestibular dysfunction resulting in gait ataxia [30].

Data collected from the National Health Interview Survey, USA found that 19.6% of 37 million older adults surveyed reported an issue with balance or dizziness during the past year [64]. The National Health and Nutrition Examination Survey (NHANEA) concluded that 35% of US adults age 40 years and older demonstrated evidence of balance dysfunction and patients who were clinically symptomatic had a 12-fold increase in the odds of falling [1]. Approximately 8 million American adults report chronic problems (lasting three months or longer) with balance, and the cost of medical care for patients with balance disorders exceeds $1 billion per year [74].

People with vestibular disorders often experience balance and gait deficits [1, 36, 67, 100]. Persons with bilateral vestibular loss report much higher fall rates than control subjects and those with unilateral peripheral loss [39]. Walking with head movements appears to be particularly difficult for persons with vestibular deficits. Persons with mixed vestibular loss appear to report more falls while walking with head movements in the pitch plane versus yaw plane [99], yet others have reported no difference in gait speed during walking with pitch and yaw head movements [81]. Gait speed has been reported to be slower in persons with either peripheral or central vestibular loss compared to control subjects [67, 81]. Walking backwards was slower than walking while performing a cognitive task consisting of counting backwards by 7 s from 100 in persons with vestibular disorders [81].

Falling [1] and fear of falling [89] can both result from having a balance/vestibular disorder. Wrist and hip fractures have been related to vestibular hypofunction in a subset of persons presenting to the emergency room [28, 48, 49], suggesting that vestibular disorders and fall events may be related. Staab has suggested that persons with fear of falling may become more unstable during gait because of diverting their gaze as a result of their anxiety [89]. Heights and surroundings that are visually provocative such as grocery stores and train stations can cause an increase in dizziness and provoke imbalance in a certain subset of persons with vestibular disorders [17, 18, 42, 80]. Persons with vestibular disorders become more rigid compared to control subjects when exposed to heights, suggesting that they may have different attentional demands and be threatened by heights [109]. Others have suggested that persons who are fearful of heights when viewing a visual cliff move their head less spontaneously and suppress eye movements [50].

Vestibular disorders have been shown to impact mood by increasing rates of anxiety and depression and reducing overall health related quality of life (HRQOL) [107]. People with vestibular disorders tend to restrict movement and exercise thereby limiting vestibular compensation and prolonging overall recovery [108]. Symptoms related to vestibular disorders are often debilitating, can lead to decreased independence in activities of daily living (ADL) [70], and increase the likelihood of falls [1].

With the increased incidence of falls and fear of falling in a subset of persons with vestibular disorders [39], physical assistance through the use of a balance aid may provide adequate support to enable people to continue to participate in their daily life roles. Balance aids include assistive devices such as canes, walking poles and walkers which help with postural stability [71] but also provide a physical sign to the community that the person has a disability. For the persons with bilateral loss, an assistive device is less effective in preventing falls in low-lit conditions due to decreased visual inputs and oscillopsia.

A substitute for vestibular information in persons with bilateral vestibular loss is needed [61] and sensory augmentation has potential to fulfill this need.

2. Sensory augmentation/sensory substitution/biofeedback/feedback

The vestibular system of the inner ear provides the central nervous system (CNS) with information about angular velocity in three dimensions. Similarly, it provides the CNS with information about linear acceleration and gravity. The CNS, in turn, processes this information to estimate the orientation of a person in space and to estimate how far he/she is tilted away from gravity vertical. The latter estimate helps people to remain upright while standing and walking. Falls may occur if the person cannot sense how far he/she is tilted away from the vertical, or if he/she lacks muscle control that contributes to balance reactions necessary to maintain stable posture and locomotion. Thus, a sufficiently sensitive and accurate estimate of body tilt is necessary for walking and standing. When the vestibular system is compromised for example by injury, disease, or ototoxic drugs the CNS may not be able to give reliable tilt estimates. An alternative is to use an electronic tilt sensor attached to the body and connected to a microprocessor to provide a real-time body tilt estimate, then to display the estimate using another sensory channel.

Sensory substitution can be defined as the delivery of sensory information from one sense through an alternate sensory channel using a translation device. The concept is attributed to Paul Bach-y-Rita who used it first in the 1960's [7]. A classic example is the display of visual information (e.g., a letter of the alphabet) with an array of vibrotactile elements placed on the skin of a blind subject [7]. Thus, somato-sensation serves as a substitute for vision. In the example above, the translation device could be a video camera trained on a letter of the alphabet. The video output is then sampled at a spatial frequency that corresponds to the number of elements in the vibrotactile elements in the array. Samples that are dark would activate the corresponding element in the array, while samples that are light would not activate their corresponding elements. The term sensory augmentation is somewhat similar to sensory substitution except it implies that the alternate pathway does not necessarily completely replace the missing sense, since that sense may not be completely absent.

A sensory augmentation device typically uses inertial measurement units or pressure sensors and an appropriate feedback display to provide cues of body motion that supplement an individual's intact sensory inputs. Visual feedback displays are the most common means of conveying knowledge of performance; however, there are practical considerations that must be taken into account for certain populations, such as persons with vestibular deficits and older adults who rely heavily on the visual system. Visual motion can produce postural responses that may supersede proprioceptive and vestibular inputs, thereby disrupting postural stability especially in persons with visually induced dizziness [19]. Persons with phobic postural vertigo (a form of visually induced dizziness) when walking with eyes closed had worsening of their gait compared to controls, suggesting that persons with phobic postural vertigo may have greater reliance on vision while ambulating [82].

Unimodal and multimodal feedback displays including vibrotactile [86, 93], electric currents applied to the tongue [5, 6], auditory [26, 27, 38], and combinations of visual, vibrotactile, and auditory cues [24, 41] offer varying degrees of non-invasive self-motion cues. Depending on the application (e.g., continuous use as a real-time balance aid, periodic rehabilitative use), some display modalities present practical difficulties. While visual feedback devices offer some of the best outcomes during certain tasks, they may not suitable for activities that involve head movements or closed eyes. Auditory displays can be problematic for the many people with vestibular loss who also have hearing problems. Technologies using head-based motion sensors may result in the "locking" of head motion to trunk motion rather than allowing the two to be decoupled as occurs during normal postural control; a primary goal of balance therapy, however, is to increase the ability of a patient to make asymptomatic head movements and increase their degrees of freedom. Torso-based vibrotactile displays, which offer less spatial resolution than visual, auditory, and electric lingual displays and require longer reaction times than head-mounted displays [4, 11] don't directly compete with tasks that involve speaking, hearing, or seeing.

3. Stance

Results from the literature have shown that vibrotactile feedback of body motion reduces the number of falls in people with severe vestibular hypofunction during standard clinical tests when there were no applied external perturbations. Using a body mounted vibrotactile display, Wall and Kentala demonstrated a significant reduction of falls during sensory organization tests (SOT) conditions 5 and 6 from 50% to 15% in eight persons with unilateral or bilateral vestibular diagnoses who had severe deficits as defined by their computerized dynamic posturography (CDP) scores [93]. The SOT 5 is designed to make somatosensory information unreliable while subjects stand with their eyes closed. The SOT 6 is designed to make both somatosensory and visual information unreliable. A second group of subjects with mild to moderate vestibular deficits did not fall as frequently as the severe group, and the number of their falls did not change significantly when they used feedback. Using a head mounted vibrotactile display

Goebel et al. showed a similar significant reduction in the number of falls during SOT conditions 5 and 6 in five persons with severe bilateral vestibular loss [32].

The effect of vibrotactile feedback on postural control has also been investigated using externally applied perturbations. Six subjects with vestibulopathies were tested during conditions that induced a mild two-axis random platform motion. Only anterior-posterior (A/P) tilt feedback was provided. Diffusion analysis showed that the vibrotactile feedback of body tilt allowed the subjects to control posture more quickly than without feedback. There was also a significant decrease for all subjects for A/P sway with A/P tilt displayed. The change in medial-lateral (M/L) sway was not significant. This is evidence of direction-specific control [96]. Further studies using pseudorandom sequences showed that vibrotactile feedback is most effective in the 0.02 Hz–0.3 Hz range [33]. Loughlin et al. have used feedback control theory to suggest that a "one size fits all" approach to providing the vibrotactile stimulus to the subject needs to be replaced with an approach that is customized to the individual [65]. This study also suggests that this approach is likely to increase the effective bandwidth of the response.

Vibrotactile feedback also promotes faster recovery from discrete surface perturbations. In one study, Wall and Kentala applied perturbations in the A/P direction using the CDP motor control tests [93]. The results were mixed, and depended upon whether the response pattern was monotonic or oscillatory. There was a tendency for the peak tilt and the time to recover to decrease with vibrotactile feedback. Sienko et al. used multidirectional discrete perturbations to characterize recovery trajectories of subjects with vestibulopathies [88]. The initial trajectory with and without feedback was ballistic and did not vary based on the presence of feedback. Vibrotactile feedback significantly decreased the recovery response times and decreased postural sway following recovery from the perturbations. The spatial resolution of the vibrotactile display was systematically varied from 90° to 22.5°. There was no significant effect on the responses due to the change of spatial resolution. Asseman et al. (2007) investigated the use of vibrotactile feedback during large backward support surface perturbations that elicit step responses in young and older adults and people with either bilateral vestibular deficits or peripheral neuropathies [4]. Only the older adults who exhibited slower stepping times during baseline trials showed significantly shorter stepping reaction times with versus without the vibrotactile cue. Lee et al. (2013) performed a similar study to examine the effects of vibrotactile feedback on the stepping responses of people with Parkinson's disease (PD) and age-matched controls [59]. The presence of vibrotactile cues did not affect the timing or the length of the steps, but it reduced trunk displacements prior to step initiation. These collective findings suggest that feedback is effective in reducing sway during normal stance and during recovery from perturbations, but not during the ballistic phase of a perturbation.

The visual system provides the CNS with information about the direction of vertical and its inputs are used in combination with inputs from the vestibular and somatosensory systems to maintain balance. Persons with vestibular loss can be expected to have increased reliance on the visual and somatosensory systems for spatial orientation; in an eyes closed condition, they have been found to heavily rely on somatosensory inputs [76]. Persons with bilateral peripheral vestibular loss have demonstrated the ability to significantly reduce pelvis roll and pitch angle sway while receiving vibrotactile and auditory feedback when standing on foam with eyes closed, however they did not demonstrate significant decreases in pelvis pitch angle sway when performing the same task with their eyes open [40]. Persons with peripheral vestibular involvement were able to use visual, vibrotactile and multimodal feedback (all conditions performed with eyes open) to improve postural sway metrics over baseline values during tandem Romberg stance; the best performance was achieved with continuous visual feedback, but some subjects reported dizziness when using it [14]. Subjects with vestibular loss used a smart phone balance trainer providing vibrotactile cues to improve several postural sway metrics during semi-tandem Romberg stance trials regardless of whether their eyes were open or closed; performance was slightly better during the feedback trials with eyes open [54]. Use of multimodal feedback (vibrotactile and auditory) during tandem stance trials with either eyes open or closed resulted in significant reduction in trunk sway in older adults [24].

4. Gait

While fall-related injuries can occur from loss of balance during either standing or walking, the latter accounts for the majority of cases and has proven significantly more difficult to address due to its greater complexity. A main challenge of treating locomotor imbalance is that its negative effects manifest themselves in a number of different gait characteristics, including gait initiation, gait velocity, step length, step width, toe clearance, continuity, symmetry, trunk sway, path adherence, and ability to turn. Although significant progress has been achieved in developing sensory augmentation methods to improve standing balance, attempts to extend this research to locomotion have been quite limited in scope due to a lack of mechanistic knowledge and supporting science regarding which biomechanical signals to measure, how to process them, and how to provide meaningful feedback signals to the user. While the sensory systems providing input to the CNS presumably operate by the same principles during standing and walking, little correlation exists between the metrics and tasks used to assess stability during standing (which has greatest instability in the sagittal plane) and those used to assess stability during walking (which has greatest instability in the frontal plane). For example, a relatively simple measure such as trunk tilt angle might be used as a feedback signal to improve balance during standing, yet effective measures during walking (which likely involve the dynamics of a number of body segments) require additional investigation. Because of this, the majority of gait-based studies have simply asked users to walk in step with an auditory or visual cadence, or have provided vibrotactile stimulation of a single body segment or joint to warn of extension beyond a desired angle.

Limited studies have been conducted to assess the capability of sensory augmentation to improve stability during locomotor tasks for people with vestibular deficits. Among the studies conducted to date, the types of locomotor tasks performed have varied considerably. Horak et al. showed that vibrotactile feedback of M/L trunk tilt reduces M/L trunk tilt in people with unilateral vestibular loss during paced heel-to-toe walking [27]. Hegeman et al. tested six compensated bilateral vestibular loss subjects and found that auditory feedback was not effective in reducing sway during various gait tasks [38]. Sienko et al. demonstrated that use of roll tilt vibrotactile feedback by subjects with compensated vestibular loss resulted in a significant decrease in roll sway solely in challenging locomotor tasks (i.e., narrow stance-walking) [87]. Janssen et al. studied the effects of multimodal head-mounted feedback on trunk motion in young adults during various locomotor activities and found that feedback significantly reduced trunk sway velocities regardless of whether feedback was provided in the A/P or M/L directions [43]. They observed greater reductions in pitch angle with A/P vs. M/L feedback when subjects climbed up and down stairs and walked over barriers, and similar reductions in pitch angle during normal and tandem walking for both feedback directions. Several vibrotactile augmented locomotor-based studies have been performed among the general aging population demonstrating improvements in clinical metrics or gait parameters. For example, Wall et al. showed that older adults could significantly increase their Dynamic Gait Index scores while using vibrotactile feedback [95]. Verhoeff et al. provided multimodal feedback to young and older adults that reduced A/P and M/L tilt and A/P tilt velocity during normal walking [92]. Shull et al. provided vibrotactile cues during walking to reduce knee adduction moments in people with knee osteoarthritis [84].

Two potentially negative side effects have emerged when subjects use sensory augmentation cues following limited training; subjects decrease their gait velocity and move in more of an "en bloc" manner. Janssen et al. (2009) displayed multimodal cues of trunk sway on the heads of young healthy subjects during several gait tasks. The subjects' trunk velocities decreased in both the A/P and M/L directions for all but one task (tandem steps). Trial duration, i.e., gait velocity, significantly increased when cues were provided [43]. The authors note that in addition to the short training period, subjects were only asked to focus on reducing their sway, not maintaining their gait velocity. Sienko et al. (2012) reported a slight increase in gait velocity in approximately half of the trials when people with vestibular deficits used vibrotactile sensory augmentation during various gait tasks [88]. In this study, subjects were observed to walk less naturally, altering their segmental control strategy likely to prevent themselves from moving beyond the feedback activation thresholds.

5. Dual tasking

One of the main concerns about providing feedback during gait is whether a person can process the external input (visual, auditory or proprioceptive) provided by a sensory augmentation device and concurrently ambulate safely while potentially performing an additional task (e.g., talking on the phone, using a map). Providing feedback during gait in young and older adults while performing a secondary task has been studied [92]. Subjects were asked to walk, walk while verbally counting backwards, and walk while carrying cups of water on a tray. The younger subjects reduced their trunk sway during the feedback trials. Older adults had less sway during the tray-carrying task but not during the counting and walking task, however they did improve on the cognitive task while receiving the feedback [92].

Greater attentional resources were required when performing a dual task during standing in both older and younger persons although it appears that older adults utilized greater attentional resources than the younger subjects [62]. Similar findings were observed in a study involving people with unilateral vestibular loss; the use of vibrotactile feedback significantly reduced reaction time performance in people with unilateral loss and age-matched controls, but people with unilateral vestibular loss had slower reaction times compared to controls [63]. Others have also demonstrated increased auditory choice reaction times in older adults during trials with vibrotactile feedback compared to the trials without feedback [35]. Even though their choice reaction times increased (worsened), their RMS trunk tilt decreased (improved). In another study involving older adults, sub-threshold vibrotactile stimulation applied to the sole of the foot during a dual task did not adversely affect the older adults' postural control [25].

6. Training/retention/carry-over effects

Only a limited number of mostly uncontrolled studies or laboratory based studies with limited number of training sessions have examined the use of sensory augmentation devices for improving rehabilitation outcomes; sensory augmentation devices have rarely been evaluated outside of the laboratory setting. Decreases in body sway over short periods of time (hours to days) have been observed in people with vestibular deficits after using a vibrotactile sensory augmentation device during a small number of sessions (two sessions, three hours each) [86]. Barros et al. demonstrated significant improvement in SOT CDP testing after two 15-min training sessions with electrotactile tongue feedback every other day for six days (total of 12 sessions); however, the study was uncontrolled and balance improvement was lost soon after training ended [12]. Polat et al. reported improved composite SOT scores for subjects undergoing a regimen combining static and dynamic training positions with electrotactile tongue feedback during ten 20-minute sessions over five days, compared to a control group which participated in an eight-week course of staged traditional vestibular rehabilitation and a loosely controlled home exercise program [77]. However, the measured improvements were not retained for more than a few days. Allum et al. used multimodal feedback to significantly reduce trunk angular displacement during real-time use and over short periods of time ($\sim$1 week) following training (three times per week for two weeks) in older adults and people with unilateral vestibular loss [3]. Basta et al. (2011) significantly reduced trunk and ankle sway as well as subjective symptom scores following short training (daily for two weeks) sessions involving a wide range of people with balance disorders including people with vestibular impairments [13]. Brugnera et al. (2015) showed significant improvements in SOT 5 and 6, the Activities-specific Balance Confidence (ABC) Scale, and the functional aspect of the Dizziness Handicap Inventory (DHI) following balance training (5 times per week for two weeks) with vibrotactile feedback in seven participants with vestibular deficits (with substandard responses to conventional vestibular rehabilitation); these changes were not observed for the six control group participants who did not receive feedback during training [20]. Only one published case study has examined usage over a large number of sessions; this study however, involved a single subject who performed 40 sessions with electrotactile tongue feedback and demonstrated balance improvements that persisted for eight weeks after the final session [5].

Technologies such as the Wii Fit and Kinect systems, which provide visual cues, have been used as an adjunct to vestibular rehabilitation and have led to decreased postural sway after six weeks of participation in healthy older adults [91]. In a pilot study by Wang et al., persons with vestibular dysfunction demonstrated decreased postural sway and improved balance function after completing 20 sessions of virtual reality enhanced vestibular rehabilitation within a 4-week period [97]. A preliminary torso-based vibrotactile sensory augmentation 6-week training study involving people with vestibular deficits suggests maintenance of improved balance performance as indicated by SOT composite scores, Mini-BESTest scores, and gait speed one month following training [10]. Exercise interventions for fall prevention require more than 10 weeks of progressively challenging balance exercises with an ongoing home program to maintain the benefits [21, 95]. For example, a recent review of balance training literature with community dwelling older adults concluded that a training period of 11–12 weeks with 36–40 sessions at 31–45 min/session is most effective for improving balance performance outcomes [60]. Furthermore, two studies have examined the negative effects of "detraining" occurring 6 to 12 weeks following documented improvement in static/dynamic balance measures and recommend ongoing balance programs, especially to negate age-related declines [79, 90].

A major barrier to performing long-term training studies is subjects' unwillingness and/or inability to travel to a clinical or research setting for a large number of sessions. Lee et al. (2012) recently described a smart phone balance trainer that can provide vibrotactile sensory augmentation along a single axis (Lee, Kim et al. 2012). An updated version of this technology provides vibrotactile feedback in both the A/P and M/L directions and includes multimodal instructions for balance exercises including icons depicting the conditions, minimal written text and videos [22, 58].

7. Mechanism

The mechanism by which information is integrated and used by the CNS is not well understood. The dominant hypothesis, which has not been supported by rigorous experimental evidence, holds that observed balance improvements are due to sensory reweighting: feedback of body motion provides the CNS with a correlate to the inputs from its intact sensory channels (e.g., vision, proprioception), so subjects receiving sensory augmentation learn to increasingly depend on these intact systems. Other possible mechanisms for observed improvement that merit further exploration include, but are not limited to: cognition (processing of sensory augmentation information is solely cognitive with no selective adjustment of sensory weights by the CNS), "sixth" sense (CNS interprets sensory augmentation information as a new and distinct sensory channel), context-specific adaptation (new sensorimotor program is developed through repeated interaction with the device and is accessible only when the device is used), and combined volitional and non-volitional response [53, 55–57, 68].

Honegger et al. investigated movement strategies and muscle synergies when subjects with bilateral vestibular loss were provided with mulitmodal feedback regarding pelvic sway angle during static balance activities. Feedback reduced amplitudes of EMG activity ratios from pairs of antagonistic muscles on the lower leg, trunk and upper arm. However, subjects with bilateral vestibular loss used the same movement strategies as healthy controls [40].

Multiple mathematical models have been developed to describe how sensory augmentation may affect postural control. For example, Goodworth et al. (2009) created a single-inverted pendulum model that incorporated the information provided by a torso-based vibrotactile sensory augmentation device with native intact sensory inputs, relatively upstream in the perceiving, processing, and responding pathway [33]. Ersal and Sienko (2013) developed a multibody model that incorporated information provided by a torso-based vibrotactile sensory augmentation device further downstream, preceding the generation of joint torques [29]. Both of these models were effective in capturing the kinematics of people with vestibular deficits using sensory augmentation. Goodworth et al. (2011) also described a time-delayed sensory feedback control model that effectively represented the motion of people with severe vestibular loss using sensory augmentation during perturbed stance and predicted that postural performance could be further improved by altering the feedback parameters [34].

Researchers have debated whether the reductions in postural sway observed when sensory augmentation is provided are the results of the use of the information conveyed or the effects of stimulation alone. Some hypothesize that stimulation alone – devoid of meaningful information – can serve as an alert mechanism to shift one's attention to the balance task or possibly elicit a general stiffening behavior. In a study involving a group of people with vestibular loss, Sienko et al. (2008) provided erroneous information during continuous multidirectional surface perturbations and demonstrated that people performed worse than when meaningful cues were provided [86]. During discrete perturbations, people also performed worse when erroneous feedback was provided compared to the feedback off condition suggesting that people are actively using the information to make postural corrections [88]. It should be noted however, that in the presence of erroneous information, people will not continue to use the information if it results in poorer performance (i.e., causes them to take a step or fall) or if the information is noticeably conflicting with information from intact sensory systems (e.g., somatosensory). Therefore it is important to introduce sham conditions at the end of data collection sessions, because subjects will not trust the information from the device after they've concluded that it isn't representative of their motion. Janssen et al. (2009) points out that training in and of itself has an effect on performance and not all gains in performance should be attributable to sensory augmentation [44]. It is also not unreasonable to think that people receiving cues interpret the cues as instructions to limit their sway and therefore limit their sway in the presence of any cues (meaningful or not). Wildenberg et al. (2010) showed that stimulation that doesn't convey information about body posture or gravity can improve balance performance in people with balance dysfunction [102]. They've also investigated the effects of electrotactile tongue stimulation on balance performance and have used imaging techniques such as MRI and fMRI to show that stimulation upregulates visual sensitivity to optic flow in people with balance impairments [102–105].

8. Sensory augmentation technology design considerations

Numerous studies have investigated the roles of various feedback display design-related factors on balance performance. Proportional plus derivative feedback has been shown to be significantly better than proportional or derivative feedback alone in a vestibular population during CDP [94]. In a study investigating the effect of feedback modality on balance performance during standing tasks, subjects with vestibular loss performed better while using visual feedback, which provided information about current and future positions, compared to vibrotactile feedback based on a proportional control signal presented on the torso [14]. Continuous vibrotactile feedback produced slightly better results than periodic feedback during locomotor tasks in people with vestibular loss [87]. Displays positioned on the torso [54, 86, 96] or head [3, 32] have yielded positive results during real-time use in people with vestibular deficits. However, faster reaction times have been observed when vibrotactile stimuli are applied to the head versus the torso [11] or sternum [4]. Both attractive ("move toward the vibration") and repulsive ("move away from the vibration") cuing strategies are effective, but repulsive cues yield slightly better results during short-term usage, while the rate of improvement is greater for attractive versus repulsive cuing [46].

9. Potential applications

9.1. Real-time aid

9.1.1. Concept

Sensory augmentation provides nearly instantaneous information about body motion and therefore, in theory, could serve as a real-time balance aid. The extrinsic feedback provides the user with information about the quality or nature of the movement pattern or "knowledge of performance" [51, 106]. In addition to real-time feedback, semi- real-time (e.g., provided every few steps) or delayed (e.g., presented about prior event) feedback can be effective in certain scenarios [84].

9.1.2. Potential beneficiaries

The most likely beneficiaries of such a real-time balance aid are people with acute vestibular conditions such as vestibular neuritis/labyrinthitis or post-operative labyrinthectomy/acoustic neuroma resection patients, who experience a sudden disruption to their balance system secondary to a partial unilateral loss of their vestibular mechanism [76, 98]. For persons with complete bilateral vestibular loss, sensory substitution devices may provide an additional channel of information to replace the otherwise missing sensory inputs. Sensory augmentation is ideal for people that do not require mechanical support (i.e., assistive device). People using such an aid would need to have both the necessary cognitive and motor capabilities to interpret and make volitional postural corrections based upon the cues, respectively. Depending on how much cognition is required to utilize feedback, such aids may not be practical for persons who are at high risk for falling with cognitive impairment. Based on the literature, the greater the sensory impairment, the greater the potential for sensory augmentation to reduce postural sway [4, 93]. Other potential beneficiaries include people with acute disorders that often result in imbalance (e.g., post-concussion/mild TBI and cerebrovascular accident, CVA), older adults, people with peripheral neuropathy, PD, Multiple Sclerosis, ataxia, and those who experience anxiety in disorienting scenarios including busy and elevated environments.

9.1.3. Summary of literature

Based on the literature reviewed for this paper, sensory augmentation appears to be most useful during quiet and dynamic standing and during the recovery phases of mild to moderate surface perturbations. However, its usefulness during locomotor activities and transitions between seated and upright stance appear to be limited.

9.1.4. Outstanding questions/issues

There are several unanswered questions regarding the usefulness of sensory augmentation as a real-time balance aid including its efficacy during locomotor activities and postural transitions. Most studies report that subjects can learn to use sensory augmentation to reduce postural sway within seconds to minutes. However, longer training periods (i.e., hours to days) may be needed for gait and other complex movements. Context-specific feedback strategies that are task appropriate are likely needed, i.e., cues changing in real-time in response to the activity. Real-time activity monitors that use MEMS inertial sensors have been developed and validated with data from reasonably large healthy populations [31]; however, it is unknown what type of display (e.g., feedback modality, display location(s), instruction associated with the cue, control signal) is best suited for which tasks. Cost, wearability, battery life, ease of use, and ease of troubleshooting and maintaining such devices will also affect long-term use.

Researchers typically assess sensory augmentation technologies in a laboratory or clinical environment and report findings in response to a collection of artificial physical perturbation schemes that do not necessarily reflect actual environmental challenges, are not readily recreated in other environments, and do not directly map to clinical functional outcomes. To date, sensory augmentation devices have not been worn continuously or used as a real-time aid in a real-word setting. The impact of such aids while walking on uneven ground, navigating curbs, ramps and stairs, and walking in busy environments such as "big box stores", which are visually provoking, are unknown. There are no completed long-term studies that characterize the utility of sensory augmentation over extended periods of time; it is unknown if people incorporate the cues in a more natural manner without negative impacts on segmental control strategies and/or gait velocity with time or if they become desensitized to the information provided. Limited studies have been performed to understand attentional requirements when using sensory augmentation. The question remains unanswered as to whether with long-term use, people will be able to dual task with the use of a sensory augmentation aid efficiently, effectively and safely.

9.2. Rehabilitation device

9.2.1. Concept

The basic idea of balance rehabilitation is to leverage the central nervous system's ability to reweight intact sensory inputs in the event of sensory declines [39]. Exercises are designed to recover, retrain, or develop new sensorimotor strategies to facilitate functional mobility, decrease dizziness, and re-establish effective coordination [37, 45, 85]. Rehabilitation programs that incorporate motor and sensory systems as well as cognitive and psychological processes have proven more effective than muscular training alone in improving balance and coordination [101]. As a rehabilitation device, feedback of body motion provided to the CNS by a sensory augmentation device could serve as a correlate to the inputs from its intact channels of sensory inputs, potentially facilitating the dependence on these intact systems (e.g., vision, proprioception, vestibular). Furthermore, sensory augmentation could serve to complement and/or mimic some of the physical cues and verbal feedback regarding position errors provided by a physical therapist facilitating the retraining of postural control. Exercise program success may also be affected by the location where the exercises are performed, the social support structures available, and the use of specific, clear exercise instructions prescribed and supervised by a physical therapist [66]. Home-based balance training coupled with sensory augmentation could increase compliance and the quality of the exercises performed.

9.2.2. Potential beneficiaries

Sensory augmentation during balance rehabilitation training may further improve functional recovery in patients who have reached a plateau with their traditional vestibular/balance therapy programs [78]. People with chronic imbalance including uncompensated unilateral vestibular hypofunction, bilateral vestibular paresis, CVA, TBI, PD, peripheral neuropathy and older adults have the potential to benefit from sensory augmentation within a rehabilitation context. High risk fall populations including persons with uncompensated unilateral vestibular and bilateral vestibular loss could potentially benefit from combined clinic- and home-based balance training to improve recovery, decrease fall risk, and maximize functional outcomes. Physical therapists are also potential beneficiaries of sensory augmentation devices. Used within a clinical setting, such devices could supplement expert instruction enabling a physical therapist to provide treatment with real-time feedback to more than one patient at a time [52] thereby enabling a therapist to increase their patient load while delivering custom individualized treatment programs [13].

A balance exercise program combined with sensory augmentation may provide progressively challenging and meaningful repetitive motor practice for static, dynamic and gait related exercises [13] with variable feedback that is conductive for promoting motor learning [106]. Multiple commercially available sensory augmentation systems are currently being used in clinical settings (e.g., Balance Freedom™ [8], Vertiguard® RT [110], VibroTactile™[15]). These commercially available devices and additional emerging products (e.g., Stabalon® [9]) could potentially support clinic- and/or home-based training. Home-based use could potentially extend the benefits of health services that are currently difficult to provide on an extended basis within clinical settings or reduce the actual number of clinic sessions needed, translating into reduced health care costs. Performance metrics captured by sensory augmentation devices during clinic- and home-based training could be used by the therapist to implement timely modifications and inform customized programs [47, 91].

9.2.3. Summary of literature

Sensory augmentation has been shown to reduce body sway in patients with balance disorders during real-time use while performing a subset of traditional balance rehabilitation exercises (e.g., semi-tandem Romberg, tandem Romberg). Retention and carry-over effects appear to be limited to days to week and it is unclear based on the existing data that there are significant benefits of training with a sensory augmentation device versus training alone. However, no systematic studies have been performed over extended periods of time.

9.2.4. Outstanding questions/issues

Numerous questions remain to be answered regarding the role of sensory augmentation during balance rehabilitation. Does balance training with sensory augmentation decrease the number of sessions required to obtain the same outcomes? What, if any, are the long-term retention and/or carry-over effects? Will training with sensory augmentation improve fall outcomes? Will training with sensory augmentation improve adherence to home-based training programs? Should sensory augmentation be used in the clinic, in the home, or in both settings? What is the ideal "dosage" for providing cues during training? Motor learning supports providing extrinsic feedback, relating to the outcome of an action or knowledge of results, intermittently, to allow an individual to obtain and synthesize information about performance errors not influenced by the feedback [106]. Constant feedback (provided continuously throughout rehabilitation training programs) promotes quick learning, but may negatively affect retention. Variable (provided periodically) or summed feedback (provided after a set of similar exercises are performed), would likely slow learning, but improve retention. Delayed feedback (provided after a slight delay) or terminal feedback (provided post completion of a particular activity) are also effective methods for delivering feedback regarding the accuracy or quality of movement depending on the application, the user's capability, and the goals of the training program [75]. The majority of studies examining retention effects have provided subjects with constant feedback. A few recent studies have begun to explore the use of variable feedback [10], but the ideal "dose" (including factors such as the frequency of use and the feedback activation thresholds) within and across training sessions is unknown. Most of the same questions and issues pertaining to effective feedback strategies for gait and postural transitions, and display design for real-time use also apply for rehabilitation training use, although the types of motions are limited and constrained due to the nature of the exercises. In a recent review article, Shull and Damian suggested that variability in subjects' responses to tactile feedback prevents the determination of optimal feedback standards and they suggested a future goal of designing feedback platforms which can provide subject-specific treatments [83].

10. Limitations

This narrative review highlights findings from the literature, but does not critically examine efficacy or the quality of the research methods used in the reviewed studies.

11. Summary

Sensory augmentation has been shown to reduce postural sway in people with vestibular deficits during static, dynamic, and mild-moderate perturbed stance conditions. Its usefulness during locomotor activities has been limited; however, increased training time and different feedback strategies may improve efficacy. The lack of significant findings during step-inducing perturbations and gait may limit the applications as an all-encompassing real-time balance aid. There have been limited systematic studies to determine the relationship between the number of training sessions with sensory augmentation and the retentive and/or carry-over effects, but a handful of studies that have involved more than 10 sessions seem to indicate benefits over training alone (i.e., without the addition of sensory augmentation). If shown to be effective following use during balance rehabilitation training, sensory augmentation may further facilitate functional recovery in patients who have reached a plateau with their traditional vestibular/balance therapy programs. Sensory augmentation devices designed for use in the home may provide an important transitional link between clinic and home with potential to provide an ongoing balance intervention to high fall risk populations.

Acknowledgments

This work was partially supported by the National Science Foundation under award numbers CAREER GARDE 0846471 and GARDE 1159635, and the National Institute on Deafness and Other Communication Disorders under award number R21DC012410. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or the National Institutes of Health. A preliminary version of this review was presented at the annual meeting of the International Society for Gait and Posture Research (ISPGR) from June 28th – July 2nd, 2015 in Seville Spain.

Competing interests

The authors state that C. Wall is an inventor on an issued patent and has equity interest in BalanceTek, Inc.

References

[1] Y. Agrawal, J.P. Carey, C.C. Della Santina, M.C. Schubert and L.B. Minor, Disorders of balance and vestibular function in US adults: Data from the National Health and Nutrition Examination Survey, 2001-2004, *Arch Intern Med* **169** (2009), 938–944.

[2] Y. Agrawal, B.K. Ward and L.B. Minor, Vestibular dysfunction: Prevalence, impact and need for targeted treatment, *J Vestib Res* **23** (2013), 113–117.

[3] J.H. Allum, M.G. Carpenter, B.C. Horslen, J.R. Davis, F. Honegger, K.S. Tang and P. Kessler, Improving impaired balance function: Real-time versus carry-over effects of prosthetic feedback, *Conf Proc IEEE Eng Med Biol Soc* **2011** (2011), 1314–1318.

[4] F. Asseman, A.M. Bronstein and M.A. Gresty, Using vibrotactile feedback of instability to trigger a forward compensatory stepping response, *J Neurol* **254** (2007), 1555–1561.

[5] P. Bach y Rita, Y. Danilov, M. Tyler and R.J. Grimm, Late human brain plasticity: Vestibular substitution with a tongue BrainPort human-machine interface, *Intellectica* **40** (2005), 115–122.

[6] P. Bach-y-Rita, Tactile sensory substitution studies, *Ann NY Acad Sci* **1013** (2004), 83–91.

[7] P. Bach-y-Rita, C.C. Collins, F.A. Saunders, B. White and L. Scadden, Vision substitution by tactile image projection, *Nature* **221** (1969), 963–964.

[8] Balance International Innovations, Balance Freedom.

[9] BalanceTek Corp., Stabalon Balance Belt.

[10] T. Bao, B.N. Klatt, W.J. Carender, C. Kinnaird, S.L. Whitney and K.H. Sienko, Long-term balance training with vibrotactile biofeedback: Two case reports, in: *ISPGR World Congress*, Seville, Spain, 2015.

[11] T. Bao, L. Su, C. Kinnaird, P.B. Shull and K.H. Sienko, The effects of tactor location on vibrotactile stimulation reaction times in healthy adults, in: *37th Annual Conference of the IEEE in Medicine and Biology Society*, Milan, Italy, 2015.

[12] C.G. Barros, R.S. Bittar and Y. Danilov, Effects of electrotactile vestibular substitution on rehabilitation of patients with bilateral vestibular loss, *Neurosci Lett* **476** (2010), 123–126.

[13] D. Basta, M. Rossi-Izquierdo, A. Soto-Varela, M.E. Greters, R.S. Bittar, E. Steinhagen-Thiessen, R. Eckardt, T. Harada, F. Goto, K. Ogawa and A. Ernst, Efficacy of a vibrotactile neurofeedback training in stance and gait conditions for the treatment of balance deficits: A double-blind, placebo-controlled multicenter study, *Otol Neurotol* **32** (2011), 1492–1499.

[14] K.E. Bechly, W.J. Carender, J.D. Myles and K.H. Sienko, Determining the preferred modality for real-time biofeedback during balance training, *Gait Posture* **37** (2013), 391–396.

[15] Biodex, VibroTactile™ System.

[16] A.R. Bisdorff, J.P. Staab and D.E. Newman-Toker, Overview of the international classification of vestibular disorders, *Neurol Clin* **33** (2015), 541–550, vii.

[17] T. Brandt, W. Bles, F. Arnold and T.S. Kapteyn, Height vertigo and human posture, *Adv Otorhinolaryngol* **25** (1979), 88–92.

[18] A.M. Bronstein, Vision and vertigo: Some visual aspects of vestibular disorders, *J Neurol* **251** (2004), 381–387.

[19] A.M. Bronstein, Multisensory integration in balance control, *Handb Clin Neurol* **137** (2016), 57–66.

[20] C. Brugnera, R. Bittar, M. Greters and D. Basta, Effects of vibrotactile vestibular substitution on vestibular rehabilitation — preliminary study, *Braz J Otorhinolaryngol* **81** (2015), 616–621.

[21] A.J. Campbell, M.C. Robertson, M.M. Gardner, R.N. Norton, M.W. Tilyard and D.M. Buchner, Randomised controlled trial of a general practice programme of home based exercise to prevent falls in elderly women, *BMJ* **315** (1997), 1065–1069.
[22] W. Carender, C. Kinnaird, P. Peethambaran, G. Fantich, S. Whitney and K. Sienko, Balance Telerehabilitation: Considering User Preferences for the Design of a Cell Phone Balance Trainer, in: *World Congress International Society for Posture & Gait Research*, Seville, Spain, 2015.
[23] H.S. Cohen, J. Wells, K.T. Kimball and C. Owsley, Driving disability and dizziness, *J Safety Res* **34** (2003), 361–369.
[24] J.R. Davis, M.G. Carpenter, R. Tschanz, S. Meyes, D. Debrunner, J. Burger and J.H. Allum, Trunk sway reductions in young and older adults using multi-modal biofeedback, *Gait Posture* **31** (2010), 465–472.
[25] M. Dettmer, A. Pourmoghaddam, B.C. Lee and C.S. Layne, Associations between tactile sensory threshold and postural performance and effects of healthy aging and subthreshold vibrotactile stimulation on postural outcomes in a simple dual task, *Curr Gerontol Geriatr Res* **2016** (2016), 9797369.
[26] M. Dozza, L. Chiari and F.B. Horak, Audio-biofeedback improves balance in patients with bilateral vestibular loss, *Arch Phys Med Rehabil* **86** (2005), 1401–1403.
[27] M. Dozza, C. Wall 3rd, R.J. Peterka, L. Chiari and F.B. Horak, Effects of practicing tandem gait with and without vibrotactile biofeedback in subjects with unilateral vestibular loss, *J Vestib Res* **17** (2007), 195–204.
[28] E. Ekvall Hansson, L.E. Dahlberg and M. Magnusson, Vestibular rehabilitation affects vestibular asymmetry among patients with fall-related wrist fractures – A randomized controlled trial, *Gerontology* **61** (2015), 310–318.
[29] T. Ersal and K.H. Sienko, A mathematical model for incorporating biofeedback into human postural control, *J Neuroeng Rehabil* **10** (2013), 14.
[30] M. Fetter, Vestibular System Disorders, in: *Vestibular Rehabilitation*, S. Herdman andR. Clendanial eds., 2014, pp. 50–57.
[31] K. Frank, M. Nadales and P. Robertson, Reliable Real-Time Recognition of Motion Related Human Activities Using MEMS Inertial Sensors, in: *Proceedings of the 23rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2010)*, Portland, OR, 2010, pp. 2919–2932.
[32] J.A. Goebel, B.C. Sinks, B.E. Parker Jr, N.T. Richardson, A.B. Olowin and R.W. Cholewiak, Effectiveness of head-mounted vibrotactile stimulation in subjects with bilateral vestibular loss: A phase 1 clinical trial, *Otol Neurotol* **30** (2009), 210–216.
[33] A.D. Goodworth, C. Wall 3rd and R.J. Peterka, Influence of feedback parameters on performance of a vibrotactile balance prosthesis, *IEEE Trans Neural Syst Rehabil Eng* **17** (2009), 397–408.
[34] A.D. Goodworth, C. Wall and R.J. Peterka, A balance control model predicts how vestibular loss subjects benefit from a vibrotactile balance prosthesis, *Conf Proc IEEE Eng Med Biol Soc* **2011** (2011), 1306–1309.
[35] S. Haggerty, L.T. Jiang, A. Galecki and K.H. Sienko, Effects of biofeedback on secondary-task response time and postural stability in older adults, *Gait Posture* **35** (2012), 523–528.
[36] C.D. Hall, M.C. Schubert and S.J. Herdman, Prediction of fall risk reduction as measured by dynamic gait index in individuals with unilateral vestibular hypofunction, *Otol Neurotol* **25** (2004), 746–751.
[37] E.E. Hansson, N.O. Mansson, K.A. Ringsberg and A. Hakansson, Falls among dizzy patients in primary healthcare: An intervention study with control group, *Int J Rehabil Res* **31** (2008), 51–57.
[38] J. Hegeman, F. Honegger, M. Kupper and J.H. Allum, The balance control of bilateral peripheral vestibular loss subjects and its improvement with auditory prosthetic feedback, *J Vestib Res* **15** (2005), 109–117.
[39] S.J. Herdman, P. Blatt, M.C. Schubert and R.J. Tusa, Falls in patients with vestibular deficits, *Am J Otol* **21** (2000), 847–851.
[40] F. Honegger, I.M. Hillebrandt, N.G. van den Elzen, K.S. Tang and J.H. Allum, The effect of prosthetic feedback on the strategies and synergies used by vestibular loss subjects to control stance, *J Neuroeng Rehabil* **10** (2013), 115.
[41] J.L. Huffman, L.E. Norton, A.L. Adkin and J.H. Allum, Directional effects of biofeedback on trunk sway during stance tasks in healthy young adults, *Gait Posture* **32** (2010), 62–66.
[42] R. Jacob, S. Woody, D. Clark, S. Lilienfeld, B. Hirsch, G. Kucera, J. Furman and J. Durrant, Discomfort with space and motion: A possible marker of vestibular dysfunction assessed by the situational characteristics questionnaire, *Journal of Psychopathology and Behavioral Assessment* **15** (1993), 299–324.
[43] L.J. Janssen, L.L. Verhoeff, C.G. Horlings and J.H. Allum, Directional effects of biofeedback on trunk sway during gait tasks in healthy young subjects, *Gait Posture* **29** (2009), 575–581.
[44] M. Janssen, R. Stokroos, J. Aarts, R. van Lummel and H. Kingma, Salient and placebo vibrotactile feedback are equally effective in reducing sway in bilateral vestibular loss patients, *Gait Posture* **31** (2010), 213–217.
[45] J.Y. Jung, J.S. Kim, P.S. Chung, S.H. Woo and C.K. Rhee, Effect of vestibular rehabilitation on dizziness in the elderly, *Am J Otolaryngol* **30** (2009), 295–299.
[46] C. Kinnaird, J. Lee, W.J. Carender, M. Kabeto, B. Martin and K.H. Sienko, The effects of attractive vs. repulsive instructional cuing on balance performance, *J Neuroeng Rehabil* **13** (2016), 29.
[47] B.N. Klatt, W.J. Carender, C.C. Lin, S.F. Alsubaie, C.R. Kinnaird and K.H. Sienko, A conceptual framework for the progression of balance exercises in persons with balance and vestibular disorders, *Phys Med and Rehabil Int* **2** (2015), 1044.
[48] E.K. Kristinsdottir, G.B. Jarnlo and M. Magnusson, Asymmetric vestibular function in the elderly might be a significant contributor to hip fractures, *Scand J Rehabil Med* **32** (2000), 56–60.
[49] E.K. Kristinsdottir, E. Nordell, G.B. Jarnlo, A. Tjader, K.G. Thorngren and M. Magnusson, Observation of vestibular asymmetry in a majority of patients over 50 years with fall-related wrist fractures, *Acta Otolaryngol* **121** (2001), 481–485.
[50] G. Kugler, D. Huppert, E. Schneider and T. Brandt, Fear of heights freezes gaze to the horizon, *J Vestib Res* **24** (2014), 433–441.
[51] B. Lauber and M. Keller, Improving motor performance: Selected aspects of augmented feedback in exercise and health, *Eur J Sport Sci* **14** (2014), 36–43.
[52] B.C. Lee, S. Chen and K.H. Sienko, A wearable device for real-time motion error detection and vibrotactile instruc-

tional cuing, *IEEE Trans Neural Syst Rehabil Eng* **19** (2011), 374–381.

[53] B.C. Lee, A. Ho, B.J. Martin and K.H. Sienko, Effects of co-vibrotactile stimulations around the torso on non-volitional postural responses, *Conf Proc IEEE Eng Med Biol Soc* **2012** (2012), 6149–6152.

[54] B.C. Lee, J. Kim, S. Chen and K.H. Sienko, Cell phone based balance trainer, *J Neuroeng Rehabil* **9** (2012), 10.

[55] B.C. Lee, B.J. Martin, A. Ho and K.H. Sienko, Postural reorganization induced by torso cutaneous covibration, *J Neurosci* **33** (2013), 7870–7876.

[56] B.C. Lee, B.J. Martin and K.H. Sienko, Directional postural responses induced by vibrotactile stimulations applied to the torso, *Exp Brain Res* **222** (2012), 471–482.

[57] B.C. Lee, B.J. Martin and K.H. Sienko, The effects of actuator selection on non-volitional postural responses to torso-based vibrotactile stimulation, *J Neuroeng Rehabil* **10** (2013), 21.

[58] J. Lee, T. Bao and K.H. Sienko, Cell phone telerehabilitation device for home-based balance training, in: *ISPGR World Congress*, 2015.

[59] P.Y. Lee, K. Gadareh, M.J. Naushahi, M. Gresty and A.M. Bronstein, Protective stepping response in Parkinsonian patients and the effect of vibrotactile feedback, *Mov Disord* **28** (2013), 482–489.

[60] M. Lesinski, T. Hortobagyi, T. Muehlbauer, A. Gollhofer and U. Granacher, Effects of balance training on balance performance in healthy older adults: A systematic review and meta-analysis, *Sports Med* **45** (2015), 1721–1738.

[61] R.F. Lewis, Advances in the diagnosis and treatment of vestibular disorders: Psychophysics and prosthetics, *J Neurosci* **35** (2015), 5089–5096.

[62] C.C. Lin, S.L. Whitney, P.J. Loughlin, J.M. Furman, M.S. Redfern, K.H. Sienko and P.J. Sparto, The effect of age on postural and cognitive task performance while using vibrotactile feedback, *J Neurophysiol* **113** (2015), 2127–2136.

[63] C.C. Lin, S.L. Whitney, P.J. Loughlin, J.M. Furman, M.S. Redfern, K.H. Sienko and P.J. Sparto, The use of vibrotactile feedback during dual task standing balance conditions in people with unilateral vestibular hypofunction, (In review).

[64] H.W. Lin and N. Bhattacharyya, Balance disorders in the elderly: Epidemiology and functional impact, *Laryngoscope* **122** (2012), 1858–1861.

[65] P. Loughlin, A. Mahboobin and J. Furman, Designing vibrotactile balance feedback for desired body sway reductions, *Conf Proc IEEE Eng Med Biol Soc* **2011** (2011), 1310–1313.

[66] M.M. Madureira, L. Takayama, A.L. Gallinaro, V.F. Caparbo, R.A. Costa and R.M. Pereira, Balance training program is highly effective in improving functional status and reducing the risk of falls in elderly women with osteoporosis: A randomized controlled trial, *Osteoporos Int* **18** (2007), 419–425.

[67] G.F. Marchetti, S.L. Whitney, P.J. Blatt, L.O. Morris and J.M. Vance, Temporal and spatial characteristics of gait during performance of the Dynamic Gait Index in people with and people without balance or vestibular disorders, *Phys Ther* **88** (2008), 640–651.

[68] B.J. Martin, B.C. Lee and K.H. Sienko, A cutaneous positioning system, *Exp Brain Res* **233** (2015), 1237–1245.

[69] E. Mira, Improving the quality of life in patients with vestibular disorders: The role of medical treatments and physical rehabilitation, *Int J Clin Pract* **62** (2008), 109–114.

[70] M. Mueller, E. Schuster, R. Strobl and E. Grill, Identification of aspects of functioning, disability and health relevant to patients experiencing vertigo: A qualitative study using the international classification of functioning, disability and health, *Health Qual Life Outcomes* **10** (2012), 75.

[71] V. Nandapalan, C.A. Smith, A.S. Jones and T.H. Lesser, Objective measurement of the benefit of walking sticks in peripheral vestibular balance disorders, using the Sway Weigh balance platform, *J Laryngol Otol* **109** (1995), 836–840.

[72] H.K. Neuhauser, A. Radtke, M. von Brevern, F. Lezius, M. Feldmann and T. Lempert, Burden of dizziness and vertigo in the community, *Arch Intern Med* **168** (2008), 2118–2124.

[73] H.K. Neuhauser, M. von Brevern, A. Radtke, F. Lezius, M. Feldmann, T. Ziese and T. Lempert, Epidemiology of vestibular vertigo: A neurotologic survey of the general population, *Neurology* **65** (2005), 898–904.

[74] NIDCD, Strategic Plan, FY 2006-2008.

[75] S. O'Sullivan and T. Schmitz, *Improving Functional Outcomes*, F. A. Davis Company, 2010.

[76] R.J. Peterka, K.D. Statler, D.M. Wrisley and F.B. Horak, Postural compensation for unilateral vestibular loss, *Front Neurol* **2** (2011), 57.

[77] S. Polat and A. Uneri, Vestibular substitution: Comparative study, *J Laryngol Otol* (2010), 1–7.

[78] B.S. Robinson, J.L. Cook, C.M. Richburg and S.E. Price, Use of an electrotactile vestibular substitution system to facilitate balance and gait of an individual with gentamicin-induced bilateral vestibular hypofunction and bilateral transtibial amputation, *J Neurol Phys Ther* **33** (2009), 150–159.

[79] L.P. Rossi, R. Pereira, M. Brandalize and A.R.S. Gomes, The effects of a perturbation-based balance training on the reactive neuromuscular control in community- -dwelling older women: A randomized controlled trial, *Human Movement* **14** (2013), 238–246.

[80] M.J. Ruckenstein and J.P. Staab, Chronic subjective dizziness, *Otolaryngol Clin North Am* **42** (2009), 71–77, ix.

[81] A. Schmidheiny, J. Swanenburg, D. Straumann, E.D. de Bruin and R.H. Knols, Discriminant validity and test retest reproducibility of a gait assessment in patients with vestibular dysfunction, *BMC Ear Nose Throat Disord* **15** (2015), 6.

[82] R. Schniepp, M. Wuehr, S. Huth, C. Pradhan, T. Brandt and K. Jahn, Gait characteristics of patients with phobic postural vertigo: Effects of fear of falling, attention, and visual input, *J Neurol* **261** (2014), 738–746.

[83] P.B. Shull and D.D. Damian, Haptic wearables as sensory replacement, sensory augmentation and trainer - a review, *J Neuroeng Rehabil* **12** (2015), 59.

[84] P.B. Shull, K.L. Lurie, M.R. Cutkosky and T.F. Besier, Training multi-parameter gaits to reduce the knee adduction moment with data-driven models and haptic feedback, *J Biomech* **44** (2011), 1605–1609.

[85] A. Shumway-Cook, F.B. Horak, L. Yardley and A.M. Bronstein, Rehabilitation of balance disorders in the patient with vestibular pathology, in: *Clinical disorders of balance, posture, and gait*, A.M. Bronstein, T. Brandt andM. Woollacott eds., Oxford University Press, Inc., New York, 1996, pp. 211–235.

[86] K.H. Sienko, M.D. Balkwill, L.I. Oddsson and C. Wall, Effects of multi-directional vibrotactile feedback on vestibular-deficient postural performance during con-

tinuous multi-directional support surface perturbations, *J Vestib Res* **18** (2008), 273–285.
[87] K.H. Sienko, M.D. Balkwill, L.I. Oddsson and C. Wall 3rd, The effect of vibrotactile feedback on postural sway during locomotor activities, *J Neuroeng Rehabil* **10** (2013), 93.
[88] K.H. Sienko, M.D. Balkwill and C. Wall 3rd, Biofeedback improves postural control recovery from multi-axis discrete perturbations, *J Neuroeng Rehabil* **9** (2012), 53.
[89] J.P. Staab, The influence of anxiety on ocular motor control and gaze, *Curr Opin Neurol* **27** (2014), 118–124.
[90] C. Toulotte, A. Thevenon and C. Fabre, Effects of training and detraining on the static and dynamic balance in elderly fallers and non-fallers: A pilot study, *Disabil Rehabil* **28** (2006), 125–133.
[91] M. van Diest, J. Stegenga, H. Wörtche, G. Verkerke, K. Postema and C. Lamouth, Exergames for unsupervised balance training at home: A pilot study in healthy older adults, *Gait Posture* **44** (2016), 161–167.
[92] L.L. Verhoeff, C.G. Horlings, L.J. Janssen, S.A. Bridenbaugh and J.H. Allum, Effects of biofeedback on trunk sway during dual tasking in the healthy young and elderly, *Gait Posture* **30** (2009), 76–81.
[93] C. Wall 3rd and E. Kentala, Control of sway using vibrotactile feedback of body tilt in patients with moderate and severe postural control deficits, *J Vestib Res* **15** (2005), 313–325.
[94] C. Wall 3rd and E. Kentala, Effect of displacement, velocity, and combined vibrotactile tilt feedback on postural control of vestibulopathic subjects, *J Vestib Res* **20** (2010), 61–69.
[95] C. Wall 3rd, D.M. Wrisley and K.D. Statler, Vibrotactile tilt feedback improves dynamic gait index: A fall risk indicator in older adults, *Gait Posture* **30** (2009), 16–21.
[96] C. Wall and M. Weinberg, Balance prostheses for postural control, *IEEE Eng Med Biol Mag* **22** (2003), 84–90.
[97] P. Wang, C. Chang, M. Su, S. Yeh and T. Fang, Virtual reality rehabilitation for vestibular dysfunction, *Otolaryngol Head Neck Sur* **145** (2011), 159.
[98] M.S. Weinberg, C. Wall, J. Robertsson, E. O'Neil, K. Sienko and R. Fields, Tilt determination in MEMS inertial vestibular prosthesis, *J Biomech Eng* **128** (2006), 943–956.
[99] S.L. Whitney, G.F. Marchetti, A. Schade and D.M. Wrisley, The sensitivity and specificity of the Timed "Up & Go" and the Dynamic Gait Index for self-reported falls in persons with vestibular disorders, *J Vestib Res* **14** (2004), 397–409.
[100] S.L. Whitney, G.F. Marchetti and A.I. Schade, The relationship between falls history and computerized dynamic posturography in persons with balance and vestibular disorders, *Arch Phys Med Rehabil* **87** (2006), 402–407.
[101] S.L. Whitney, D.M. Wrisley, G.F. Marchetti, M.A. Gee, M.S. Redfern and J.M. Furman, Clinical measurement of sit-to-stand performance in people with balance disorders: Validity of data for the Five-Times-Sit-to-Stand Test, *Phys Ther* **85** (2005), 1034–1045.
[102] J.C. Wildenberg, M.E. Tyler, Y.P. Danilov, K.A. Kaczmarek and M.E. Meyerand, Sustained cortical and subcortical neuromodulation induced by electrical tongue stimulation, *Brain Imaging Behav* **4** (2010), 199–211.
[103] J.C. Wildenberg, M.E. Tyler, Y.P. Danilov, K.A. Kaczmarek and M.E. Meyerand, Electrical tongue stimulation normalizes activity within the motion-sensitive brain network in balance-impaired subjects as revealed by group independent component analysis, *Brain Connect* **1** (2011), 255–265.
[104] J.C. Wildenberg, M.E. Tyler, Y.P. Danilov, K.A. Kaczmarek and M.E. Meyerand, High-resolution fMRI detects neuromodulation of individual brainstem nuclei by electrical tongue stimulation in balance-impaired individuals, *Neuroimage* **56** (2011), 2129–2137.
[105] J.C. Wildenberg, M.E. Tyler, Y.P. Danilov, K.A. Kaczmarek and M.E. Meyerand, Altered connectivity of the balance processing network after tongue stimulation in balance-impaired individuals, *Brain Connect* **3** (2013), 87–97.
[106] C.J. Winstein, Knowledge of results and motor learning–implications for physical therapy, *Phys Ther* **71** (1991), 140–149.
[107] L. Yardley, N. Owen, I. Nazareth and L. Luxon, Prevalence and presentation of dizziness in a general practice community sample of working age people, *Br J Gen Pract* **48** (1998), 1131–1135.
[108] L. Yardley and M.S. Redfern, Psychological factors influencing recovery from balance disorders, *J Anxiety Disord* **15** (2001), 107–119.
[109] L.R. Young, L. Bernard-Demanze, M. Dumitrescu, J. Magnan, L. Borel and M. Lacour, Postural performance of vestibular loss patients under increased postural threat, *J Vestib Res* **22** (2012), 129–138.
[110] Zeisberg GmbH, Vertiguard.