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Application of vibrotactile feedback of body motion to improve rehabilitation in individuals with imbalance

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Abstract

Background and Purpose—Balance rehabilitation and vestibular/balance prostheses are both emerging fields that have a potential for synergistic interaction. This paper reviews vibrotactile prosthetic devices that have been developed to date and ongoing work related to the application of vibrotactile feedback for enhanced postural control. A vibrotactile feedback device developed in the author's laboratory is described.

Methods—Twelve subjects with vestibular hypofunction were tested on a platform that moved randomly in a plane, while receiving vibrotactile feedback in the anterio-posterior direction. The feedback allowed subjects to significantly decrease their anterio-posterior body tilt, but did not change mediolateral tilt. A tandem walking task using subjects with vestibulopathies demonstrated a reduction in their medio-lateral sway due to vibrotactile feedback of medio-lateral body tilt, after controlling for the effects of task learning. The findings from two additional experiments conducted in the laboratories of collaborating physical therapists are summarized.

Results—The Dynamic Gait Index scores in community-dwelling elderly individuals who were prone-to-fall were significantly improved with the use of medio-lateral body tilt feedback.

Discussion and Conclusions—While more work is needed, these results suggest that vibrotactile tilt feedback of subjects' body motion can be used effectively by physical therapists for balance rehabilitation. A preliminary description of the 3rd generation device that has been reduced from a vest format to a belt format is described to demonstrate the progressive evolution from research to clinical application.

INTRODUCTION

Prosthetic devices are currently being developed to help replace loss of self-motion information due to disease, injuries, and aging. Balance/vestibular prostheses can be categorized into one of two classes: 1) internal or implant devices, and 2) external or sensory substitution devices. How might these devices be useful in helping to rehabilitate people with balance disorders? Internal or implantable devices will likely be first used to augment the angular vestibulo-ocular reflex (aVOR) and perhaps provide improved spatial orientation input – but mainly by activating reflexive neural pathways. In contrast, the external sensory substitution devices will not provide reflexive inputs, but rather provide information about body motion, that while intuitive, would need some level of conscious attention by the wearer to use. The most likely first uses of sensory substitution devices will be for spatial orientation cueing that helps people maintain their balance while standing and walking. Balance rehabilitation therapy can be divided into two categories: (1) vestibular habituation exercises that have the patient move their eyes, head, or body from one position to another repeatedly sometimes deliberately pairing

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antagonistic vestibular and visual stimuli,[1–5] (2) positioning exercises to reposition particles in the peripheral vestibular system,[6, 7] and; (3) exercises that include balancing and walking.[8–11] The logical application of a sensory substitution would be for the latter approach. Balance rehabilitation therapy that requires the individual to learn or change some of their stability limits while standing or walking, or that helps to “tune” extra-vestibular motion inputs to improve postural control, could likely benefit from properly applied external or sensory substitution devices.

Other sensory substitution devices to aid balance control have used auditory,[12–15] or electro-tactile[16,17] feedback with some degree of success. Since communication between the therapist and the patient is an important factor during rehabilitation, this investigator and collaborators have chosen tactile feedback. Tactile sensory substitution has been applied with varying degrees of success to replace senses lost due to disease or trauma. Examples include the use of Braille for the blind and various tactile speech encoders developed for the deaf. Dynamic tactile displays[18] have been demonstrated successfully as both auditory (e.g., TactAid) and visual prostheses (e.g., Optacon[19]). Vibrotactile displays have also been demonstrated to be successful in aviation. [20–22] For example, a blindfolded pilot can make a complete loop and return to level flight using virbrotactile displays. Moreover, much data have been collected on the properties of the skin that can be used in building a tactile display. [23–28]

This paper will first describe a prototype balance prosthesis that has been used in a variety of experiments. New results for vestibulopathic subjects standing on a randomly moving 2-axis platform, with and without vibrotactile tilt feedback will be described next; these preliminary results are part of a larger study that is ongoing. The paper then reviews findings from two published studies using vibrotactile tilt feedback to summarize current application, and evolving experience with the device by the authors and colleagues.

The prototype balance prosthesis

A balance prosthesis prototype using a vibrotactile display of subjects’ body motion has been shown to reduce significantly the chance of a fall in subjects with severe peripheral vesibulopathies, and to reduce the amount of trunk sway in individuals with moderate vestibulopathies. [29]

The device (Figure 1) uses a 6-degree of freedom motion sensor (3 linear accelerometers and 3 rate gyroscopes) that provides linear acceleration and angular rate information to an algorithm in order to estimate trunk tilt relative to the vertical. The device then feeds back this tilt information to the subject via an array of tactile vibrators (tactors) that rings the torso. [30–32] The device displays both magnitude and direction of body tilt using a 16-column-by-3-row array of tactors, and is held in contact using a wide elastic belt. Columns display tilt direction, while rows are used to display magnitude. During standing, only one tactor is activated at a time, and is driven by a continuous 250 Hz sinusoid. We form a signal magnitude by adding the estimated tilt angle to one-half of the tilt rate, because this signal reflects the appropriate state variables needed to control the most simple model of posture – a single inverted pendulum (manuscript in preparation). We refer to this signal as the tilt signal (TS). TS = tilt angle + tilt rate/2.

The magnitude of the tilt signal is displayed in the step-like fashion. The resolution for the display of tilt magnitude is determined using a dynamic manual control paradigm,[33] and was set at four discrete levels (including a “dead zone”). The direction of the tilt signal is displayed by selecting the column to be activated. With 16 columns, the best spatial resolution is thus 22.5 degrees. The front and back columns are aligned along the anterior-posterior body axis. We can choose how many columns to use for a given experiment (*stance mode versus walking mode*), for standing experiments all 16 columns have been typically chosen. The column in which a tactor is activated is selected on the “nearest neighbor” principle. For walking, only the columns on or near the right and left sides are activated.

For walking experiments, we typically use a modified display. The magnitude of the tilt signal’s ML component is displayed in columns on either the right side or the left side of the subject’s body. Subject tilt to the right is displayed on the right column, tilt to the left is displayed on the left column, etc. The step-like magnitude display is also modified. If the subject is walking normally, then the signal is set so that the subject receives an alternating right-left pattern of vibration on just the lowest row of tactors. If the subject’s ML tilt signal exceeds a threshold (typically set at 5 degrees) then all the tactors in a column are activated simultaneously. The objective is to provide the subject with a reassuring stimulus under conditions of nominal locomotion, but to provide them an alerting stimulus when their ML tilt signal is off-nominal, providing feedback that will allow them to correct during the next gait cycle. While the effective bandwidth of the present device is not as wide as vestibular system information,[34] the device does allow vestibulopathic and fall-prone elderly subjects to significantly reduce their ML body sway during locomotion.[35] Sensitivity to vibrotactile input is known to decrease somewhat with increasing age in humans.[36–38] Nonetheless, our device was able to be used successfully by our elderly prone-to-fall subjects.[35]

The vibrotactile tilt feedback device has been used on over 100 subjects in protocols that span five institutions. The basic finding is that when the feedback contains information about a person’s body motion, the amount of wavering is decreased when the feedback is on compared to the same situation when subject wears the device with the feedback turned off.

Effects of vibrotactile feedback on standing postural control

Methods—We are currently performing experiments on the effects of vibrotactile feedback on standing posture control in individuals with vestibulopathy. Subjects stand on a randomly moving 2-axis platform, while receiving 1-axis feedback. Twelve individuals, (5 males and 7 females, age 55±9, range 43–71 yrs), with well-compensated vestibular lesions (typically from removal of acoustic neuromas) were recruited from the medical practice of physicians at the Massachusetts Eye and Ear Infirmary, and were tested during continuous horizontal surface perturbations, using a moveable balance perturbation platform, while they either received or did not receive vibrotactile feedback reflecting sagittal plane body tilt. The utility of vibrotactile feedback to improve subjects’ postural control was tested under eyes closed conditions and instructions to stand as still as possible, but were asked not to stand stiffly. All subjects gave informed consent in a protocol that was approved by the Boston University and the Massachusetts Eye and Ear Infirmary Human Subjects Committees. Subjects were classified as having either unilateral vestibular hypofunciton (UVH) or bilateral vestibular hypofunction (BVH) on the basis of vestibular functional testing that included the electronystagmography test battery (ENG), rotation about the vertical, and computerized dynamic posturography (CDP). The four BVH subjects had zero or near zero scores for CDP sensory organization tests 5 and 6, while the eight UVH subjects had scores that were near or below the normal limits for their age group.

All subjects had normal CDP motor control tests. The test trials reported herein were a subset of trials that were performed in randomized order with each trial lasting 35 seconds. The horizontal perturbation signal represented each subjects’ own center of pressure (COP) recorded during the initial part of the session, and was scaled up (1.5–2.0 times) to provide a noticeable and challenging perturbation. The perturbation trials were not unlike standing on a moving bus or train. Vision was occluded under all conditions.

Subjects performed a brief training session prior to testing to become familiar with the task and the vibrotactile feedback signal. Ground reaction forces during stance trials were measured using an AMTI ORG-5 force platform (Newton, MA, USA) that was mounted in the balance perturbation platform. The center-of-pressure (COP), representing the instantaneous point of application of the resultant ground reaction force, was calculated from the force plate data. Data were sampled at 100 samples per second, and stored on computer disk for later analysis. The vibrotactile feedback device used in the current study differed slightly from the previously described multi-axis device. The device used in this study was a single-axis system based on one accelerometer and a tilt sensor module with a gyroscope to sense angular rate. The two sensor signals were processed to obtain a sagittal tilt angle estimate that was accurate within 2 milliradians over 0–10 Hz bandwidth. The device used three tactors placed above each other in a column secured in the front and the back of the subject's trunk. No feedback was provided for mediolateral trunk tilt (roll angle).

Tilt data from the prototype balance prosthesis was recorded and stored on the PC laptop that communicates with the device. Tilt and COP data were analyzed using MATLAB. Conditions with and without vibrotactile feedback were compared with a non-parametric statistical procedure, Wilcoxon's matched pairs test, using Statistica 5.5 software package (Statsoft Inc., Tulsa, OK) was used. The threshold for statistical significance was set at $p \leq 0.05$.

Results—Effects of vibrotactile feedback during continuous horizontal support surface perturbations on COP and trunk tilt parameters are shown in Table 1. Antero-posterior trunk tilt showed a statistically significant decrease in variability in the presence of vibrotactile feedback (38% decrease in A/P sway). In addition, subjects demonstrated a statistically significant increase in median frequency of trunk sway (45%) as well as a decrease in root mean square (RMS) amplitude of trunk sway (28%) indicating that they were able to use the vibrotactile information to comply with the task of reducing trunk sway. Furthermore, a decrease in trunk sway range (19%) was found in the presence of vibrotactile feedback. These findings are consistent with another study that report that use of 2-axis feedback during 2-axis random motion resulted in significant reductions in tilt in all directions.[39]

Effects of vibrotactile feedback on trunk tilt during tandem walking

Methods—In a separate study to assess the effects of vibrotactile feedback on trunk tilt during tandem walking,[40] ten subjects with documented unilateral peripheral vestibular lesions (5 males and 5 females, age: 53±16yrs, height: 172±9cm, and weight: 87±21kg) were divided into two groups. The average age, height, and weight in the two groups were not statistically different. All subjects were free from orthopedic and neurological diseases or disorders, except for a total unilateral vestibular loss. The subjects were asked to tandem-walk on a firm 2.5 m surface while being paced with a metronome at 30 beats per minute. During all trials the subjects were wearing a vibrotactile tilt feedback system[32] consisting of a vest with 4 columns of 3 tactors each and a tilt sensor. The vest was placed around the trunk of the subject so that 2 columns of tactors could vibrate the left side of the subject's trunk and the other 2 columns could vibrate the right side of the subject's trunk. The 6 tactors of each side were activated two-at-a-time, starting with the lowest ones, passing to the middle ones, then to the highest ones the more the subject's trunk was tilting in the direction where the vibration was applied. After familiarization and training, subjects performed two sets of 24 trials of tandem walking. A crossover design was used in which group one had the first set of trials with vibrotactile tilt information fed back to them, and the second set of trails with no feedback. In group two, the order of presentation was reversed. The purpose of the crossover design was to control for effects due to training (practice) versus effects due to feedback. The RMS ML tilt was then averaged over all subjects for each condition (feedback and no feedback) separately for each trial number.

Results—ANOVA revealed significant effects for both feedback and training. The effect of practicing tandem gait with and without vibrotactile feedback is illustrated in Figure 2. There was a decrease in ML tilt with increasing trial number that is indicative of the effects of training for both conditions ($p < 0.05$).

There was also less ML tilt when the feedback was on compared to the control (no feedback) condition ($p < 0.05$). Thus, vibrotactile feedback of ML body tilt appears to have enhanced training in these subjects with vestibulopathy during tandem walking. The potential significance of these findings for fall prevention is that increased ML tilt is correlated with increased fall risk.[41]

Effects of vibrotactile feedback on fall risk in older adults

Methods—In a study of the effects of vibrotactile feedback on fall risk in older adults, twelve community dwelling elderly subjects (3 males and 9 females, age: 79.6±5.4 yrs) were tested.[35] Subjects were included if they were between the ages of 65 and 90 years of age, had no neurological or orthopedic impairment that would limit their ability to stand and walk, were able to stand independently for 5 minutes, and perceived they had balance problems. Subjects were characterized as healthy elderly based on the Activities-specific Balance Confidence (ABC) Scale[42, 43] (78.1±23.7), Vestibular Disorders Activities of Daily Living (VADL) Scale [44, 45] (mean 1.78), and Berg Balance Scale [46, 47] (52.3±2.4). During all trials the subjects were wearing a vibrotactile tilt feedback system[31] described above. A reassuring stimulus (activation of only the lowest tactor) was given during normal locomotion and an alerting stimulus (activation of all three tactors in one column) was given when the ML tilt was off-normal. A baseline Dynamic Gait Index[48] (DGI) scored by an experienced physical therapist was measured for each subject. The DGI is an 8 item clinical functional gait test that includes gait on normal surfaces, gait with horizontal and vertical head turns, velocity changes during gait, stepping around and over obstacles, turning and ascending and descending stairs. The DGI is scored on a 4 level ordinal scale with a maximum score of 24 and scores of 19 or less indicating an increased risk of falling.[49]

During the baseline DGI test, vibrotactile feedback was not given. Each subject was then trained for 20–30 minutes to use the vibrotactile vest. Vibrotactile feedback and visual feedback of the subject's trunk tilt was provided for several minutes while the subject stood with eyes open. Each subject was then provided with several minutes of vibrotactile feedback of trunk tilt without visual feedback while standing with eyes open and then with eyes closed. Next, each subject was given feedback of ML trunk sway during normal paced walking with eyes open and eyes closed, slow paced walking with eyes open and eyes closed, and narrow base walking with eyes open and eyes closed. Training concluded when the subject was able to understand and use the vibrotactile feedback of trunk tilt angle during standing and walking. A second DGI test was conducted with each subject while they received feedback about their ML body tilt from the vibrotactile device.

Results—Examplar data from one DGI trial (Walk while making vertical head movements) with feedback OFF and ON is shown in Figure 3A.

The DGI score was 1 for the OFF condition and 2 for the ON condition, while the RMS tilt decreased from 1.33 degrees with feedback off to 1.12 degrees with feedback on. The subject made a cross-step at about 6 seconds with the feedback off. The basic effect of using feedback is that it helps people stay more closely aligned with the vertical as is shown in Figure 3B.

Statistical analysis revealed that total DGI scores significantly increased by 3.0±1.5 points from 17.4±1.5 (no feedback) to 20.4±1.6 (with vibrotactile feedback) as shown in Figure 3C (t test, $p < 0.001$) suggesting that fall risk, for the group as a whole, was reduced when the vest was applied. All 12 subjects had higher DGI scores with the vest compared to without the vest.[49] A change of 3 or more points in the total DGI score has been suggested to represent a clinically significant change (i.e. after a rehab intervention).[50, 51] Ten of our twelve subjects demonstrated improvements of 3 or more points in the total DGI score when wearing the vest. In addition, there was also a decrease in ML tilt when feedback was provided during locomotion. The RMS ML tilt for both standard and narrow gait walking trials with the eyes open and eyes closed decreased in all four instances when feedback was used. Thus, vibrotactile feedback of ML body tilt appears to decrease ML trunk tilt as well as fall risk in healthy elder subjects. This conclusion is supported by both the DGI and the RMS ML tilt measures.

From the total DGI score, it is also possible to make an estimate of the effect of changes in the DGI score on changes in the probability of falling. This estimate is based upon a prior study of falls in community based elderly adults[51] in which the authors plotted subjects' frequency of falling versus Berg Balance Scale scores, and then fit the data with a smooth curve. Applying this model to our study, a similar smooth curve was derived using frequency of falling data and DGI scores (Figure 3C). From this model, a DGI score of 17.4 (no feedback) corresponded to an 83% chance of falling in a six-month period, while a score of 20.4 (feedback used) corresponded to a 23% chance falling in the same period. While not all falls occur while walking, if this reduced risk of falls could be realized in clinical practice, it could result in a significant reduction of the number falls in this population.

Progressive development of vibrotactile balance aids for rehabilitation

Vibrotactile tilt feedback may also be useful for individuals with acute imbalance from stroke, surgery, accident, vestibular neuroticism, amputation, and chronic imbalance, (e.g., elderly people prone to falling or those with uncompensated balance dysfunction). For these populations, we envision a logical progression of vibrotactile tilt feedback devices. The first device might be a laboratory-based device dedicated to balance/vestibular rehabilitation. Clinicians may also want to provide their patients with a take-home version of the device to supplement the clinical training. Finally, there might be a device for elderly individuals and others who are prone to falling that could be worn full-time under clothing and would need only a simple alignment calibration once a day.

Recently, we have developed a third generation device prototype that is more compact, user-friendly, lighter in weight, and resembles a belt instead of a vest.

Two main factors allowed this improvement. First, we have been able to use only four directions instead of the original 16 directions. Second, we have been able to signal changes in tilt magnitude with a single tactor by using a set of complex vibratory signals that a subject can react to as quickly as they can using the former three-tactor scheme. Thus, the number of tactors has been reduced from 48 to four without any loss in performance. The human factors aspect of the belt was evaluated by surveying users of the older vest version and by subsequent re-design using anthropomorphic data. The new vibrotactile belt is shown in Figure 4.

Conclusions

The results of several sets of experiments show that vibrotactile feedback of body tilt can be used to help control body motion under a variety of conditions and tasks. While more work is needed, vibrotactile feedback may eventually be a valuable adjunct to balance rehabilitation that can be used by physical therapists and individuals with balance dysfunction. Further refinement of prosthetic devices for balance rehabilitation using vibrotactile feedback is currently ongoing, including testing of a slim, light belt-like device, which may greatly enhance the clinical applicability of this emerging technology.

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References

1. Brandt T, Daroff RB. Physical therapy for benign paroxysmal positional vertigo. Arch Otolaryngol Aug;1980 106(8):484–485. [PubMed: 7396795]
2. Brandt T, Steddin S, Daroff RB. Therapy for benign paroxysmal positioning vertigo, revisited. Neurology May;1994 44(5):796–800. [PubMed: 8190277]
3. Cawthorne T. The Physiological Basis for Head Exercises. The Journal of The Chartered Society of Physiotherapy 1944;30:106.
4. Cohen HS, Kimball KT. Increased independence and decreased vertigo after vestibular rehabilitation. Otolaryngol Head Neck Surg Jan;2003 128(1):60–70. [PubMed: 12574761]
5. Cooksey F. Rehabilitation in vestibular injuries. Proc R Soc Med 1946;39:273–275. [PubMed: 19993269]
6. Epley JM. The canalith repositioning procedure: for treatment of benign paroxysmal positional vertigo. Otolaryngol Head Neck Surg Sep;1992 107(3):399–404. [PubMed: 1408225]
7. Semont A, Freyss G, Vitte E. Curing the BPPV with a liberatory maneuver. Adv Otorhinolaryngol 1988;42:290–293. [PubMed: 3213745]
8. Campbell AJ, Robertson MC, Gardner MM, Norton RN, Buchner DM. Falls prevention over 2 years: a randomized controlled trial in women 80 years and older. Age Ageing 1999;28(6):513–518. [PubMed: 10604501]
9. Lord SR, Ward JA, Williams P, Strudwick M. The effect of a 12-month exercise trial on balance, strength, and falls in older women: a randomized controlled trial. J Am Geriatr Soc 1995;43(11):1198–1206. [PubMed: 7594152]
10. Tinetti ME, Baker DI, McAvay G, et al. A multifactorial intervention to reduce the risk of falling among elderly people living in the community. N Engl J Med 1994;331(13):821–827. [PubMed: 8078528]
11. Wolf SL, Barnhart HX, Kutner NG, McNeely E, Coogler C, Xu T. Reducing frailty and falls in older persons: an investigation of Tai Chi and computerized balance training. Atlanta FICSIT Group. Frailty and Injuries: Cooperative Studies of Intervention Techniques. J Am Geriatr Soc 1996;44(5):489–497. [PubMed: 8617895]
12. Chiari L, Dozza M, Cappello A, Horak FB, Macellari V, Giansanti D. Audio-biofeedback for balance improvement: an accelerometry-based system. IEEE Trans Biomed Eng 2005;52(12):2108–2111. [PubMed: 16366234]
13. Dozza M, Chiari L, Chan B, Rocchi L, Horak FB, Cappello A. Influence of a portable audio-biofeedback device on structural properties of postural sway. J Neuroengineering Rehabil 2005;2:13.
14. Dozza M, Chiari L, Horak FB. Audio-biofeedback improves balance in patients with bilateral vestibular loss. Arch Phys Med Rehabil 2005;86(7):1401–1403. [PubMed: 16003671]
15. Hegeman J, Honegger F, Kupper M, Allum JH. The balance control of bilateral peripheral vestibular loss subjects and its improvement with auditory prosthetic feedback. J Vestib Res 2005;15(2):109–117. [PubMed: 15951624]
16. Bach-y-Rita P, Danilov Y, Tyler ME, Grimm RJ. Late human brain plasticity: vestibular substitution with a tongue BrainPort human-machine interface. Intellectica 2005;1(40):115–122.

17. Tyler ME, Danilov Y, Bach-y-Rita P. Closing an open-loop control system: Vestibular substitution through the tongue. International Journal of Integrative Neuroscience 2003;2(2):159–166.
18. Craig, JC.; Sherrick, CE.; Schiff, W.; Foulke, E. Tactual perception: A sourcebook. Cambridge: Cambridge University Press; 1982. Dynamic tactile displays; p. 209-233.
19. Bliss JC, Katcher MH, Rogers CH, Shepard RP. Optical-to-tactile image conversion for the blind. IEEE Transactions of Man-Machine Systems 1970;MMS-11(1)
20. Rupert, A.; Guedry, F.; Reschke, M. The Use of a Tactile Interface to Convey Position and Motion Perceptions. Paper presented at: North Atlantic Treaty Organization. Advisory Group for Aeronautics Research and Development. Aerospace Medical Panel. Virtual interfaces: research and applications; 1993; Lisbon, Portugal.
21. Rupert AH. Tactile situation awareness system: proprioceptive prostheses for sensory deficiencies. Aviat Space Environ Med 2000;71(9 Suppl):92–99.
22. Rupert, AH., et al. Tactile interface to improve situation awareness. Paper presented at: Aerospace Medical Association; 1996; Washington, DC.
23. Cholewiak, RW.; Collins, AA.; Heller, MA.; Schiff, W. The Psychology of Touch. Hillsdale, NJ: Laurence Erlbaum Assoc; 1991. Sensory and physiological bases of touch; p. 23-60.
24. Lamore PJ, Keemink CJ. Evidence for different types of mechanoreceptors from measurements of the psychophysical threshold for vibrations under different stimulation conditions. J Acoust Soc Am 1988;83(6)
25. Bensmaia S, Hollins M, Yau J. Vibrotactile intensity and frequency information in the pacinian system: a psychophysical model. Percept Psychophys Jul;2005 67(5):828–841. [PubMed: 16334055]
26. Bensmaia SJ, Hollins M. Complex tactile waveform discrimination. J Acoust Soc Am Sep;2000 108 (3 Pt 1):1236–1245. [PubMed: 11008823]
27. Enriquez M, Maclean KE. Backward and common-onset masking of vibrotactile stimuli. Brain Res Bull Apr 15;2008 75(6):761–769. [PubMed: 18394522]
28. Seah SA, Griffin MJ. Normal values for thermotactile and vibrotactile thresholds in males and females. Int Arch Occup Environ Health Apr;2008 81(5):535–543. [PubMed: 17901976]
29. Wall C 3rd, Kentala E. Control of sway using vibrotactile feedback of body tilt in patients with moderate and severe postural control deficits. J Vestib Res 2005;15(5–6):313–325. [PubMed: 16614476]
30. Wall C 3rd, Merfeld DM, Rauch SD, Black FO. Vestibular prostheses: the engineering and biomedical issues. J Vestib Res 2002;12(2–3):95–113. [PubMed: 12867668]
31. Wall C 3rd, Weinberg MS. Balance prostheses for postural control. IEEE Eng Med Biol Mag 2003;22 (2):84–90. [PubMed: 12733464]
32. Wall C 3rd, Weinberg MS, Schmidt PB, Krebs DE. Balance prosthesis based on micromechanical sensors using vibrotactile feedback of tilt. IEEE Trans Biomed Eng 2001;48(10):1153–1161. [PubMed: 11585039]
33. Kadkade PP, Benda BJ, Schmidt PB, Wall C 3rd. Vibrotactile display coding for a balance prosthesis. IEEE Trans Neural Syst Rehabil Eng 2003;11(4):392–399. [PubMed: 14960115]
34. Peterka RJ, Wall C, Kentala E. Determining the effectiveness of a vibrotactile balance prosthesis. J Vestib Res 2006;16(1–2):45–56. [PubMed: 16917168]
35. Wall C, Wrisley D, Statler K. Vibrotactile tilt feedback improves dynamic gait index: a fall risk indicator in older adults. Gait Posture 2009;30:16–21. [PubMed: 19345107]
36. Era P, Jokela J, Suominen H, Heikkinen E. Correlates of vibrotactile thresholds in men of different ages. Acta Neurol Scand 1986;74(3):210–217. [PubMed: 3788484]
37. Gescheider GA, Beiles EJ, Checkosky CM, Bolanowski SJ, Verrillo RT. The effects of aging on information-processing channels in the sense of touch: II. Temporal summation in the P channel. Somatosens Mot Res 1994;11(4):359–365. [PubMed: 7778412]
38. Goble AK, Collins AA, Cholewiak RW. Vibrotactile threshold in young and old observers: the effects of spatial summation and the presence of a rigid surround. J Acoust Soc Am 1996;99(4 Pt 1):2256–2269. [PubMed: 8730072]
39. Sienko KH, Vichare VV, Balkwill MD, Wall C. Assessment of vibrotactile feedback on postural stability during pseudorandom multidirectional platform motion. IEEE Trans BME. 2009 (in press).

40. Dozza M, Wall C, Peterka R, Chiari L, Horak F. Effects of practicing tandem gait with and without vibrotactile biofeedback in subjects with unilateral vestibular loss. J Vestib Res 2007;17:195–204. [PubMed: 18525145]
41. Rogers MW, Hedman LD, Johnson ME, Cain TD, Hanke TA. Lateral stability during forward-induced stepping for dynamic balance recovery in young and older adults. J Gerontol A Biol Sci Med Sci 2001;56(9):M589–M594. [PubMed: 11524454]
42. Myers AM, Fletcher PC, Myers AH, Sherk W. Discriminative and evaluative properties of the activities-specific balance confidence (ABC) scale. J Gerontol 1998;53A(4):M287–M294.
43. Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. J Gerontol A Biol Sci Med Sci 1995;50A(1):28–34.
44. Cohen HS, Kimball KT. Development of the vestibular disorders activities of daily living scale. Archives of Otolaryngology -- Head and Neck Surgery 2000;126(7):881–887. [PubMed: 10889001]
45. Cohen HS, Kimball KT, Adams AS. Application of the vestibular disorders activities of daily living scale. Laryngoscope 2000;110(7):1204–1209. [PubMed: 10892697]
46. Berg K, Wood-Dauphinee S, Williams JI. The Balance Scale: reliability assessment with elderly residents and patients with an acute stroke. Scand J Rehabil Med 1995;27(1):27–36. [PubMed: 7792547]
47. Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. Can J Public Health 1992;83 (Suppl 2):7–11.
48. Shumway-Cook, A.; Woollacott, M. Motor Control: Theory and Practical Applications. Baltimore, MD: Williams and Wilkins; 2001.
49. Shumway-Cook A, Baldwin M, Polissar NL, Gruber W. Predicting the probability for falls in community-dwelling older adults. Phys Ther 1997;77(8):812–819. [PubMed: 9256869]
50. Wolf B, Feys H, De W, et al. Effect of a physical therapeutic intervention for balance problems in the elderly: a single-blind, randomized, controlled multicentre trial. Clin Rehabil 2001;15(6):624–636. [PubMed: 11777093]
51. Shumway-Cook A, Gruber W, Baldwin M, Liao S. The effect of multidimensional exercises on balance, mobility, and fall risk in community-dwelling older adults. Phys Ther 1997;77(1):46–57. [PubMed: 8996463]

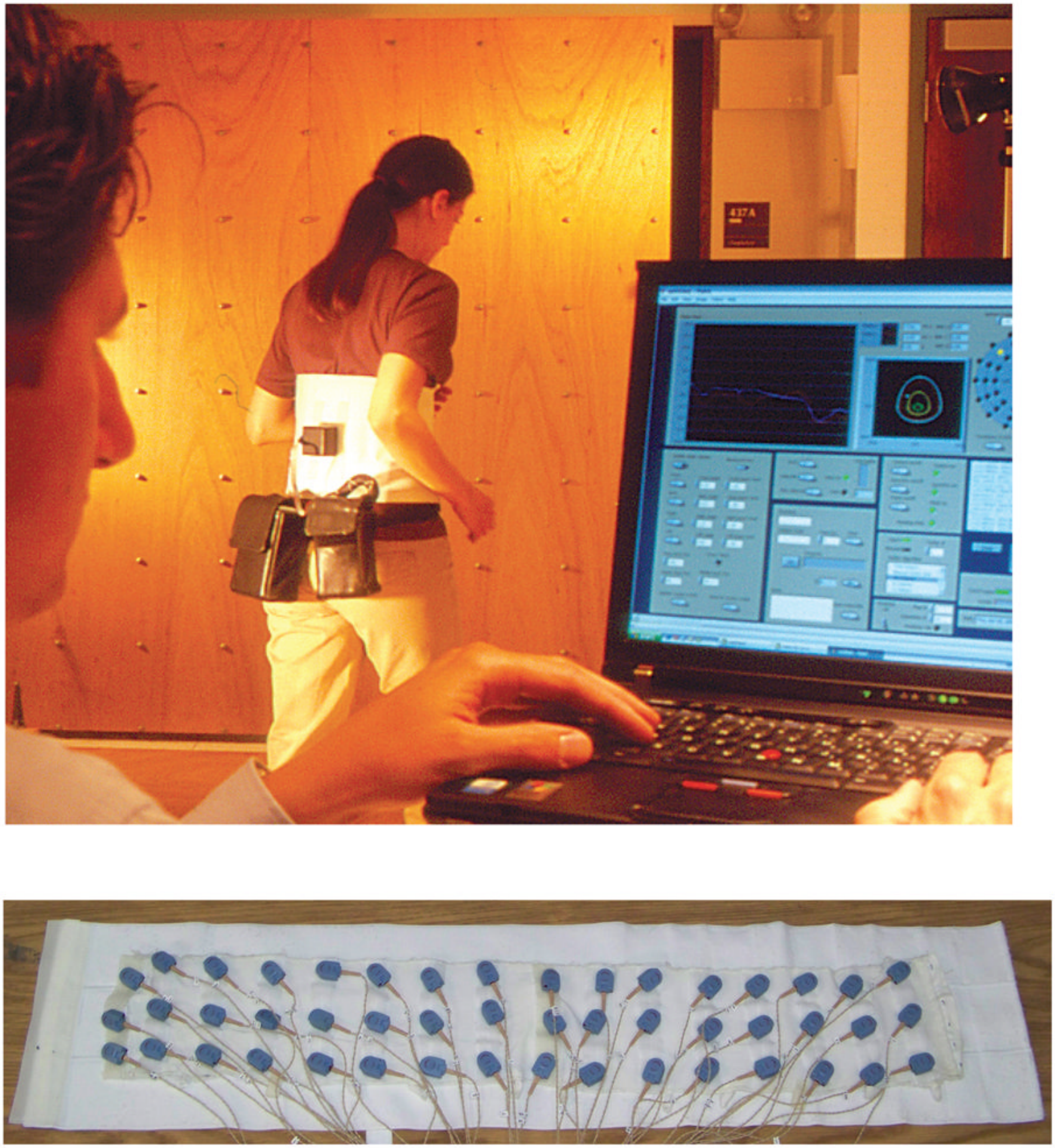

Figure 1.

Balance Vest or 2nd generation research test-bed. The device being worn by the female subject is autonomous and consists of three major parts. The wide white elastic band which rings the torso contains an array of 48 tactile vibrators (tactors). This array is shown at the left bottom. Direction is displayed by selection one of the 16 columns of tactors, while magnitude is displayed by selection one of three rows in that column. A 6 degree of freedom motion sensor package is mounted at the small of the back on top of the white band. The signals from the motion sensor unit are processed by a PC 104 computer that activates individual amplifiers connected to each of the 48 tactors. These electronic components and their battery power are mounted in two black leather holsters worn around the waist. Signals to and from the on-board computer are transmitted via WiFi to the laptop computer shown in the foreground. The experimenter (male subject) is thus able to monitor and to control the on-board computer remotely. The details are published in Wall and Weinberg.[31]

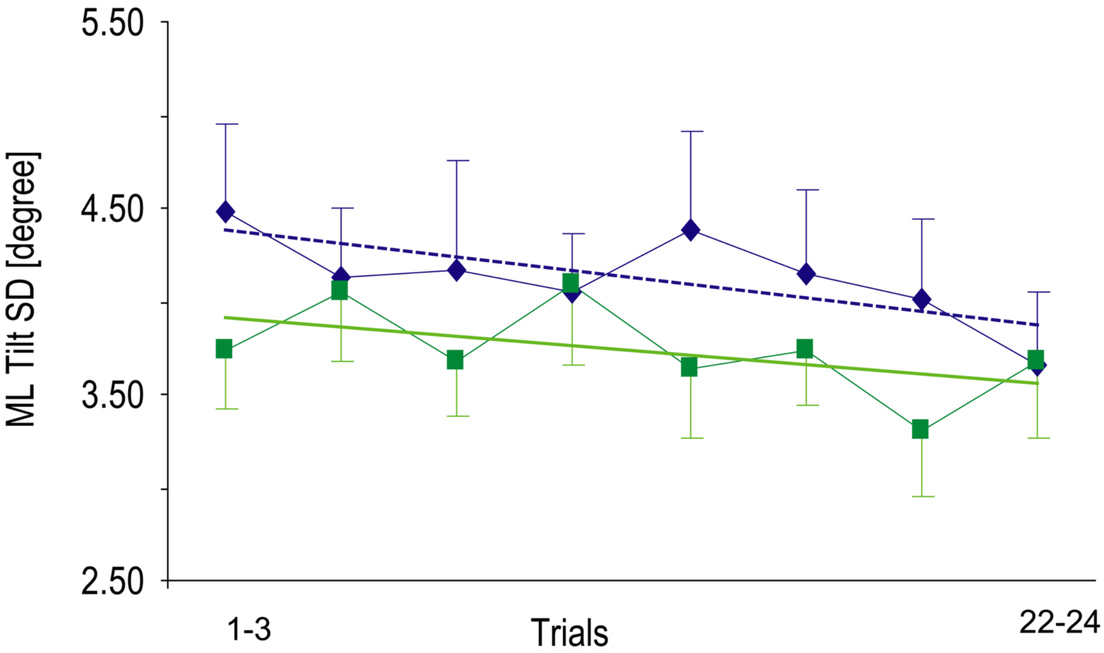

Figure 2.

Root mean square ML tilt during 24 tandem walking trails with and without vibrotactile tilt feedback, for 10 vestibulopathic subjects. Blue diamonds show control (no feedback) and green squares show trials using feedback. Three neighboring trials were averaged to yield 8 points for all 24 trials. Error bars show one standard deviation. Linear trends in the data are shown by dashed blue line for the control condition, while the solid green line shows the tilt feedback trend.

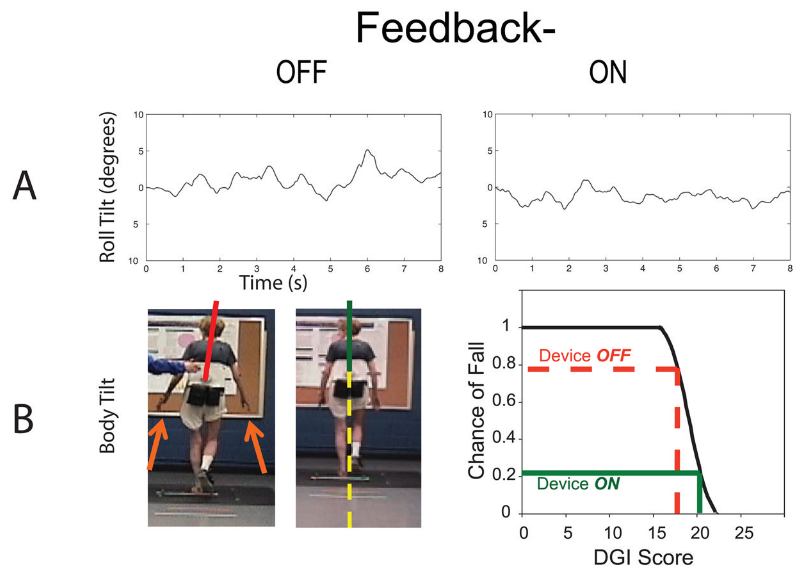

Figure 3.

A) Example of M/L trunk tilt estimate time series for one DGI subtest (Walk while making vertical head movements) with feedback OFF and ON. B) Left and Center -- photos of a subject at the end of a DGI subtest (i.e. walk while making horizontal head movements). Note body alignment and position of the hands. C) Right -- change in average DGI score with feedback OFF (dashed red lines) and feedback ON (solid green lines) plotted versus the chance of falling in community based elders versus Dynamic Gait Index, scores from a model based upon Shumway-Cook et al[51].

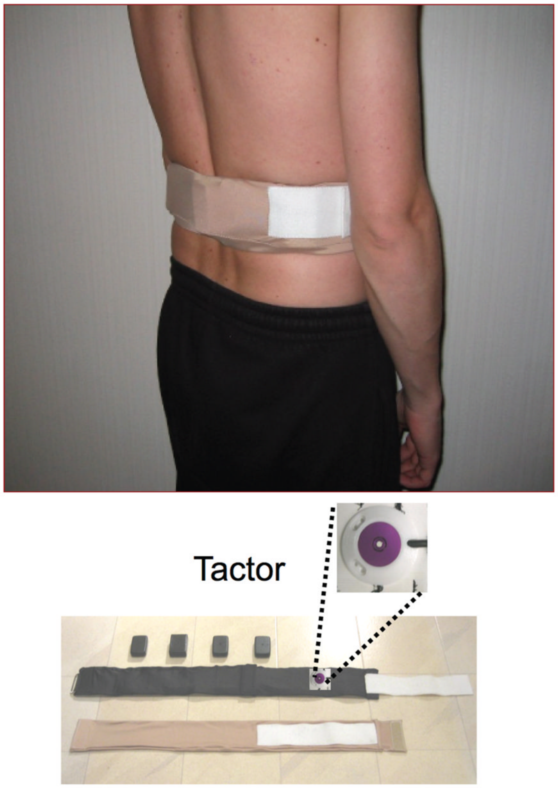

Figure 4.

Balance Belt or 3rd generation prosthesis prototype. Decreasing the number of tactile vibrators from 48 to four has resulted in a smaller, light-weight, belt-like device. The motion sensors, tactors, and supporting electronics are now contained within a flexible, moisture-resistant “skin” than can be worn under a blouse or shirt without being noticed. Four black plastic boxes house the electronic parts. Because the whole belt is stretchable, two sizes will fit the 99th percentile of the adult human population.

Table 1

Statistically Significant Effects of Vibrotactile Feedback during Pseudo-Random Perturbations

Parameter	**Control**	**Change from Control**	***p***
Body Tilt AP Av Standard Deviation	0.55±0.33deg	−0.23 deg	.023
Body Tilt AP Av Range	3.11±1.02deg	−0.54 deg	.019
Body Tilt AP Av Root Mean Square	0.80±0.29deg	−0.21 deg	.019
COP ML Av Range	34.3 ±23.3 mm	−5.2 mm	.050
COP AP Av Range	54.8 ±17.1 mm	−5.1 mm	.028
COP AP Median Frequency	0.44 ±0.15Hz	+0.15 Hz	.002
COP AP Velocity	34.7±12.8 mm/s	+4.05 mm/s	.005

Abbreviations: AP, Antero-posterior; Av, average; ML, mediolateral; COP, center of pressure.