Published in final edited form as:

Gait Posture. 2009 July ; 30(1): 16–21. doi:10.1016/j.gaitpost.2009.02.019.

Vibrotactile Tilt Feedback Improves Dynamic Gait Index: a Fall Risk Indicator in Older Adults

Conrad Wall III, PhD, Diane M. Wrisley, PhD, PT, NCS, and Kennyn D. Statler, PhD

From the Massachusetts Eye and Ear Infirmary, Department of Otolaryngology, Harvard Medical School (Wall, Statler); Department of Rehabilitation Science, State University of New York, University at Buffalo (Wrisley)

Abstract

The purpose of this study was to determine the effectiveness of vibrotactile feedback of body tilt in improving dynamic gait index a fall risk indicator in community dwelling older adults. Twelve healthy elderly subjects (3 males and 9 females, age 79.7 ± 5.4 yrs) were tested in an institutional balance rehabilitation laboratory to investigate changes between the feedback off and on conditions. Subjects were acutely exposed to a vibrotactile display that indicated the magnitude and direction of their body tilt from the vertical. Dynamic gait index (DGI) and mediolateral sway were determined during locomotion with, and without, vibrotactile tilt feedback

All subjects were at risk for falls based on their initial DGI Score (range: 15-19, mean 17.4 ± 1.56), which was taken with the vibratory stimulus turned off. Subjects learned to use the trunk tilt information from the vibrotactile feedback vest through 20-30 minutes of gait and balance training consisting of activities that challenged their balance. Subjects were then retested on the DGI. Statistically significant changes were demonstrated for the DGI total score while using the vibrotactile tilt feedback. DGI total scores improved from 17.1 ± 0.4 to 20.8 ± 0.3 ($p < 0.05$). We conclude that vibrotactile tilt feedback improves both control of mediolateral sway during gait and Dynamic Gait Index Both are fall risk indicators for this population.

Keywords

Prostheses and Implants; Postural Balance; Falls; Accidental; Biofeedback

INTRODUCTION

A predominant source of healthcare costs in the United States is due to injuries that occur as a consequence of falls during locomotion. Estimates for recurrent fallers vary somewhat from 17% to 35%. Tinetti, *et al*¹ and Nevitt, *et al*.² in two different studies report that about 17

Address all correspondence to: Conrad Wall, III, Ph.D., Jenks Vestibular Diagnostic Laboratory, Massachusetts Eye and Ear Infirmary, Boston, MA 02114, 617 573 4160(W), 617 573 4154(F), cwall@mit.edu.

CONFLICT OF INTEREST

We certify that we have affiliations with or financial involvement (eg, employment, consultancies, honoraria, stock ownership or options, expert testimony, grants and patents received or pending, royalties) with an organization or entity with a financial interest in, or financial conflict with, the subject matter or materials discussed in the manuscript AND all such affiliations and involvements are acknowledged below.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

percent of elders have two or more falls per year. The *Guideline for the Prevention of Falls in Older Persons*³ mentions that 35 % of adults over the age of 65 years report falling more than once in the previous year. This number has been reported to increase to 50% in adults over 75 years.⁴ Falls account for 4% of hospital admissions,⁵ 14% of emergency admissions⁶ and are the leading cause of injury related hospitalization in adults over 65 years of age.⁶

One of the strongest risk factors in determining fall risk is that of impaired balance, mobility, and gait.⁷ Prospective studies have demonstrated that tests of standing, leaning, reaching, stepping, and walking can distinguish adults who fall from those who do not fall, with more challenging balance tasks having stronger association with the risk of falling.⁷⁻¹⁰

Falls in the elderly are attributed to several factors including: decline in sensory function, central nervous system integration, neuromuscular function, and musculoskeletal function.⁷ Both proprioception and tactile sensitivity decrease with age with older adults demonstrating a reduction in vibratory and touch stimuli thresholds.^{11,12} Visual acuity and visual contrast sensitivity also decrease as a person ages.⁸ Age related changes are seen in the vestibular system with approximately 70% loss of vestibular neurons⁸ and a decrease in the gain of the visual vestibular ocular reflex gain causing retinal slip.^{13,14} These sensory changes may make it difficult for older adults to determine their orientation in space and to produce appropriate balance strategies.

Horak et al⁹ have suggested that it is pathologies in the elderly that contribute to balance problems and falls. Several authors have suggested that many of these pathologies may be subclinical and be unrecognized either by the patient or their health care practitioner.¹⁶⁻¹⁸ Older adults demonstrate falling during slips or trips,^{4,19} with difficulty generating the appropriate motor response to recover their balance.²⁰⁻²³ However, intrinsic factors such as orthostatic hypotension, joint disorders, or unknown mechanisms are more common causes of falling in older adults than trips and slips due to extrinsic factors.^{4,24,25} Falls due to intrinsic or unknown causes are related to head movements or turning.^{4,24,25} Falls in the elderly also are attributed to the difficulty adapting one's balance in response to changes in sensory information,¹⁰ increased sway in the anterior-posterior and mediolateral (ML) directions compared to young adults and abnormal stepping response with trunk perturbations.^{15,16,27,28} Increased ML sway during stance is correlated with increased fall risk²⁶⁻²⁸ Abnormal sensory input or abnormal integration of sensory input may be responsible for any or all of these responses.

Tactile sensory substitution has been applied with varying degrees of success to replace senses lost due to disease or trauma. A balance prosthesis prototype using vibrotactile display of subjects' body motion has been shown to reduce significantly the chance of a fall in subjects with severe peripheral vestibulopathies, and to reduce the amount of trunk sway in patients with moderate vestibulopathies as measured by a standard clinical test of balance, computerized dynamic posturography.¹¹ The device 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) which ring the torso.³⁰⁻³¹ The resolution for the display of tilt magnitude was determined using a dynamic manual control paradigm,¹² and was set at four discrete levels. We will refer to this as vibrotactile tilt feedback (VTTF). Figure 1 shows the device being worn by one of the subjects in our experiment. We will refer to this device as the VTTF vest. Previous studies have shown that the VTTF vest does allow vestibulopathic subjects to significantly reduce their ML body sway during locomotion, and will briefly be reviewed below.

Pilot walking with vestibulopathic subjects

Eight vestibular deficient subjects participated in a half-day training and experimental session that explored the usefulness of the VTTF vest during locomotion. The results indicate that the VTTF vest had the greatest effect on reducing ML sway during walking on foam and narrowed stance walking tasks. The most severely deficient subject showed the greatest amount of improvement¹³.

Tandem walking with vestibulopathic subjects

In this cross-over design study, 9 unilateral vestibular loss subjects practiced narrow gait with and without VTTF¹⁴. After adjusting for the effects of practice, the use of VTTF consistently increased postural stability during tandem gait, beyond the effects achieved by practice alone.

Given this initial success with vestibulopathic subjects, we hypothesized that VTTF would also provide older adults additional orientation information that would decrease sway. Therefore, the purpose of this study was to determine if wearing the VTTF vest can increase locomotor performance measures in community dwelling older adults. We focused upon two measures: ML tilt, and dynamic gait index.

METHODS

To determine whether the VTTF vest increased locomotor performance in older adults we performed a pre-test post-test experiment. All subjects gave informed consent to a protocol that was approved by the institutional Human Studies Committees. Twelve community dwelling older adults (mean age 79.9 ± 5.8 years, 9 females and 3 males) were recruited from a university community and senior living facility. 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. Each subject completed a neurological screen to ensure that they met all the inclusion criteria and to document the subject's lower extremity range of motion, muscle strength and sensation. Subjects completed the Romberg test and the Berg Balance Scale¹⁵ to document balance ability, and the Activities-specific Balance Confidence¹⁶ (ABC) Scale and Vestibular Disorders Activities of Daily Living¹⁷ (VADL) Scale to quantify the subject's perception of their balance and ADL function. Subject demographics and test scores are shown in Table 1. The subjects were then instrumented with the VTTF vest. The VTTF vest is a completely wearable, battery-powered research prototype device consisting of a body-mounted 6-degree-of-freedom (DOF) motion sensor package, a PC 104 computer with peripherals, and a 3×16 array of tactile vibrators (tactors) with amplifiers to drive them (Figure 1). The tactors were model VBW 32, from Audiological Engineering, Somerville, MA. The wide white elastic band which rings the torso contains the array of 48 tactile vibrators. Direction is displayed by selecting one of the 16 columns of tactors, while magnitude is displayed by selecting one of three rows in that column. The 6 degree of freedom motion sensor package (3 rate gyroscopes and 3 linear accelerometers) is mounted at the small of the back on top of the white band. The signals from the motion sensor unit are processed by the computer that activates individual amplifiers connected to each of the 48 tactors. When activated, the tactor provided a continuous 250 Hz vibratory stimulus to the skin. The electronic components and their battery power are mounted in two black leather holsters worn around the waist. The details are published elsewhere.¹⁸

After donning the VTTF vest, a baseline Dynamic Gait Index¹⁹ (DGI) was measured for each subject while wearing the device, but with the vibrating tactors turned off. 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 of 24 with scores of less than 20 indicating an increased risk of falling. Inter-rater and intra-rater reliability of the DGI is moderate to good.¹⁰ All clinical testing and DGI scoring was performed by a physical therapist board certified in neurological physical therapy and experienced in the evaluation and treatment of balance disorders.

For kinematic analysis of gait with and without VTTF, subjects were instrumented with 31 reflective markers with 6 markers on the floor for reference. An 8 camera motion capture system collected the 3-D coordinates of the markers which were used to calculate the spatial and temporal characteristics of gait using Orthotrak™ software. Subjects performed 3 trials for each of 4 gait conditions: eyes open normal stance, eyes closed normal stance, eyes open narrow stance, and eyes closed narrow stance. All walking trials were performed in dim light on a 26 foot long firm surface walkway with an instructor walking alongside for safety.

Following a short break, subjects were trained to use the VTTF vest. Training lasted about 20 minutes and consisted of stance training with the vibratory tactors turned on around the trunk and visual feedback indicating the subject's amount of trunk lean in real time, and gait training using varying stance widths with the eyes open and closed. For training during standing, the tilt direction could be displayed on all 16 columns (22.5 deg spatial resolution) using the nearest neighbor principle – only the column nearest to the tilt direction was used. Tilt magnitude was displayed in a step-wise fashion. Zero to one degree produced no signal. One to three degrees of tilt actuated the lowest of the three tactors in the column. Three to five degrees activated the second tactor, while a tilt that exceeded 5 degrees activated the uppermost tactor. For training during locomotion only the ML tactor columns were turned on. Tilt to the right activated tactors on the right column, while tilt to the left activated the left ones. No tactor was activated when the subject was in the zero to one degree dead zone. ML tilts between one and three degrees activated only the lowest tactor. Tilts that exceeded three degrees activated all three tactors on that side. The objective was to use a very mild signal to tell subjects that they only had a small amount of tilt, and thus establish an alternating right left pattern during normal locomotion. If the amount of tilt exceeded those limits then a much stronger “alerting signal” was displayed.

The DGI and gait analysis were then repeated with the VTTF turned. Because of subject fatigue due to both the subjects' age, and the weight of the equipment, we were not able to do a third set of evaluations with VTTF turned off.

Data Analysis

Subject demographics including age, gender, muscle strength, range of motion, lower extremity sensation, BBS, and Romberg were characterized using descriptive statistics. Scores on the DGI, differences on temporal and spatial characteristics of gait, and the amount of trunk tilt obtained with and without VTTF were analyzed using Wilcoxon matched pairs analysis. Significance level was set at $p < 0.05$.

RESULTS

A sample run that shows ML tilt from one subject doing horizontal head turns while walking is shown in Figure 1, Right. Note the relatively large excursion at about 6 sec in the VTTF off run (A). This excursion coincides with the subject having to make a cross-over step in order to keep from falling during this trial. All subjects improved in their DGI total scores while using the vibrotactile tilt feedback (Table 1). A significant improvement of 3.0 ± 1.5 points was seen for the total DGI while wearing the vest (Figure 2A). Sixty-seven percent improved by a clinically significant amount (≥ 3 points²⁰) on the DGI and improved their score above the cutoff risk for falling on the DGI (Total score > 19 ²¹). Previous studies on intra-rater reliability indicate that this is outside the range of measurement error²². Significant improvements were

seen in DGI individual items 3: walking with horizontal head turns, 4: walking with vertical head turns, 5: walking with a pivot turn, and 6: stepping over an obstacle (Figure 2B).

Significant decreases in the amount of trunk tilt were seen while walking while using VTTF (Figure 3). Gait velocity decreased (Figure 4A), and percent double limb support increased (Figure 4B) while using VTTF for gait with normal stance with eyes open and closed and for gait with narrow stance eyes open. However, this change was significantly different only for double support in gait normal stance eyes open ($p=0.18$, $z=-2.366$) and eyes closed ($p=0.012$, $z=-2.521$) conditions. A significant increase in velocity ($p = 0.017$, $z = -2.380$) and a decrease in double limb support ($p=0.025$, $z=-2.240$) was seen in gait with narrow stance eyes closed.

DISCUSSION

Areas where greatest improvements were seen

The change in DGI score that resulted from turning the VTTF on was clearly not uniform across all 8 DGI subtests. Over two thirds of the increase in the total score came from only three subtests: Gait with horizontal and vertical head turns, and stepping over obstacles (Figure 5). These three tasks closely mimic important activities of everyday living in which a potential fall might be prove to be dangerous. For example, it is not always possible to look solely at the path ahead while walking across a street. Part of one's attention must used to visually observe other relevant information such as oncoming vehicles, walk signals, or other pedestrians. Thus, during the time that vision is being used for these other tasks, it may be that VTTF can provide extra useful information about body motion that can be used to help prevent a fall.

This result is in agreement with Whitney et al²² who demonstrated that item 1 walking on level surfaces, item 3 walking with horizontal head turns, and item 4 walking with vertical head turns had the strongest relationship to falls in people with vestibular dysfunction.

We are not completely able to rule out the possibility that some of the increase in DGI score might have been due to a learning effect instead of the effect of feedback because we were not able to run a third round of evaluations after the VTTF on trials due to subject fatigue. Other studies have shown, however, that there is little or no significant effect of learning when DGI tests are repeated on the same subject²²

Functional significance of the changes in mediolateral tilt, gait velocity, and percent double support time and the role of feedback

VTTF decreased the ML tilt in older adults during gait. Increased ML sway may increase the risk of falling during standing and walking activities.²³ Older adults fall due to intrinsic factors,^{4,24} that may contribute to a decreased ability to detect how they are moving in space. VTTF provided supplemental sensory information on how a person is moving and therefore may be able to decrease the risk of a fall due to these intrinsic factors. Decreased ML tilt correlates to improved control of the center of gravity within the base of support and may increase a person's confidence in moving and performing activities of daily living and counteract some of these intrinsic factors.

Subjects demonstrated increased velocity and double support time when using VTTF -- but only during the most difficult task of walking with a narrow base of support with the eyes closed. Interestingly the only changes in subjects' gait kinematics while using the vest was an increase in head and trunk extension allowing the subject to achieve a more upright position and rotation of the head, trunk and pelvis orienting the subject more to midline.

Comparison to results of previous intervention studies

We demonstrated an immediate increase in the Dynamic Gait Index of community dwelling older adults by wearing a VTTF vest that provided extra information on ML trunk tilt to the subject. This increase in Dynamic Gait Index is correlated with chance of falling for this population. Thus we regard VTTF as a potential means for reducing their risk of fall. Exercise interventions for fall prevention and risk reduction have been inconsistent in reducing fall risk and number of falls. Exercise interventions that are successful require over 10 weeks of progressively difficult exercise with instruction in a home exercise program as the benefits of exercise are lost when the exercise is discontinued. The VTTF vest may be useful as an intervention to quickly decrease potential risk of falling and the numbers of falls after a person is identified as at risk.

Conclusions

The use of vibrotactile tilt feedback (VTTF) with minimal training decreases mediolateral sway and increases locomotor a clinical gait measure. Both measures are correlated with risk of falls. VTTF is an exciting and promising new intervention for potentially decreasing the fall risk in older adults and other patient populations.

Acknowledgments

Balance Prosthesis. US patent 6,546,291. 2003 Apr 8.

Supported by NIH NICDC R01DC0006210, and New York Physical Therapy Association (NYPTA) Research Designated Funds.

Some of this material was presented at the American Speech and Hearing Association, November 15, 2007, in Boston, MA, the American Neurotology Society September 15, 2007 in Washington, DC, and at the American Physical Therapy Association February 16, 2007 in Boston, MA. Honoraria were received for 2 of these presentations (ASHA & ANS)

References

1. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *The New England journal of medicine* 1988;319(26):1701–7. [PubMed: 3205267]
2. Nevitt MC, Cummings SR, Kidd S, Black D. Risk factors for recurrent nonsyncopal falls. A prospective study. *JAMA* 1989;261(18):2663–8. [PubMed: 2709546]
3. American Geriatrics S, British Geriatrics S. American Academy of Orthopedic Surgeons Panel on Falls P. Guideline for the Prevention of Falls in Older Persons. *Journal of the American Geriatrics Society* 2001;49:664–72. [PubMed: 11380764]
4. Campbell AJ, Borrie MJ, Spears GF, Jackson SL, Brown JS, Fitzgerald JL. Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study. *Age Ageing* 1990;19(2):136–41. [PubMed: 2337010]
5. Baker SP, Harvey AH. Fall injuries in the elderly. *Clin Geriatr Med* 1985;1(3):501–12. [PubMed: 3913506]
6. Close J, Ellis M, Hooper R, Glucksman E, Jackson S, Swift C. Prevention of falls in the elderly trial (PROFET): a randomised controlled trial. *Lancet* 1999;353(9147):93–7. [PubMed: 10023893]
7. Close JC, Lord SL, Menz HB, Sherrington C. What is the role of falls? *Best Pract Res Clin Rheumatol* 2005;19(6):913–35. [PubMed: 16301187]
8. Baloh RW, Ying SH, Jacobson KM. A longitudinal study of gait and balance dysfunction in normal older people. *Archives of Neurology* 2003;60(6):835–9. [PubMed: 12810488]
9. Horak FB, Shupert CL, Mirka A. Components of postural dyscontrol in the elderly: a review. *Neurobiol Aging* 1989;10(6):727–38. [PubMed: 2697808]

10. Woollacott MH, Shumway-Cook A, Nashner LM. Aging and posture control: changes in sensory organization and muscular coordination. *Int J Aging Hum Dev* 1986;23(2):97–114. [PubMed: 3557634]
11. 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(56):313–25. [PubMed: 16614476]
12. 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):392–9. [PubMed: 14960115]
13. Sienko, KH. Perturbation-based Detection and Prosthetic Correction of Vestibulopathic Gait [PH.D.]. Cambridge, MA: Massachusetts Institute of Technology; 2007.
14. Dozza M, Wall C, Peterka RJ, Chiari L, Horak FB. Effects of Practicing Tandem Gait with and without Vibrotactile Biofeedback in Subjects with Unilateral Vestibular Loss. *Journal of Vestibular Research* 2007;17(4):195–204. [PubMed: 18525145]
15. 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:S7–11. [PubMed: 1468055]
16. Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. *J Gerontol A Biol Sci Med Sci* 1995;50A(1):M28–34. [PubMed: 7814786]
17. Cohen HS, Kimball KT, Adams AS. Application of the vestibular disorders activities of daily living scale. *Laryngoscope* 2000;110(7):1204–9. [PubMed: 10892697]
18. Wall C 3rd, Weinberg MS. Balance prostheses for postural control. *IEEE Eng Med Biol Mag* 2003;22(2):84–90. [PubMed: 12733464]
19. Shumway-Cook, A.; Woollacott, M. *Motor Control: Theory and Practical Applications*. Baltimore, MD: Williams and Wilkins; 2001.
20. Wolf B, Feys H, De W, van der MJ, Noom M, Aufdemkampe G, 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):624–36. [PubMed: 11777093]
21. Shumway-Cook A, Baldwin M, Polissar NL, Gruber W. Predicting the probability for falls in community-dwelling older adults. *Phys Ther* 1997;77(8):812–9. [PubMed: 9256869]
22. Whitney SL, Marchetti GF, Schade A, Wrisley DM. 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* 2004;14(5):397–409. [PubMed: 15598995]
23. 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–M94. [PubMed: 11524454]
24. Clark RD, Lord SR, Webster IW. Clinical parameters associated with falls in an elderly population. *Gerontology* 1993;39(2):117–23. [PubMed: 8514201]
25. Rynnönen OP, Kivelä SL, Honkanen R. Times, places, and mechanisms of falls among the elderly. *Z Gerontol* 1991 May-Jun;24(3):154–61. [PubMed: 1927005]
26. Berg KO, Maki BE, Williams JI, Holliday PJ, Wood-Dauphinee SL. Clinical and laboratory measures of postural balance in an elderly population. *Arch Phys Med Rehabil* 1992;73(11):1073–80. [PubMed: 1444775]
27. Oyer DS, Saxon D, Shah A. Quantitative assessment of diabetic peripheral neuropathy with use of the clanging tuning fork test. *Endocr Pract* 2007;13(1):5–10. [PubMed: 17360294]
28. Rolke R, Magerl W, Campbell KA, Schalber C, Caspari S, Birklein F, et al. Quantitative sensory testing: a comprehensive protocol for clinical trials. *European journal of pain (London, England)* 2006;10(1):77–88.
29. Weinstein S. Fifty years of somatosensory research: from the Semmes-Weinstein monofilaments to the Weinstein Enhanced Sensory Test. *J Hand Ther* 1993;6(1):11–22. [PubMed: 8343870]
30. Jerosch-Herold C. Assessment of sensibility after nerve injury and repair: a systematic review of evidence for validity, reliability and responsiveness of tests. *Journal of hand surgery (Edinburgh, Scotland)* 2005;30(3):252–64.
31. Cohen HS, Kimball KT. Development of the vestibular disorders activities of daily living scale. *Archives of Otolaryngology -- Head and Neck Surgery* 2000;126(7):881–7. [PubMed: 10889001]

Figure 1.

Top. Elderly, prone-to-fall subject wearing the vibrotactile tile feedback vest during a DGI test session. The tactile vibrators are enclosed under the wide white elastic material that surrounds the subject's torso. The instrument unit is mounted on the outside of the elastic band while the processor and control units are mounted in black pouches that are suspended from a belt.

Reflective markers used for motion capture and movement analysis are placed to the trunk and limbs. **Bottom.** Example of ML tilt estimate time series for one DGI subtest with feedback Off (A) and ON (B). 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.

Figure 2.

A) Mean DGI Scores for all 8 DGI subtests averaged over all 12 subjects, with VTTF Off and VTTF On. Error bars show $\pm$ one Standard Error. DGI scale 0-24 with higher scores indicating better function. B) Average DGI score, by subtest, for VTTF Off and VTTF On conditions. Error bars show $\pm$ one Standard Error. The subtests include: 1. Gait on level surface, 2. Change in gait speed, 3. Gait with horizontal head turn, 4. Gait with vertical head turn, 5. Gait and pivot turn, 6. Step over obstacle, 7. Step around obstacle, 8. Walk up and down stair steps. DGI scale 0-24 with higher scores indicating better function.

Figure 3.
Average ML tilt during four locomotor tasks for VTTF Off and VTTF On. Error bars show $\pm$ one Standard Error

Figure 4.

A) Mean ($\pm$ standard error of the mean) of gait velocity during the 4 walking tasks. Note that during the 3 easier tasks the subjects walk slower while using the vibrotactile tilt feedback possibly learning to rely on the information and during the difficult task (EC narrow) the subjects walk faster utilizing the information for improved postural control. B) Percent double support time (mean $\pm$ standard error of the mean) during the 4 walking tasks.

Figure 5. Percent contribution of each DGI subtest towards the change in DGI score (100 %) between the VTTF Off and VTTF On conditions.

Table 1

Subject Demographics

Vibration: the ability to detect either a 128 or 256 Hz tuning fork at the first metatarsal phalangeal joint. Detection of 256 Hz indicates better vibratory sense.^{26, 27} Monofilament: the amount of force (in grams) detected on the sole of the foot using the Weinstein Enhanced Monofilament Test.^{28, 29} The ability to detect 10 grams of force is considered essential for protective sensation. ABC: Activities-specific Balance Confidence Scale,¹⁶ VADL: Vestibular Activities of Daily Living Scale,^{17, 30} BBS: Berg Balance Scale,²⁵ DGI: Dynamic Gait Index¹⁹, off: without VTTF, on: with VTTF.

Subject	Age	Gender	Vibration		Monofilament		ABC	VADL	BBS	DGI off	DGI on
			Right	Left	Right	Left					
1	70	F	256	256	0.5	2	95	1	55	19	22
2	73	M	absent	absent	50	50	82	1	52	19	22
3	74	F	256	256	0.5	0.5	75	2	55	18	19
254	75	M	256	256	0.5	0.5	100	1	52	17	22
5	80	F	128	128	2	2	85	1	54	15	21
6	80	F	256	256	10	10	14	4	49	16	20
7	81	F	128	absent	50	2	51	1	55	15	18
8	83	F	128	128	2	0.5	85	1	50	16	17
9	84	F	256	256	10	2	91	1	52	19	21
10	85	M	absent	absent	10	10	95	1	49	19	21
11	85	F	absent	absent	10	10	83	1	50	18	21
12	186	F	128	128	2	2	81	2	55	18	21