Application of Vibrotactile Feedback of Body Motion to Improve Rehabilitation in Individuals With Imbalance

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Background and Purpose: Balance rehabilitation and vestibular or balance prostheses are both emerging fields that have a potential for synergistic interaction. This article 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 anteroposterior direction. The feedback allowed subjects to significantly decrease their anteroposterior body tilt but did not change mediolateral tilt. A tandem walking task performed by subjects with vestibulopathies demonstrated a reduction in their mediolateral sway due to vibrotactile feedback of mediolateral body tilt, after controlling for the effects of task learning. Published findings from 2 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 falls were significantly improved with the use of mediolateral body tilt feedback.

Discussion and Conclusions: Although 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 third-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.

Key words: balance rehabilitation, vibrotactile tilt feedback, biofeedback, balance prosthesis

INTRODUCTION

Prosthetic devices are currently being developed to help replace loss of self-motion information due to disease, injuries, and aging. Balance or vestibular prostheses can be categorized into 1 of the 2 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 and perhaps provide improved spatial orientation input—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, which although 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 to maintain their balance while standing and walking. Balance rehabilitation therapy can be divided into 3 categories: (1) vestibular habituation exercises that have the patient to move their eyes, head, or body from 1 position to another repeatedly sometimes deliberately pairing antagonistic vestibular and visual stimuli; (2) positioning exercises to reposition particles in the peripheral vestibular system; and (3) exercises that include balancing and walking. 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” extravestibular 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 or electrocutaneous feedback with some degree of success. Because communication between the therapist and the patient is an important factor during rehabilitation, the investigator and collaborators have chosen tactile feedback. Tactile sensory substitution has been applied with varying degrees of success to replace senses lost because of disease or trauma. Examples include the use of braille for the blind and various tactile speech encoders developed for the deaf. Dynamic tactile displays have been demonstrated successfully as both auditory (eg, TactAID) and visual prostheses (eg, Optacon). Vibrotactile displays have also been demonstrated to be successful in aviation. For example, a blindfolded pilot can make a complete loop and return to a level flight using vibrotactile displays. Moreover, many data have been collected on the properties of the skin that can be used in building a tactile display.

This article first describes 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.

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are described next; these preliminary results are part of a larger study that is ongoing. The article then reviews findings from the 2 published studies using vibrotactile tilt feedback to summarize current application and evolving experience with the device by the author 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 vestibulopathies and to reduce the amount of trunk sway in individuals with moderate vestibulopathies.29

The device (Fig. 1) uses a 6 degrees of freedom motion sensor (3 linear accelerometers and 3 rate gyroscopes) that provides linear acceleration and angular rate information to an algorithm to estimate trunk tilt relative to the vertical. The device then feeds back this tilt information to the subject through 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, whereas rows are used to display magnitude. During standing, only 1 tactor is activated at a time and is driven by a continuous 250-Hz sinusoid. We generate 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 review). We refer to this signal as the tilt signal. Tilt signal = tilt angle + tilt rate/2.

The magnitude of the tilt signal is displayed in a steplike fashion. The resolution for the display of tilt magnitude is determined using a dynamic manual control paradigm33 and was set at 4 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 anteroposterior body axis. We can choose the number of columns to use for a given experiment (stance mode versus walking mode); for standing experiments, all 16 columns have typically been 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 mediolateral (ML) component is displayed in columns on either the right side or the left side of the subject’s body. Subject’s tilt to the right is displayed on the right column, tilt to the left is displayed on the left column, etc. The steplike 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 (ie, wherein performance is within acceptable limits) and 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. Although the effective bandwidth of the present device is not as wide as vestibular system information,34 the device does allow elderly subjects who have vestibulopathy or who are fall prone to significantly reduce their ML body sway during locomotion.35 Sensitivity to vibrotactile input is known to decrease 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 >100 subjects in protocols that span 5 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 with 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 indi-
Tense individuals with vestibulopathy. Subjects stand on a randomly moving 2-axis platform, while receiving 1-axis feedback. Twelve individuals (5 men and 7 women; aged 55 ± 9 years, range 43–71 years) 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 they 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 with instructions to stand as still as possible but 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 hypofunction or bilateral vestibular hypofunction on the basis of vestibular functional testing that included the electronystagmography test battery, rotation about the vertical, and computerized dynamic posturography (CDP). The 4 subjects with bilateral vestibular hypofunction had 0 or near 0 scores for CDP sensory organization tests 5 and 6, whereas the 8 subjects with unilateral vestibular hypofunction 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 before 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) that was mounted in the balance perturbation platform. The 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 were stored on computer disk for later analysis. The vibrotactile feedback device used in this study differed slightly from the previously described multiaxis device. The device used in this study was a single-axis system based on 1 accelerometer and a tilt sensor module with a gyroscope to sense angular rate. The 2 sensor signals were processed to obtain a sagittal tilt angle estimate that was accurate within 2 mrad over 0- to 10-Hz bandwidth. The device used 3 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 were recorded and then stored on the laptop computer that communicates with the device. Tilt and COP data were analyzed using MATLAB. Conditions with and without vibrotactile feedback were compared with a nonparametric statistical procedure, Wilcoxon’s matched pairs test, using Statistica version 5.5 software package (Statsoft Inc., Tulsa, OK) was used. The threshold for statistical significance was set at $p \leq .05$.

### Results

Effects of vibrotactile feedback during continuous horizontal support surface perturbations on COP and trunk tilt parameters are shown in Table 1. Anteroposterior trunk tilt showed a statistically significant decrease in variability in the presence of vibrotactile feedback (38% decrease in anteroposterior sway). In addition, subjects demonstrated a statistically significant increase in median frequency of trunk sway (45%) and 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 reports the 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 10 subjects with documented unilateral peripheral vestibular lesions (5 men and 5 women; age, 53 ± 16 years; height, 172 ± 9 cm; and weight, 87 ± 21 kg) were divided into 2 groups. The average age, height, and weight in the 2 groups were not statistically different. All subjects were free from orthopedic and neurologic 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 system32 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 2-at-a-time, starting with the lowest ones, passing to

### Table 1. Statistically Significant Effects of Vibrotactile Feedback During Pseudorandom Perturbations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control</th>
<th>Change From Control</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body tilt AP Av (degrees)</td>
<td>0.55 ± 0.33</td>
<td>−0.23</td>
<td>.023</td>
</tr>
<tr>
<td>Body tilt AP Av range (degrees)</td>
<td>3.11 ± 1.02</td>
<td>−0.54</td>
<td>.019</td>
</tr>
<tr>
<td>Body tilt AP Av root mean square (degrees)</td>
<td>0.80 ± 0.29</td>
<td>−0.21</td>
<td>.019</td>
</tr>
<tr>
<td>COP ML Av range (mm)</td>
<td>34.3 ± 23.3</td>
<td>−5.2</td>
<td>.050</td>
</tr>
<tr>
<td>COP AP Av range (mm)</td>
<td>54.8 ± 17.1</td>
<td>−5.1</td>
<td>.028</td>
</tr>
<tr>
<td>COP AP median frequency (Hz)</td>
<td>0.44 ± 0.15</td>
<td>+0.15</td>
<td>.002</td>
</tr>
<tr>
<td>COP AP velocity (mm/s)</td>
<td>34.7 ± 12.8</td>
<td>+4.05</td>
<td>.005</td>
</tr>
</tbody>
</table>

Abbreviations: AP, anteroposterior; Av, average; ML, mediolateral; COP, center of pressure; SD, standard deviation.
the middle ones; then to the highest ones, with progressively higher pairs being activated the more the subject’s trunk was tilting in the direction where the vibration was applied.

After familiarization and training, subjects performed 2 sets of 24 trials of tandem walking. A crossover design was used in which group 1 had the first set of trials with vibrotactile tilt information fed back to them, and the second set of trials with no feedback. In group 2, 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**

Analysis of variance 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 ($P < .05$).

There was also less ML tilt when the feedback was on compared with the control (no feedback) condition ($P < .05$). Thus, vibrotactile feedback of ML body tilt seems 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 risk of falls.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, 12 community-dwelling elderly subjects (3 men and 9 women, aged 79.6 ± 5.4 years) were tested.35 Subjects were included if they were between the ages of 65 and 90 years, had no neurologic 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 subjects based on the Activities-specific Balance Confidence Scale42,43 (78.1 ± 23.7), Vestibular Disorders Activities of Daily Living Scale44,45 (mean 1.78), and Berg Balance Scale46,47 (52.3 ± 2.4). During all trials, the subjects were wearing a vibrotactile tilt feedback system31 described earlier. A reassuring stimulus (activation of only the lowest tactors) was given during normal locomotion and an alerting stimulus (activation of all 3 tactors in 1 column) was given when the ML tilt was off-normal. A baseline Dynamic Gait Index48 (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 to 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**

Exemplar data from 1 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 feedback off. The basic effect of using feedback is that it helps people to stay more closely aligned with the vertical as 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, $P < .001$), 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 sig-
significant change (ie, after a rehabilitation intervention).50,51 Ten of 12 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 4 instances when feedback was used. Thus, vibrotactile feedback of ML body tilt seems to decrease ML trunk tilt and risk of falls in healthy elderly 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 on a previous study of falls in community-based elderly adults50 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 the data of frequency of falls and DGI scores (Fig. 3C). From this model, a DGI score of 17.4 (no feedback) corresponded to an 83% chance of falling in a 6-month period, whereas a score of 20.4 (feedback used) corresponded to a 23% chance falling in the same period. Although 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 of falls in this population.

FIGURE 3. A, Example of M/L trunk tilt estimate time series for 1 DGI subtest (walk while making vertical head movements) with feedback off and on. B (left and center), Photographs of a subject at the end of a Dynamic Gait Index (DGI) subtest (ie, 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 DGI scores from a model based on Shumway-Cook et al.50

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 neuropathy, amputation, and chronic imbalance (eg, 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 or 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 developed a third-generation device prototype that is more compact, user-friendly, and 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 4 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 to which a subject can react quickly as they could using the former 3-tactor scheme. Thus, the number of tactors has been reduced from 48 to 4 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 redesign 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. Although 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 beltlike device, which may greatly enhance the clinical applicability of this emerging technology.

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