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4 AUTHORS, INCLUDING:

Lars Ingimar Eugen Oddsson
University of Minnesota Twin Cities

Conrad Wall
Massachusetts Eye and Ear Infirmary

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Effects of multi-directional vibrotactile feedback on vestibular-deficient postural performance during continuous multi-directional support surface perturbations

K.H. Sienko[a,b,e,*], M.D. Balkwill[b], L.I.E. Oddsson[d,f] and C. Wall[b,c]
[a]*Division of Health Sciences and Technology, Harvard-Massachusetts Institute of Technology, Cambridge, MA, USA*
[b]*Jenks Vestibular Diagnostic Laboratory, Massachusetts Eye and Ear Infirmary, Boston, MA, USA*
[c]*Department of Otology & Laryngology, Harvard Medical School, Boston, MA, USA*
[d]*NeuroMuscular Research Center, Boston University, Boston, MA, USA*
[e]*Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA*
[f]*Sister Kenny Research Center, Sister Kenny Rehabilitation Institute, Minneapolis, MN, USA*

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Abstract. Single-axis vibrotactile feedback of trunk tilt provided in real-time has previously been shown to significantly reduce the root-mean-square (RMS) trunk sway in subjects with vestibular loss during single-axis perturbation. This research examines the effect of multi-directional vibrotactile feedback on postural sway during continuous multi-directional surface perturbations when the subjects' eyes are closed. Eight subjects with vestibular loss donned a multi-axis feedback device that mapped body tilt estimates onto their torsos with a 3-row by 16-column array of tactile actuators (tactors). Tactor row indicated tilt magnitude and tactor column indicated tilt direction. Root-mean-square trunk tilt, elliptical fits to trunk sway trajectory areas, percentage of time spent outside a no vibrotactile feedback zone, RMS center of pressure, and anchoring index parameters indicating intersegmental coordination were used to assess the efficacy of the multi-directional vibrotactile balance aid. Four tactor display configurations in addition to the tactors off configuration were evaluated. Subjects had significantly reduced RMS trunk sway, significantly smaller elliptical fits of the trajectory area, and spent significantly less time outside of the no feedback zone in the tactors on versus the tactors off configuration. Among the displays evaluated in this study, there was not an optimal tactor column configuration for standing tasks involving continuous surface perturbations. Furthermore, subjects performed worse when erroneous information was displayed. Therefore, a spatial resolution of 90° (4 columns) seems to be as effective as a spatial resolution of 22.5° (16 columns) for control of standing.

Keywords: Vibrotactile, balance prosthesis, biofeedback, balance, intuitive display

1. Introduction

Sensory substitution is a technique of replacing or augmenting compromised sensory information. Var-

*Corresponding author: Kathleen Sienko, 2350 Hayward Street, 3116 GG Brown, Ann Arbor, MI 48109-2125, USA. Tel.: +1 734 647 8249; Fax: +1 734 615 6647; E-mail: sienko@umich.edu.

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ious modes of delivering sensory substitution including electrotactile, vibrotactile, and auditory body sway biofeedback have been effective in improving postural stability during stationary tasks while simultaneously being fairly easy to use [4,7,8,13,22]. We have previously demonstrated increased postural stability for subjects with unilateral and bilateral vestibular loss donning a vibrotactile balance aid during computerized posturography experiments [13,22,23,25]. During test conditions that induced a mild two-axis random platform motion, all subjects significantly reduced their anterior-posterior (A/P) sway when only A/P tilt was displayed. However, the change in medio-lateral (M/L) sway was not significant, suggesting direction-specific control [25]. The aid has also been shown to decrease sway in subjects with normal sensory function, however, the margin of improvement in this group is less than it is in subjects with moderate or severe vestibular loss [15,20].

The vibrotactile feedback device consists of a motion-sensing system mounted on the lower back of the subject, a vibrotactile display, and a laptop computer with analog and digital interfaces. The experiments with the vibrotactile balance aid to date have used an input to the vibrotactile display that is the summation of a body tilt estimate and one-half of its first derivative (tilt rate). This feedback scheme is supported by a previous investigation that showed the greatest reduction of root-mean-square (RMS) trunk tilt was achieved during computerized dynamic posturography with proportional plus derivate feedback versus proportional or derivative feedback alone (Wall, manuscript in preparation).

Other modalities are also being explored for tilt biofeedback including display of body position via a lingual stimulator [4,5,21] and auditory biofeedback [6, 7,12]. Dozza et al. has shown that audio biofeedback does not simply increase stiffness, but aids in the central nervous system (CNS) actively adapting its control activity over standing posture [6].

The primary aim of this study is to determine whether or not multi-directional feedback during multi-directional surface perturbations improves postural stability in subjects with vestibular loss. This research also seeks to determine the optimal number of columns of tactors for achieving postural stability during multi-directional support surface perturbations. An argument can be made for a vibrotactile display with the greatest spatial resolution allowable by two-point discrimination in order to supply the subject with the most accurate information regarding his/her tilt. This is offset by the potential increase in cognitive workload required to interpret and use that information and the anatomical joint constraints influencing the corrective ankle, knee, and hip movements. We hypothesized that multi-axis (4–16 columns of tactors) display of body tilt during multi-directional surface perturbations would reduce sway in both A/P and M/L directions and that the 16-column configuration would result in the lowest RMS tilt, smallest sway trajectory area, and least amount of time spent outside of a one-degree dead zone where no vibrotactile feedback is provided.

2. Methods

2.1. Subjects

Eight weakly compensated vestibulopathic subjects were referred by the Massachusetts Eye & Ear Infirmary (MEEI) Department of Otolaryngology clinicians for this study. Weakly compensated was defined as those subjects who failed the NeuroCom® EquiTest® computerized dynamic posturography Sensory Organization Tests (SOT) 5 and 6. During SOT 5, the subject's eyes are closed and the posture platform is sway referenced (i.e. moves in synchrony with the subject's A/P body sway). SOT 6 is performed with the subject's eyes open while both the platform and visual surround are sway referenced. Subjects with histories of mental illness and/or motor deficits were excluded. Additionally, individuals with a body mass index greater than 30 were excluded due to the size constraints of the vibrotactile balance aid. Table 1 shows the subjects' vestibular test results and relevant demographic information. The Massachusetts Eye & Ear Infirmary, Boston University, and Massachusetts Institute of Technology Institutional Review Boards approved the experimental protocol, which conformed to the Helsinki Declaration. Informed consent was obtained from each subject prior to the start of the experiment. The subjects wore a safety harness that was suspended from the ceiling for the entirety of the experiment. A sufficient amount of slack in the safety harness system was provided to account for platform displacements during the perturbation protocol. Freitas et al. has shown that the contact of the safety harness with the body does not affect sway during quiet stance [10] and subjects verbally confirmed that they could not perceive support from the safety harness prior to the start of the experiment (i.e. the harness was not pulling on them). Additionally, a safety spotter stood on the platform directly behind the subject.

Table 1
Subject demographics and vestibular diagnostic results

Subject demographics				Computerized dynamic posturography				Classification	Rotation test			Caloric test	
Subject ID	Age	Gender	Inter-test period	SOT score	SOT 5	SOT 6	MCT score	UVH or (pBVH)*	Probability of normal VOR	VOR midrange gain	Time constant(s)	RVR (%)	Caloric sum (°/s)
1	55	M	72	49	Fall, Fall, Fall	Fall, Fall, Fall	N/A	BVH†	< 0.001	0.333	N/A	-100	3
2	55	F	–	32	Fall, Fall, Fall	Fall, Fall, Fall	128	BVH†	< 0.001	0.816	N/A	0	0
3	45	M	1	45	Fall, Fall, Fall	Fall, Fall, Fall	128	($p <$ 1e-14)	< 0.001	0.841	2.02	0	0
4	59	M	60	N/A	N/A	N/A	N/A	BVH†	< 0.001	0.04	N/A	0	0
5	51	F	40	56	Fall, 26, 45	Fall, Fall, 45	158	**	0.118	0.956	14.02	-4	23
6	32	M	56	46	Fall, Fall, Fall	Fall, Fall, Fall	151	BVH†	< 0.001	0.514	N/A	0	0
7	67	F	–	36	Fall, Fall, Fall	Fall, Fall, Fall	126	($p <$ 1e-14)	< 0.001	0.285	3.19	-100	3
8	45	M	12	49	Fall, Fall, Fall	Fall, Fall, Fall	130	BVH†	< 0.001	0.899	N/A	-11	9

Inter-test Period - Number of days between test sessions for the six subjects who participated in both sessions.
SOT – Sensory Organization Test: Normal mean composite scores are 80 for 20–59 years old (yo) & 77 for 60–69 yo. Abnormal classification threshold (5th percentile) for SOT 5 is 52 for 20–59 years old (yo) & 51 for 60–69 yo. Abnormal classification threshold for SOT 6 is 48 for 20–59 yo & 49 for 60–69 yo.
MCT – Motor Control Test: Normal mean composite scores are 143 for 20–59 yo & 152 for 60–69 yo. Abnormal classification thresholds (5th percentile) are 161 for 20–59 yo & 171 for 60–69 yo.
N/A – Not available.
VOR – Vestibuloocular reflex, as tested by 50 deg/sec peak sinusoidal vertical axis rotation, 0.05 Hz–1 Hz.
RVR – Reduced vestibular response to bilateral, bithermal caloric stimulation.
*UVH or (pBVH) – Unilateral (UVH) or bilateral vestibular hypofunction, based upon Dimitri et. al., 2002. If subject is scored as bilateral hypofunction (BVH), then the probability of this occurring by chance is given in parentheses.
†Response was too low for accurate estimation of time constant; classified as BVH by low VOR gain and low bilateral ice water calorics.
**Classified as abnormal by low scores on CDP SOT 5 & 6.
Midrange gain (0.2 Hz–1 Hz) and time constant estimated with parametric fit to gain and phase data (based on Dimitri et al., 1996).

2.2. Equipment

Data were collected in the Injury Analysis and Prevention Laboratory in the NeuroMuscular Research Center at Boston University. Subjects stood on a custom-built BALance DisturbER (BALDER platform) [17], 2.1 m square, which moved in an earth horizontal plane. The primary components of the BALDER platform include a force-plate (ORG-6 AMTI, Newton, MA, USA) embedded in a wooden platform, two AC-servo motors controlled by two linear servo drivers, two high precision linear position transducers (Novotechnik, Germany), and a 16 channel data acquisition board (Microstar 3200e/415). Two-axis platform position and center of pressure (COP) data were digitized at 100 Hz. Kinematic data were collected using an Optotrak 3020 system (Northern Digital, Waterloo, Ont.). Rectangular arrays consisting of six infrared emitting diodes (IREDs) were placed on the subject's pelvis, sternum, and head, and a single IRED was affixed to the platform. The IRED array positions were estimated at 100 Hz. The Optotrak 3020 was placed 3.5 m from the BALDER platform within the system's optimal viewing area. The 3D IRED translations were recorded and converted to six degree of freedom data using the Data Analysis Package provided with the system.

The vibrotactile balance aid consisted of a two-axis motion-sensing system mounted on the lower back of the subject, a vibrotactile display, and a laptop with analog and digital interfaces (Fig. 1). The inertial motion-sensing system was composed of microelectromechanical (MEMS) gyroscopes that sense angular rate and MEMS accelerometers that sense linear accelerations [24]. The gyroscope and accelerometer signals were sampled at 100 Hz and processed to obtain a tilt angle estimate accurate to within 2 milliradians over a 0 to 10 Hz bandwidth. Tilt estimates were displayed on the subjects' torsos via a 3-row by 16-column tactile vibrator array; rows of the array displayed estimated tilt magnitude and columns displayed tilt direction. The tactile actuators (Tactaid, Cambridge, MA), referred to as tactors, operated at a constant amplitude (200 mA) and frequency (250 Hz). All subjects reported that they were able to perceive the tactor vibrations.

The tactor firing range was set on a subject-by-subject basis. Limits of postural stability were defined by the subject's maximum possible straight body tilt without loss of balance in each of the four cardinal directions during quiet stance. An elliptical fit to these values produced an estimate of the limits of stability (LOS) in all directions (Fig. 2). No tactors were activated within a subject-specific zone to allow for normal body sway. This zone will be referred to as the dead zone. The lowest row was activated when the tilt exceeded the dead zone threshold (0.5° for subject #3,

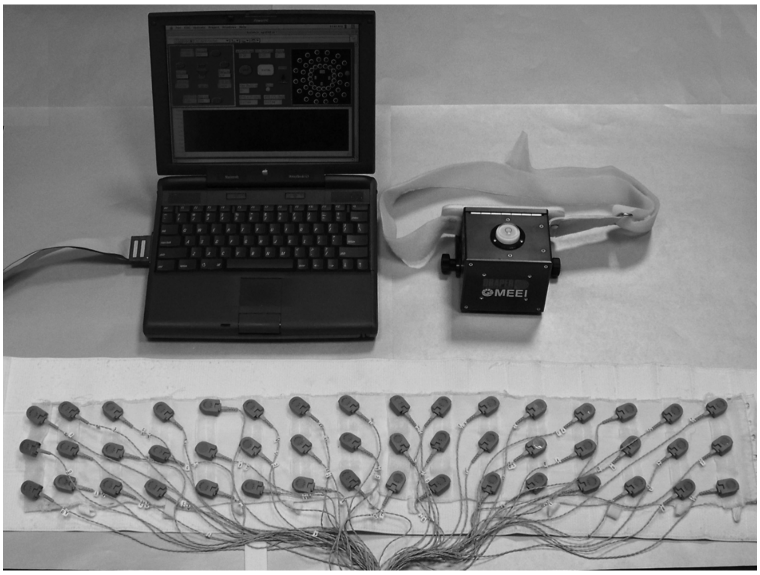

Fig. 1. Vibrotactile balance aid 3 × 16 tactor array and electronics.

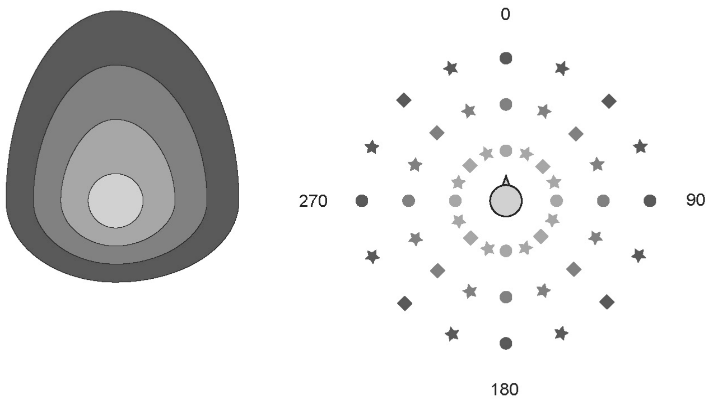

Fig. 2. Tactor zones and column displays. Tactor column configurations are shown on the left with the coordinate definitions as viewed from the top-down perspective with the triangle corresponding the subject's nose. Tactor column positions are indicated by circles for the 4-column displays, circles and diamonds for the 8-column display, and circles, diamonds, and stars for the 16-column display. The right panel depicts typical tactor zone definitions. No tactors are activated as long as the subject's sway remains in the circular dead zone (lightest region). As sway increases, the subject progresses into zones 1, 2, and 3 (as denoted by increasing grey levels) and the corresponding tactor row is activated. The outer limit of zone 3 is determined by finding the maximum possible straight body tilt in each of the four cardinal directions, and fitting an ellipse in each quadrant.

1° for the others). With increasing body sway, tactor firing progressed from the bottom to the top tactor row along the appropriate tactor column in a stepwise fashion. Activation of the middle and highest tactor rows corresponded to a tilt in excess of, respectively, 33% and 67% of the remaining LOS. Subjects were instructed to always move to null out the vibration by staying within the dead zone; zones 1, 2, and 3 were defined as the regions in which the first, second, and third rows of tactors were active, respectively. The tilt signal displayed to the subject for this study was the tilt estimate plus one half the tilt rate. This is a special case of a proportional–integral–derivative controller (PID controller). PID controllers are commonly used in feedback control systems [18].

The tactor coordinate system was defined as shown in Fig. 2 (0° corresponds to the axis perpendicular to the intra-aural axis and 90° corresponds to the subject's right as viewed from above). Sixteen columns of tactors were equally spaced about the torso at 22.5° in-

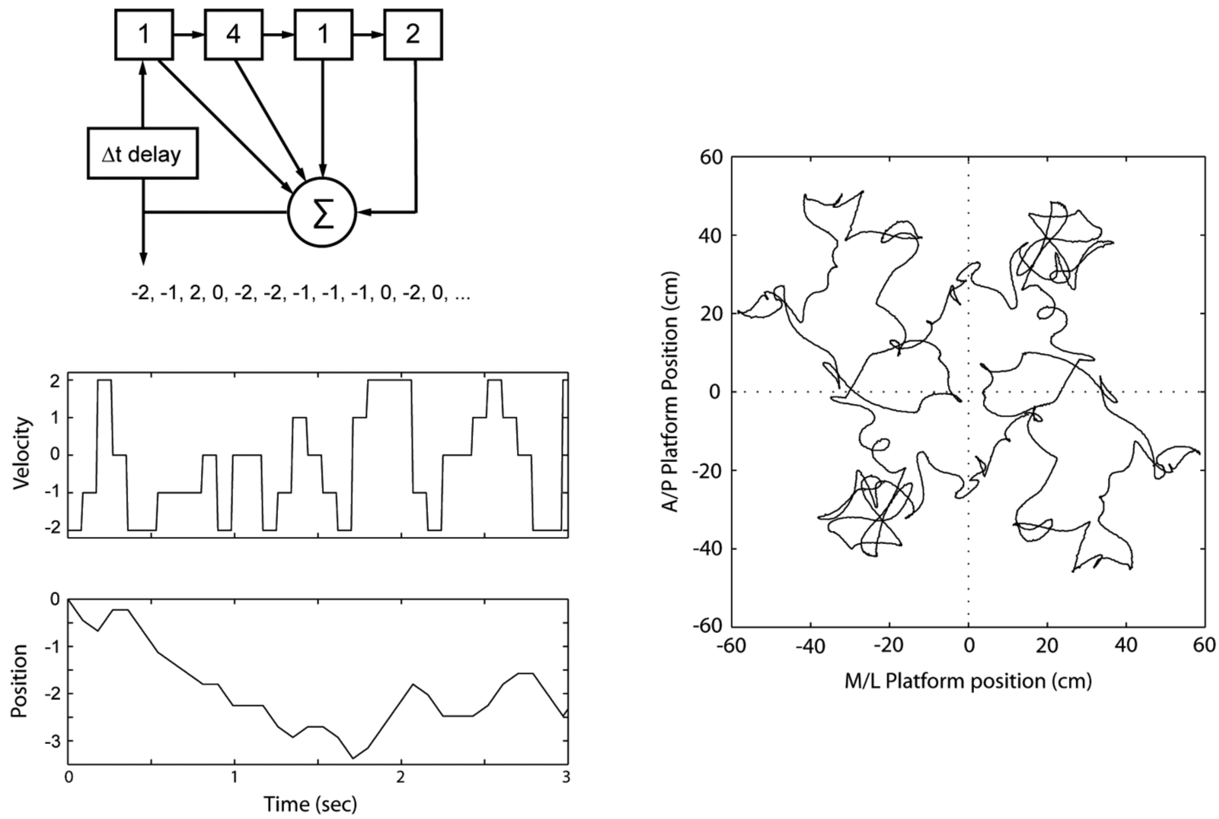

Fig. 3. Continuous perturbation stimulus profile. Four stage shift register with feedback generates a pseudorandom pentary sequence (PRPS) using modulo 5 addition. At each time increment ($\Delta t = 0.09$ s) the value of each register is shifted to the right. The PRPS sequence is converted to a stimulus velocity. The stimulus velocity and its time integral are shown in the lower left panels. This signal controlled the motion for one axis of motion. Another uncorrelated PRPS sequence (not shown) was used for the second axis. The right panel depicts the overhead view of the actual platform motion from a typical subject.

tervals and numbered sequentially in a clockwise direction, with the first column aligned with 0°. Three tactor configurations (4, 8, and 16) evaluated the effects of spatial resolution by using different numbers of columns: the 4-column display used only the tactors in the four cardinal directions (columns 1, 5, 9, and 13, denoted as circles in Fig. 2), the 8-column display used the odd-numbered columns (denoted as circles and squares), and the 16-column display used all columns. The direction of tilt (azimuth) was calculated from the arctangent of A/P and M/L tilt components and used to activate the appropriate column on a "nearest neighbor" principle. For example, a tilt of 4° forward and 2° rightward would result in a tilt direction of 26.6° which would correspond to column 1 in the 4-column configuration, column 3 in the 8-column configuration, or column 2 in the 16-column configuration; the overall tilt magnitude of 4.5° would typically activate the middle tactor in that column. No more than a single tactor was activated in these three configurations. A fourth tactor configuration (4I) used four columns by combining two independent single-axis systems, displaying A/P tilt information on columns 1 and 9, and M/L tilt information on columns 5 and 13. This scheme activated no tactors when both A/P and M/L tilt were less than the dead zone threshold, one column when motion along one axis exceeded the threshold, or two columns when both tilt components exceeded the threshold. In the aforementioned example, the 4° forward tilt would typically activate the middle tactor in column 1 and the 2° rightward tilt would typically activate the lowest tactor in column 5, with both tactors fired simultaneously. Subjects were also tested while wearing the balance aid without receiving any vibrotactile feedback, referred to as the no tactor (NT) configuration.

2.3. Platform stimuli

Pseudorandom translation of the support surface was selected for the continuous motion stimulus based on the previous use of a ternary sequence by Peterka to investigate sensorimotor integration in human postural control [19]. We chose a 5-level pseudorandom pentary sequence (PRPS) in order to produce platform motion having a wider range of movement directions than can be achieved with a 3-level stimulus. A linear velocity command sequence was created from a 624-length (maximal) PRPS sequence by assigning fixed values of $+2$v, $+$v, 0, $-$v, or -2v °/s to a four stage/modulo 5 addition shift register output with a state duration of Δt = 0.09 s (Fig. 3). The total duration of each resultant sequence was approximately one minute. This sequence was low pass filtered (4th order Butterworth, f_c = 3 Hz) and integrated to create a position waveform. The initial value of the shift register was selected so that the position waveform was balanced between positive and negative values. Two independent (i.e. uncorrelated) waveforms were used as the x and y platform velocity command signals during the training session; the RMS velocity of platform motion ranged from 2.4 to 4.2 cm/s. Three repetitions of a separate pair of waveforms were concatenated in time to generate a three-minute stimulus for the testing trials. Figure 3 shows an overhead view of one cycle of the continuous test stimulus. The magnitude of the stimulus was adjusted during the training session based on each subject's subjective balance capabilities.

2.4. Training procedure

Each subject was trained on the use of each balance aid configuration totaling approximately 30 minutes at the beginning of the experimental session. Initially, the subject stood with eyes open while the platform was moved according to the one-minute training stimulus with no tactor feedback. This was followed by a second training run during which the eyes were initially open, but were closed after 30 seconds, and a third training run during which the eyes were closed throughout the entire minute. Then, the 4-column tactor configuration was described and the subject was allowed to gain familiarity with the tactor feedback while the platform was stationary. The series of three one-minute training runs (eyes open, eyes open for 30 s, eyes closed) was then performed with the 4-column configuration active. Subsequently, this same combination of description, familiarization, and three training runs was repeated for each of the other configurations: 4-independent, 8-column, and 16-column. The training order was identical for all subjects.

The subject was asked throughout the training to verbally rate the perceived balance difficulty on a scale of 1 to 10, where 10 was defined as the subject's most difficult balance challenge. The magnitude of the platform motion was adjusted so that balance could be maintained without eliciting a step and the difficulty was rated as a 7. In general, the perturbations were small enough that it appeared to a visual observer that subjects primarily used an ankle strategy, i.e. the body was maintained straight and postural corrections were performed at the ankle.

2.5. Experimental design

The order in which the four tactor configurations were presented to the subject varied based on a Balanced Latin Squares design with tactor configuration as the primary factor. This produced four groups consisting of two subjects each. All trials were conducted with the subjects' eyes closed. All subjects were first tested with no tactors (NT1). This was followed by tests of the four tactor configurations, and then a second no tactor trial (NT2) resulting in a core test battery of six trials. Subjects were given a 5-minute break after the third trial. When the core tests were completed, and after a 20-minute rest, a third no tactor trial (NT3) was performed to evaluate short-term retention and fatigue effects. Finally, subjects completed a trial in which erroneous tilt information, instead of real-time trunk tilt estimates, was fed back to them in order to examine a potential placebo effect (i.e., non-specific stiffening, balance-task specific attention cueing, etc.). For this test, the subject's own sway previously recorded during a training stimulus was displayed to the subject. The training stimulus differed from the testing stimulus and therefore the feedback information was erroneous and unrelated to the subject's actual sway in response to the testing stimulus. This erroneous playback trial was the final trial during each session in order to prevent the subjects from losing confidence or questioning the validity of the balance aid in subsequent trials.

Six of the eight subjects returned on a subsequent date ranging between one day and two months later during which two continuous perturbation tests were performed without any additional training. The first of the two trials was conducted with no tactors active (NT4) as part of a long-term retention study. The second trial (16B) used the 16-column display to assess the intuitiveness of the device and the subjects' ability to perform the task of using the device without recent practice. Table 1 indicates the varying times between the first and second testing dates. Note, the erroneous feedback and Session 2 testing comprised only six subjects.

Subjects wore a lightweight polyester tee-shirt (Patagonia silk weight Capilene®) and were instrumented with the vibrotactile balance aid and optical markers. During the testing session, subjects were not told which tactor configuration they were using unless it was an NT trial. Subjects were instructed to move to null out the vibrations regardless of the display configuration. Subjects were instructed to close their eyes for all trials and keep their arms placed at their sides. Their feet were positioned in a standard configuration on the BALDER force plate (slightly less than hip-width apart and skewed slightly outward).

A modified five point Likert scale [14] was used to assess the subjects' impression regarding the usefulness of the device in improving stability. Subjects could select the following responses when asked to complete the statement: "I found the device to be": (1) very unhelpful; (2) moderately unhelpful; (3) neutral-neither helps nor hurts; (4) moderately helpful; and (5) very helpful. In addition to the Likert question, subjects were verbally asked to rate their perception of task difficulty and fatigue level on a scale of 1 (very easy balance task, no fatigue, respectively) to 10 (most difficult balance task, completely fatigued, respectively) following every trial. The fatigue scale was used to determine when additional rest periods were to be taken (greater than 6 out of 10).

2.6. Data analysis

All post-processing was performed using MATLAB (The MathWorks, Natick, MA). Following data collection, the data were low-pass filtered with a 4th order phaseless Butterworth filter (MATLAB filtfilt.m) with a corner frequency of 10 Hz to remove high frequency noise. Statistical analyses were conducted using STATA (StataCorp LP, College Station, TX). Each continuous perturbation stimulus contained three identical concatenated sequences referred to as cycles. The reported parametric analyses delineated below were calculated on a cycle-by-cycle basis and then averaged. The average of the NT1 cycles, which were performed without vibrotactile feedback, was used for normalizing subsequent trials to facilitate comparisons across subjects. A repeated measures ANOVA was performed with tilt magnitude, tilt path length, trajectory area, zones, and anchoring indices as dependent variables. The independent factors were trial type, subject, and cycle repetition. Significance was defined at the $p < 0.05$ level.

Tilt magnitude, referred to as phi tilt, was calculated as the square root of the squared sum of roll and pitch tilt components. The root mean square (RMS) of the A/P, M/L, and phi tilt were computed by taking the square root of the time average of the squares. Tilt path length was computed by summing the magnitudes of the differential sample-to-sample tilt changes. Similar parameters were generated from the COP data. In order to capture the difference in trajectory area, the resultant two-axis tilt vector was fit with 95% confidence interval ellipses.

The region between the subject-specific dead zone and the limits of stability was divided into three zones (see Fig. 2). For each of these three zones, Z_i was calculated as the fraction of time during the cycle that the tilt was in the corresponding zone. A severity parameter was defined as a linear weighted sum of the fraction of time spent in the various zones.

$$\textit{Severity} = Z_1 + 2 \times Z_2 + 3 \times Z_3$$

where, Z designates zone.

The anchoring index is a previously published parameter for characterizing head and trunk stabilization strategies in the frontal plane during unperturbed locomotion [1–3]. The index describes the relative angular distribution of the body segment being considered with respect to axes linked to an inferior anatomical segment. The anchoring index is defined as:

$$\mathrm{AI} = [(\sigma_r) - (\sigma_a)]/[(\sigma_r) + (\sigma_a)]$$

where, σ_a is the angular dispersion of any body segment and σ_r is the standard deviation of the relative angular distribution of the body segment being considered with respect to axes linked to an inferior anatomical segment. A positive value of the anchoring index indicates a tendency for trunk stabilization in space rather than on the hip, whereas a negative value would indicate a tendency for trunk stabilization on the hip rather than in space. In theory, this index reveals whether an individual adopts an "en bloc" or inverted-pendulum like stabilization strategy. The head anchoring index explores the relationship of the head to the sternum and sternum anchoring index explores the relationship of the sternum with respect to the pelvis.

3. Results

3.1. Tilt data

Figure 4 shows an example of tilt data from a representative subject. The left subplot depicts the sway

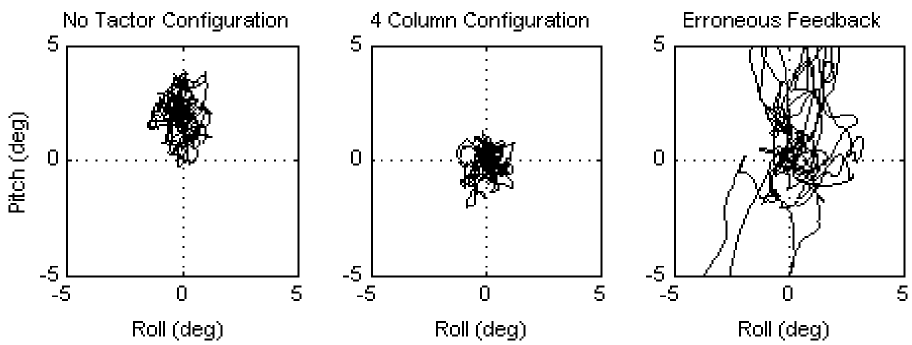

Fig. 4. Sample data representative of subject performance from a single subject, one cycle of continuous stimulus. The first plot shows the bird's eye view of one subject's tilt in the no tactor configuration. The second plot shows the performance when the tactors are turned on in the 4 column display configuration. The third plot shows the subject's errant trunk tilt when the erroneous feedback was provided.

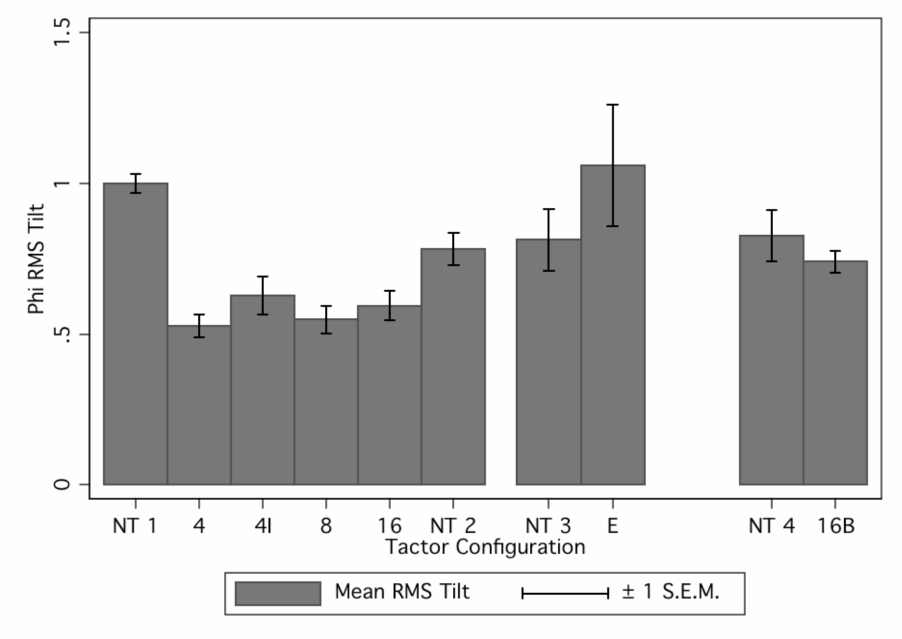

Fig. 5. Normalized phi RMS trunk tilt by display configuration. NT denotes "no tactors" trials. NT1 is the pretest trial and NT2 is the posttest trial. NT3 occurred during Session 1 testing after a 20-minute rest following the completion of the NT2 trial. E denotes the erroneous feedback trial. NT4 and 16B occurred during Session 2. The error bars show the standard error of the mean.

trajectory of the subject with no tactors. The center subplot shows the sway trajectory when the device is turned on and the 4-column display "nearest neighbor" principle is used. The right subplot shows the sway trajectory during the erroneous feedback trial. The subject had approximately a two-degree pitch forward bias without the tactors. When the tactors were turned on, the subject was able to maintain balance about the vertical (zero degree pitch and roll). During the erroneous feedback trial, the sway excursion increased in both the A/P and M/L directions.

Data for each display configuration were averaged regardless of the order in which that configuration was tested; no significant order effects were found unless otherwise noted. Error bars represent the standard error of the mean.

Figure 5 shows the mean normalized phi RMS trunk tilt averaged across all subjects for each trial type. An analysis of variance was performed with normalized phi RMS tilt as the response variable and trial type, subject, and cycle as the factor variables. Trial type ($p < 0.0001$), subject ($p < 0.0001$) and cycle were statistically significant ($p < 0.0465$). Cycle 1 had a mean phi tilt equal to 0.699, while cycle 2 and 3 had mean values of 0.708 and 0.768, respectively. The NT results were significantly larger than the tactor on configuration trials with the exception of the erroneous feedback trial; however, there was not a significant difference amongst tactor configurations.

Broken down into tilt components, the M/L and A/P RMS trunk tilt were also significantly larger for the NT1 and NT2 trials than for the tactor on configurations. However, NT2 and NT3 produced lower RMS tilt values than NT1. The erroneous feedback trial yielded higher values than either the NT2 or NT3 trials and slightly (but not significantly) larger values than NT1. The long-term retention trial (NT4) showed a similar value to NT2 and NT3. Of the four tactor on configurations, the 4I column configuration produced the largest RMS tilt values. The 16B trial on the second day of testing was lower, but not significantly lower than the tactors off trial on that same day.

The mean ellipse area findings were similar to those for phi RMS tilt. Figure 6 shows the mean normalized ellipse areas averaged across all subjects for each trial type. Trial type ($p < 0.0001$) and subject ($p < 0.0001$) were statistically significant. The no tactor trials (NT1, NT2, NT3, and NT4) values were significantly larger compared to all four tactor on conditions; however, there was not a statistically significant difference amongst tactor configurations. The erroneous feedback trial had a statistically significantly greater mean ellipse area compared to all other trial types, including both the tactors off and tactors on configurations.

Table 2 ranks subject performance with each of the four display types, according to phi RMS trunk tilt and ellipse area. A rank of 1 indicates that the subject had the lowest phi RMS tilt value or the smallest ellipse area while using that display type. A rank of 4 corresponds to either the highest phi RMS tilt value or the largest ellipse area. On average, the 4-column display ranked the best among subjects for phi RMS tilt values and tied the 8-column display for smallest ellipse areas. For both parameters, the 4I display had the worst rankings.

Figure 7 depicts the results from the zonal analysis. The percentage of time spent in zones 2 and 3 was significantly greater ($p < 0.0006$ and $p < 0.0025$, respectively) for NT1 and NT2 than for the tactor on configurations. Additionally, the percentage of time spent in zone 3 was significantly greater in the erroneous feedback trial compared to any of the other trials. The only zone that did not show a statistically significant change was zone 1.

The severity parameter was significantly higher ($p < 0.0009$) for NT1 compared to all four tactor on conditions. There was no statistically significant difference amongst tactor configurations. Although the NT2 value is approximately one third of the NT1 value, it is still significantly higher than those of the four balance aid configurations.

3.2. Kinematic and center of pressure data

There were no statistically significant differences for any angular dispersion values or anchoring indices. RMS COP and path length results mirrored the RMS tilt results (statistically significant by trial type and subject, but not by cycle).

3.3. Subjective findings

Some subjects were able to rank order their display configurations in terms of preference while others were not. Four of the eight subjects preferred the 4 column display, two preferred the 16 column display, one preferred the 8 column, and one preferred the 4 independent column display. Preferences did not correlate with performance; one subject preferred the 16 column display, but it was that subject's worst display in terms of RMS tilt and ellipse area.

4. Discussion

This study is the first to demonstrate that subjects with vestibular loss can use vibrotactile feedback to control their body tilt during multi-directional planar continuous support surface perturbations. Subjects had significantly reduced RMS trunk sway, significantly smaller elliptical fits of the trajectory area, and spent significantly less time in the dead zone in the tactors on versus the tactors off configuration. To our knowledge, this is the first time that multi-directional vibrotactile feedback has been used to supplement body orientation information.

Based on the results of this preliminary experiment, which used weakly compensated vestibulopathic subjects, no optimal tactor display configuration emerged. However, overall postural performance was superior when any of the tactor configurations were used compared to the no tactor configuration. On a subject-by-subject basis, individual performance varied as did personal preference for tactor display. The most common complaint about the 16-column configuration was

Table 2
Ranked performance for phi RMS trunk tilt and ellipse area by subject across display types

	Phi RMS tilt				Ellipse area			
Subject	**4**	**4I**	**8**	**16**	**4**	**4I**	**8**	**16**
1	1	3	4	2	1	2	4	3
2	4	3	2	1	4	2	1	3
3	3	4	1	2	1	3	2	4
4	2	4	3	1	1	4	2	3
5	1	4	3	2	1	4	3	2
6	2	4	1	3	3	4	1	2
7	3	1	2	4	3	4	2	1
8	1	2	3	4	3	1	2	4
Mean rank	**2.13**	**3.13**	**2.38**	**2.38**	**2.13**	**3.00**	**2.13**	**2.75**

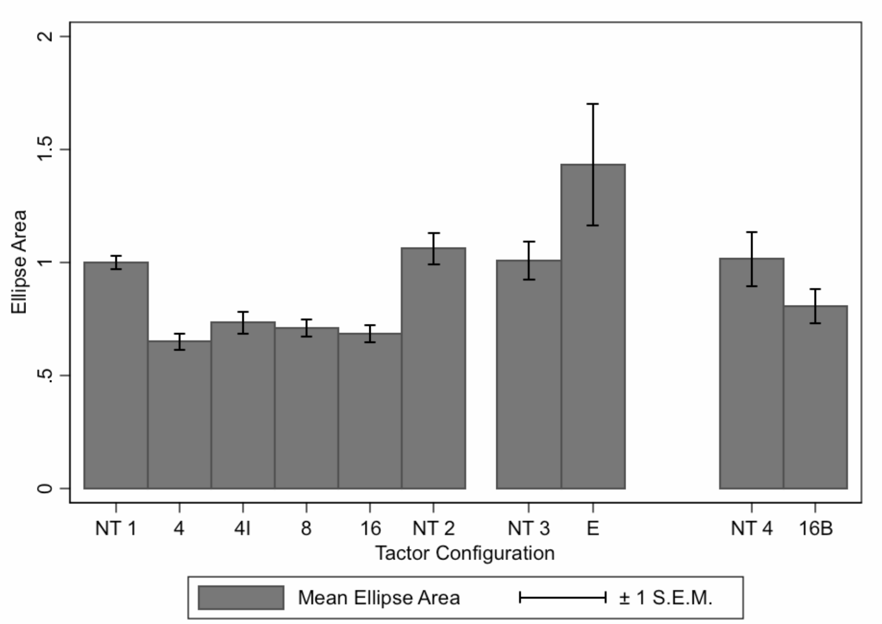

Fig. 6. Normalized elliptical fits of tilt trajectory areas by display configuration. NT denotes "no tactors" trials. NT1 is the pretest trial and NT2 is the posttest trial. NT3 occurred during Session 1 testing after a 20-minute rest following the completion of the NT2 trial. E denotes the erroneous feedback trial. NT4 and 16B occurred during Session 2. The error bars show the standard error of the mean.

that too much information was being provided. At the same time, the most common acclaim for the same display was that the subject felt confident that he/she was receiving the best and most complete information about his/her body movements. In terms of assigning a ranking for lowest phi RMS trunk tilt and smallest ellipse area, the 4- and 8- column configurations had the best mean performance ranking, respectively. Analyses were also performed on the A/P and M/L tilt components of sway. In all cases where the two-axis (phi) tilt was significantly improved, A/P tilt was also improved. However, M/L tilt, although reduced in the various tactors configurations, was not significantly lower in all cases. This is likely due to the fact that humans are least stable in the A/P direction during bipedal stance and therefore the A/P axis provided the greatest opportunity for postural stability improvement.

Our study compares the response of subjects with vestibular loss on a moving platform under two conditions; (1) eyes closed, with no vibrotactile feedback, and (2) eyes closed, with vibrotactile feedback. Given those conditions, it would be fair to say that vision plays no part, vestibular inputs play a limited part, and that proprioception inputs play a major role for sensory input in both test conditions. This issue has been considered in detail by Peterka [19]. In condition (2),

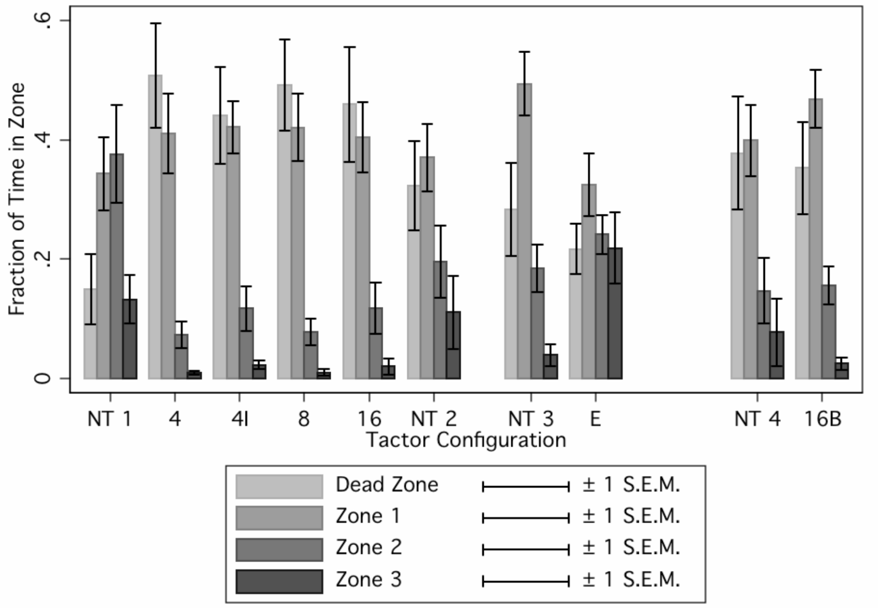

Fig. 7. Percentage of time spent in tactor firing zone by display configuration. NT denotes "no tactors" trials. NT1 is the pretest trial and NT2 is the posttest trial. NT3 occurred during Session 1 testing after a 20-minute rest following the completion of the NT2 trial. E denotes the erroneous feedback trial. NT4 and 16B occurred during Session 2. The error bars show the standard error of the mean.

vibrotactile feedback is also available to provide putative additional information about the subject's motion. A previous study of vibrotactile tilt feedback [20] concluded that this feedback was best thought of as an additional channel, not as a re-weighting channel. This implies for our study that the CNS is always weighting the proprioceptive input in the same way, but that in condition (2) there is an additional input from the balance aid. We believe that the CNS is not selectively changing the proprioceptive weighting as a function of the spatial resolution of the additional input channel. We are currently applying a similar assumption in a study that varies the ratio of tilt displacement to tilt rate in the vibrotactile feedback signal while subjects stand on a 1-axis randomly moving platform [11]. Thus, we conclude that the results we have observed are relatively insensitive to the various tactor configurations, when averaged over our subject pool.

Several factors likely contribute to the statistically equivalent performance of the various vibrotactile display configurations evaluated in this study, including: 1) relatively larger A/P tilt as compared to M/L tilt (see Fig. 4), 2) dominant ankle- versus hip-control strategy, 3) measures that are not sufficiently sensitive, and 4) individual variability across subjects (such as ability to interpret and respond to stimulation and personal preference). Regarding the first two likely factors, Matjacic et al. [16] have shown that the CNS controls the recovery from multiple direction perturbations by decoupling postural space into two orthogonal directions (A/P and M/L). As previously mentioned, humans are least stable in the A/P direction during natural bipedal stance. A/P sway is actively controlled by both ankle and hip strategies; however, the talocrural joint (ankle), responsible for dorsiflexion and plantar flexion, is the dominant control mechanism during quiet stance and small perturbations [26]. The similarity in performance of all tactor configurations is reasonable given both the inverted pendulum-like A/P motion about the ankle elicited in this study by small magnitude perturbations, and the fact that all display configurations (4, 8, and 16 columns) provided feedback along the A/P axis (see Fig. 2, 0° and 180°).

Performance was significantly worse, in terms of the mean elliptical area encompassed by the subjects' tilt, when erroneous tilt information was displayed to the subjects. Although not statistically significant, subjects' mean RMS tilt during the erroneous feedback trials was markedly higher than that of the two prior trials that provided no tilt feedback. These results demonstrate that subjects actively perceived and responded to the information that was being presented to them via the vibrotactile display. Therefore, our results invalidate the following two alternative hypotheses: 1) Tactor stimulation alone, regardless of the information conveyed, causes subjects to "stiffen up" and therefore reduce their sway; 2) Tactor stimulation triggers an attention cueing mechanism which focuses the subjects' attention on the balance task at hand. As an aside, it was not surprising that subjects did not fall during the erroneous feedback trials because all of the subjects employed in this study had intact proprioceptive function.

The results from the short- and long-term retention trials suggest that subjects preserve the reduced RMS tilt values and average ellipse areas following both repeated exposure to the stimulus and training with the balance aid. This result could have substantial impact in terms of balance rehabilitation training. If repeated exposure to a continuously moving platform coupled with the use of a vibrotactile biofeedback device were used, subjects might be expected to experience improved postural control both immediately following the training as evidenced by the short-term retention findings and over a period of time up to a month as shown by the second day testing results.

Dozza et al. [9] demonstrated in a cross-over design study that subjects with unilateral vestibular loss improve M/L postural stability during tandem gait with the use of M/L trunk vibrotactile biofeedback, beyond the effects of practice alone. Furthermore, the observed improvement in M/L stability occurred at the beginning of a series of repeated trials, with no practice period required. However, practice with biofeedback within a single experimental session did not result in conclusive short-term after-effects consistent with short-term retention of motor performance without this additional biofeedback. This was concluded to be "an integration of augmented sensory information" in which practice makes the integration became more near automatic. We believe that the subjects in our multi-directional perturbation study used multi-directional vibrotactile feedback in a similar fashion to those subjects in Dozza's tandem gait study. In other words, vibrotactile feedback acts similarly to natural sensory feedback in improving dynamic motor performance and not as a method to recalibrate motor performance to improve function after short-term use.

One concern surrounding the torso vibrotactile display is that subjects would "stiffen up" and behave as an inverted pendulum when receiving vibrotactile stimulation. There were no statistically significant differences for any angular dispersion values or anchoring indices, suggesting that subjects did not merely stiffen up when the device was turned on, but rather that the subjects employed similar stabilization strategies in all situations. Dozza et al. [6] came to a similar conclusion regarding the use of an audio biofeedback device when standing on a foam surface.

The research involving the vibrotactile balance aid published thus far has shown that a subject with vestibular loss can use the real-time information displayed to reduce his/her sway and sway area while donning the device. Further evaluation should be made of the efficacy of the device to reduce the risk of falling outside the laboratory environment, and to improve balance in the long term subsequent to being worn.

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