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Assessing the effect of vibrotactile feedback during continuous multidirectional platform motion: A frequency domain approach

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Abstract—**This study uses frequency domain techniques to demonstrate the effect of vibrotactile feedback during continuous multidirectional perturbations of a support platform. Eight subjects with bilateral or unilateral vestibular loss were subjected to two-axis pseudo random surface platform motion while donning a multi-axis feedback balance aid that mapped body tilt estimates onto their trunks via a 3-row by 16-column array of tactile vibrators (tactors). Four tactor display configurations with spatial resolutions ranging between 22.5° and 90°, in addition to the tactors off configuration, were evaluated. Power spectral density (PSD) functions of body sway in the anterior-posterior (A/P) and medial-lateral (M/L) directions were computed at frequencies ranging from 0.0178 Hz to 3.56 Hz. Transfer functions between the platform motion and body sway were also computed. Vibrotactile feedback produced significant decreases in A/P and M/L spectral power, decreased transfer function gains up to a frequency of 1.8 Hz and 0.6 Hz in the A/P and M/L directions, respectively, and increased phase leads above 0.3 Hz. The lack of a consistent difference among tactor configurations argue in favor of the simplest 4-column configuration during multidirectional continuous surface perturbations.**

INTRODUCTION

Sensory substitution is a technique of replacing or augmenting compromised sensory information. Balance aids using various modes of sensory substitution such as electrotactile, vibrotactile, and auditory feedback of body motion have been developed and found effective in improving postural stability of subjects with vestibular loss during stationary tasks and during single-axis perturbed stance [1-5].

Sienko et al. [6] recently demonstrated that subjects with vestibular loss donning a multi-axis vibrotactile feedback balance aid during continuous multidirectional surface perturbations: (1) significantly reduced their root-mean-square trunk sway, (2) decreased the elliptical fits of their trunk trajectory area, and (3) spent significantly less time outside of the immediate threshold zone where there is no feedback in the feedback on versus the feedback off configuration. The goal of this study is to apply frequency domain techniques such as power spectral density (PSD) analysis and frequency transfer function analysis to gain further insight into the frequency-dependent effects of vibrotactile feedback during continuous multidirectional surface perturbations.

PSD analysis is a standard tool that is used to characterize the distribution of a signal's or a time-series' power content across frequencies [7]. In the context of human postural control, PSD analysis can be used to determine body sway spectral power content and the dominant frequency of sway during quiet and perturbed stance. A transfer function, defined as the mathematical relationship between the output and its input for a linear time-invariant system, characterizes system dynamics with a gain and phase at each frequency point. Previous studies have developed a frequency transfer function framework for quantifying postural stability in subjects with vestibular loss [8] and have used that framework to assess the effectiveness of balance aids during single-axis perturbations [9]. In this study, we extend the analysis to assess the utility of a vibrotactile balance aid during multidirectional surface perturbations. Specifically, we explore the frequency dependent effect of tactor display spatial resolution on postural stability.

METHODS

The methodology has been detailed previously [6]. Only the main points will be discussed here.

A. Subjects

Eight subjects (51 years ± 10 years) with unilateral or bilateral vestibular loss (details described in [6]) were referred by the Massachusetts Eye and Ear Infirmary (MEEI) Department of Otolaryngology clinicians for this study. Subjects gave their informed consent prior to the start of the experiment. The experimental protocol, which conformed to the Helsinki Declaration, was approved by the MEEI, Boston University, and Massachusetts Institute of Technology Institute Review Boards.

B. Equipment & Instrumentation

Subjects stood on a custom-built 2.1 m square BALance DisturbER (BALDER) platform [6] that could independently move in two orthogonal directions (x- and y-directions) in an earth horizontal plane. Two-axis platform position data were collected after digitization at 100 Hz.

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The vibrotactile balance aid (Fig. 1) consisted of a two-axis inertial measurement unit (IMU) mounted on the lower back of the subject to capture the trunk dynamics, a vibrotactile array worn around the trunk to intuitively display body motion, and a laptop with analog and digital interfaces. The trunk tilt estimates in the anterior-posterior (A/P) and medial-lateral (M/L) directions, which aligned with the platform y and x directions, respectively, were obtained by processing the IMU's accelerometer and gyroscope measurements. The tilt estimates were displayed on a 3-row by 16-column vibrotactile array worn about the subjects' trunk; the rows displayed estimated tilt magnitude and the columns displayed tilt direction. The tilt signal was a combination of tilt estimate and half the tilt rate. Three tactor display configurations (4, 8, and 16) evaluated the effects of spatial resolution by varying the number of active tactor columns: the 4-column display used only the tactors in the four cardinal directions, the 8-column display used every second column and the 16-column display used all columns. The direction of tilt (azimuth) was calculated from the arctangent of the A/P and the M/L components which in turn activated the appropriate tactor column using the "nearest neighbor" principle. Depending on the direction of the tilt in these three configurations, a single tactor was activated when the tilt magnitude exceeded a subject-specific threshold of approximately 1^{o}, while no feedback was given within this threshold. A fourth configuration (4I) was treated as two separate single-axis systems, thus displaying A/P tilt and M/L tilt information independently of each other.

Fig. 1. Vibrotactile feedback balance aid.

B. Platform Stimuli:

The support surface was driven by a linear velocity command sequence created from a 624-length (maximal) pseudorandom pentary sequence (PRPS). This sequence was obtained by assigning fixed values of +2v, +v, 0, -v, -2v to a four stage, modulo 5 addition, shift register output with a state duration of $\Delta t = 0.09$ s. The total duration of each resultant sequence was approximately one minute. This sequence was low-pass filtered (4th order Butterworth, cut-off frequency $f_c = 3$ Hz) and then was integrated to create the position waveform. The initial value of the shift register was selected such that the position waveform was balanced between negative and positive values over one stimulus cycle. The x and y platform velocity command signals were given by two uncorrelated waveforms and the RMS velocity of platform motion ranged from 2.4 to 4.2 cm/s. A three minute stimulus for the testing trials was generated by concatenating three repetitions of a separate pair of waveforms. The magnitude of the stimulus was adjusted during the training session based on each subject's subjective balance capabilities.

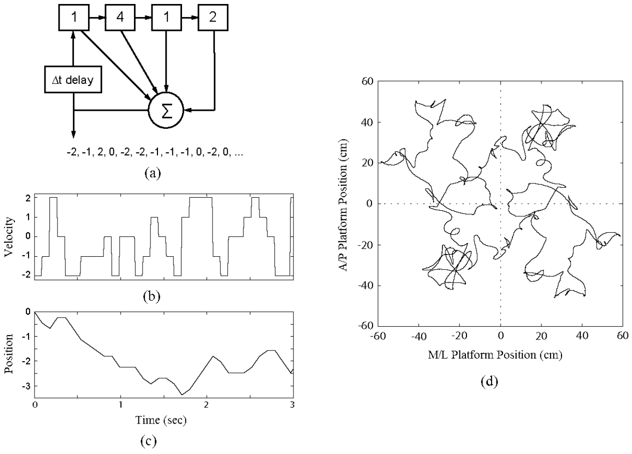

Fig. 2. (a) Modulo 5 Shift Register, (b) Resultant PRPS time series, (c) Commanded displacement along one axis, (d) Bird's eye view of the actual platform motion

C. Experimental Protocol

The subject was presented with four tactor display configurations, the order of which was based on a Balanced Latin Squares design with tactor configuration as the primary factor. This produced four groups with two subjects in each group. All subjects were subjected to a core test battery of six trials: first a trial with no tactors (NT1) followed by trials with the four tactor configurations, and finally a second no tactors trial (NT2). The present analysis is based on these six core trials.

Subjects were not told which tactor configuration they were using unless it was a no tactors (NT) trial. Subjects were instructed to close their eyes for all trials and to move in such a manner as to null any vibrations regardless of the display configuration. Their feet were positioned hip-width apart and skewed slightly outwards on the BALDER force plate.

II. FREQUENCY DOMAIN ANALYSIS

Frequency domain analyses were performed on the body sway measures (trunk tilt in the A/P and the M/L directions) and platform velocity by computing their PSD functions as well as the transfer function and coherence function estimates between the stimulus (platform motion) and the response (trunk tilt).

PSD functions were computed using a discrete Fourier transform (DFT) to decompose the PRPS stimulus and the response signals into sinusoidal components [8]. The DFT was applied to each 56.16s (624 x 0.09s) cycle of each trial's stimulus and response waveforms. The DFT was calculated at 200 frequencies ranging from $f = 1/56.16 = 0.0178$ Hz to $f = 200/56.16 = 3.56$ Hz. The even frequency points, which have almost zero amplitude, were discarded, leaving 100 frequency samples. Computed PSD functions were first averaged over the three cycles for each trial and then smoothed by averaging adjacent points into 17 frequency bins generated such that the number of points averaged increased with the frequency.

The characteristic of the PSD function of the PRPS stimulus is that equal power is contained across all the frequencies up to a cut-off frequency. Frequency transfer functions and coherence estimates were computed from the spectra as described in [8]. Coherence function estimates show the degree of correlation between the response and the stimulus as a function of frequency with values ranging from 0 to 1. The value of 1 implies a perfect linear relationship between the stimulus and response and no noise in the system or measurements. The 95% confidence intervals for the transfer functions using coherence function estimates were computed as described in [7].

III. RESULTS

A. Power Spectral Density Analysis

PSD analysis provides the spectral distribution of the trunk tilt in the M/L and the A/P directions.

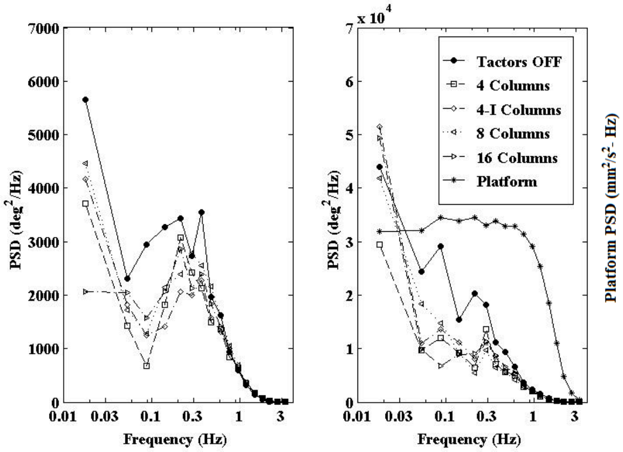

Fig. 3. (a) PSD plot of M/L trunk tilt for all tactor configurations, (b) PSD plot of A/P trunk tilt for all tactor configurations and platform stimulus.

Fig. 3 shows the PSD of the platform stimulus and the A/P and the M/L trunk tilts averaged across the subjects for each tactor configuration. The subplots illustrate the reduction in tilt power at low frequencies as compared to high frequencies. However, there was no consistent trend observed across the various tactor configurations. The only consistent trend observed was the reduction in spectral power across the frequency bins in tactors ON conditions (4, 4I, 8, and 16 tactors configurations) in comparison with the tactors OFF conditions (average PSD function computed for NT1 and NT2 trials). Mean power was reduced 28% and 36% in M/L and A/P directions, respectively ($p < 0.0001$). Moreover, the cut-off frequency up to which there was a reduction in power associated with trunk tilt across various tactor configurations remained the same in the range of 0.8 to 1.5 Hz across the eight subjects.

B. Transfer Function Analysis

Transfer functions were computed with platform velocities along x and y directions as the stimuli (inputs) and trunk tilt in M/L and A/P directions as the responses (outputs).

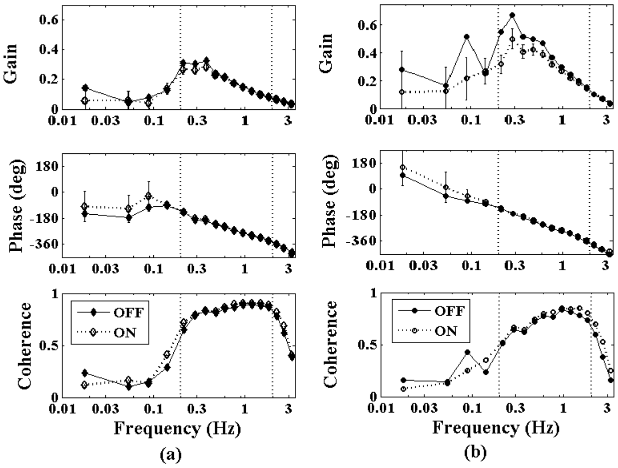

Fig. 4. Mean gain, phase and coherence function estimate for eight subjects in (a) M/L direction and (b) A/P direction.

Fig. 4 shows the mean gain and phase and the mean coherence function estimate averaged across all subjects in the tactors ON and OFF conditions; error bars denote 95% confidence intervals of the mean. The gain of the transfer function indicates the extent of trunk tilt in response to the translational velocity of the platform at a particular frequency; a value of 1 implying trunk tilt amplitude of 1^{o} for translational motion amplitude of 1 mm/s at a particular frequency. As observed in Fig. 4, there is a reduction in the gain in the tactors ON condition in comparison to tactors OFF condition.

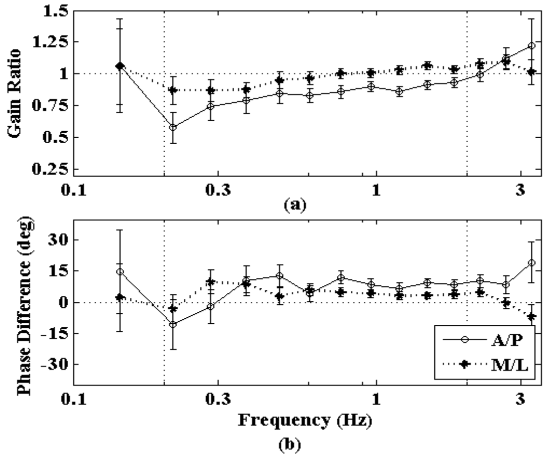

Fig. 5. (a) Gain ratio and (b) Phase difference plotted for the tactors OFF and tactors ON conditions for M/L and A/P tilt directions.

The graph of the ratio of the mean gain for eight subjects computed for the tactors ON to tactors OFF conditions quantifies the extent to which the vibrotactile feedback was effective across different frequency bins (Fig. 5). Statistically significant gain reduction (gain ratio less than 1) was observed at frequencies ranging between 0.2 and 2.0 Hz for all tactor configurations in the A/P direction whereas for the M/L direction, it was observed between 0.2 Hz and 0.6 Hz. Also, there was an increase in gain ratio (gain ratio greater than 1) for frequencies greater than 2.0 Hz in the A/P and the M/L directions. However, the spectral power content associated with trunk tilt was very low at these frequencies. The degree of gain reduction was greater in the A/P direction than in the M/L direction. The phase changes were significant for frequencies greater than 0.3 Hz and there was a decrease in the phase in the tactors ON condition.

Coherence was consistently high in the frequency range from 0.2 to 2.0 Hz (Fig. 4), indicating a high correlation between the stimulus and response in both the A/P and M/L directions, regardless of whether the tactors were on or off. Statistically significant changes in the gain were also observed in this range. Gain was reduced to a greater extent at lower frequencies (< 0.2 Hz), but this was not significant due to the low coherence values. The average of these coherence functions contrasts with the cross-axis coherence function plot (stimulus as x-direction platform velocity and response as A/P trunk tilt) for tactors ON and OFF (Fig. 6). This low cross-axis correlation suggests decoupling of postural control strategy in the A/P and M/L directions.

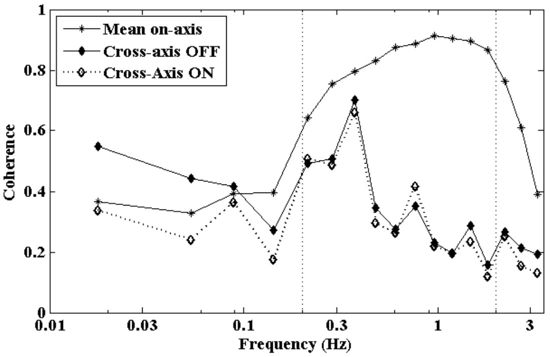

Fig. 6. Coherence function for the mean of same axis, cross-axis coherence functions for the means of tactors ON and OFF conditions.

IV. DISCUSSION

This study provides information about the frequency dependent reductions in body sway measures (specifically, trunk tilts), thereby providing insight into the human postural control mechanism both with and without vibrotactile feedback during multidirectional perturbations. Since the study was performed on subjects with vestibular loss who had no visual cues (eyes closed), the subjects relied on their native compromised vestibular cues and proprioceptive cues along with the information provided by the vibrotactile feedback balance aid. The reduction in gains of the frequency transfer functions computed for body sway responses in the A/P and the M/L directions suggest that the vibrotactile feedback improves the sensitivity of the human postural control system to external platform disturbances since lower gain values imply lower body trunk tilts. This is achieved by "reweighting" the information provided by other sensory systems and augmenting it with the cues provided by the vibrotactile feedback.

Frequency domain analysis suggests that the spatial resolution (over the range we investigated) of the vibrotactile display does not affect the frequency bandwidth over which the feedback reduces trunk tilt in the A/P or the M/L directions. It has been previously shown that the central nervous system controls the recovery from multiple direction perturbations by decoupling the postural space into two orthogonal directions (A/P and M/L) [10]. Low cross-axis coherence values along with no consistent differences in spatial resolution of the vibrotactile display provide strong evidence that the use of the lowest spatial resolution display (4 column configuration) is optimal from the standpoint of reduced device design complexity for applications of multidirectional perturbed stance. However, the extent to which the feedback restores the normal postural balance in subjects with vestibular loss cannot be determined unless a comparison is made with the results of a similar experiment tested on subjects with intact vestibular function.

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