33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Augmenting Sensory-Motor Conflict Promotes Adaptation of Postural Behaviors in a Virtual Environment

Emily A. Keshner, Jill C. Slaboda, Ravi Buddharaju, Lois Lanaria, and Jeremy Norman
Dept. of Physical Therapy, Dept. of Electrical and Computer Engineering, Dept. of Mechanical Engineering, and Dept. of Kinesiology
Temple University
Philadelphia PA 19122
ekeshner@temple.edu

***Abstract*— We present results from a series of studies that investigated how multimodal mismatches in a virtual environment modified postural response organization. Adaptation of motor commands to functional circumstances is driven directly by error signals. Thus, motor relearning should increase when performing in environments containing sensory mismatch. We hypothesized that kinematics of the response would be linked to specific characteristics of the sensory array. Sensory weighting was varied by: 1) rotating the visual field about the talo-crural joint or the interaural axis, 2) adding stochastic vibrations at the sole of the foot, and 3) combining galvanic vestibular stimulation with rotations of the visual field. Results indicated that postural responses are shaped by the location of a sensory disturbance and also by the processing demands of the environmental array. Sensory-motor demands need to be structured when developing therapeutic interventions for patients with balance disorders.**

Keywords-error correction; sensory mismatch; balance; vibration; galvanic vestibular stimulation

I. INTRODUCTION

Falls in the elderly is a major public health concern and a large body of evidence has emerged suggesting that postural instability can be caused by the inability to process multiple task demands. The human balance system relies on multimodal sensory inputs from visual, tactile, and vestibular systems, and the integration of the current sensory information with expected sensory consequences is necessary to produce an appropriate motor output. Postural control treatment approaches have included practice of specific, well-defined automatic postural reactions [1-3]. But, if relearning of postural control is to have any functional carryover, it needs to be incorporated into more complex motor behaviors [4-6]. Adaptation of motor commands to functional circumstances is driven directly by error signals rather than by performer initiated error corrections [7]. Thus the impact of rehabilitation interventions might increase if the sensory feedback can be manipulated so it does not precisely match the expected reafference [8-12].

Virtual reality is an excellent tool for presenting environments that contain controlled sensory mismatches thereby requiring constant correction to the sensory reafference. The most recognized sensory characteristics of virtual reality are the absence of haptic and force feedback. But virtual reality also creates a strong conflict between visual and vestibular senses [13]. When the optic flow field in a virtual environment is not matched to the performer's head motion, disparity between visual and vestibular signals occurs that creates the perception of self-motion called vection [14-17]. By adding tools such as robots [18, 19], treadmills [20], and dynamic platforms [21, 22] into the virtual environment, we can further manipulate the demands during motor tasks.

In prior studies [5, 17, 23-25], we have shown significant effects of visual velocity and direction on the magnitude of the trunk and lower limb responses. Visual field motion influenced the orientation of the head as trials progressed, even when there was no disturbance to the position of the body. When self-motion from disturbances at the base of support conflicted with motion of the visual field, motion of the whole body became more complex incorporating frequency parameters from both stimuli rather than selecting a single salient input [5]. Once

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Manuscript received March 24, 2011. This work was supported by NIH grant AG26470 from the NIA and H133F100010 from NIDRR.

E.A. Keshner is with the Department of Physical Therapy and the Department of Electrical and Computer Engineering at Temple University, Philadelphia PA 19140 USA (phone: 215-707-4824; fax: 215-707-7500 e-mail: ekeshner@temple.edu).

J. C. Slaboda is with the Department of Physical Therapy at Temple University, Philadelphia PA 19140 USA (e-mail: jslaboda@temple.edu).

R. Buddharaju is with the Department of Physical Therapy at Temple University, Philadelphia PA 19140 USA (e-mail: tuc35892@temple.edu)

L. Lanaria is with the Department of Mechanical Engineering at Temple University, Philadelphia PA 19122 (e-mail: lois.lanaria@temple.edu)

J. Norman was with the Department of Kinesiology at Temple University, Philadelphia PA 19122.

destabilization resulting from platform motion had subsided, orientation of the body was biased toward the direction of visual field motion and magnitude of joint motion increased as visual velocity increased [23].

In this paper we present results from a series of studies that investigated how multimodal mismatches in a virtual environment modified postural response organization. We examined the effects of altering the visual axis, combining mismatched visual and vestibular signals, and combining vibration of the feet with unreliable proprioceptive inputs from the ankles because these are the principal pathways involved in postural control. We hypothesized that kinematics of the postural response would be linked to specific characteristics of the environment. We varied the prominence of the sensory pathways by: 1) rotating the visual field either about the talo-crural joint at the ankle or the interaural axis of the head, 2) exploring responses to visual field disturbances following stochastic vibrations at the sole of the foot, and 3) combining galvanic vestibular stimulation with rotations of the visual field.

II. METHODS

A. Subjects

Data will be shown from 30 healthy young adults (age 21-40 yrs) and one older adult (50 yrs) 3 years post-stroke who gave informed consent to participate in these studies.

B. Virtual Environment

A 3-degree of freedom posture platform (Neurocom International Inc., Clackamas, OR) with integrated dual triaxial force plates (AMTI, Watertown, MA) sits within a 3-wall virtual reality back projection system. Three transparent 1.2 m x 1.6 m screens are placed 90 cm in front and to the right and left of the platform. Two Panasonic PT-D5600U DLP-based projectors located behind each screen projected a full-color workstation field (1024x768 stereo) at 60 Hertz (Hz) onto each screen. Polarized filters placed in front of the projector provided left eye and right eye views of the image on each screen, and passive stereo glasses delivered the correct view to each eye. Three dual processor computers created the imagery projected in the virtual environment and were synchronized via the CAVELib application (MechDyne, Virginia Beach, VA).

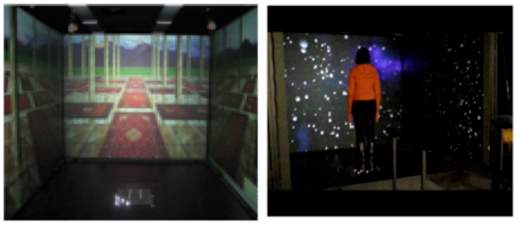

Fig. 1. Examples of virtual images projected on the three screens. (*Left*) A virtual room with carpets and columns and a distant horizon. (*Right*) White spheres on a black background. Subject is standing on the dual forceplates.

Two projected images (scene) were used in these experiments. The first consisted of a 30.5 m wide by 6.1 m high by 30.5 m deep room containing round columns with patterned rugs and a painted ceiling and the second contained white spheres on a black background (Fig. 1).

C. Data Collection and Analysis

Center of pressure (COP) recordings were collected at a rate of 200 Hz from the two force plates. Resultant vectors in the anterior-posterior (AP) and side-to-side (ML) directions were calculated as a weighed sum from the individual signals from the right and left force plates. Electromyographic (EMG) signals from right tibialis anterior (TA) muscle were recorded with pairs of 2.5 mm diameter Ag-AgCl surface electrodes (Noraxon, USA Inc., Scottsdale, AZ). EMG data were amplified, bandpass filtered at 10-500 Hz, and sampled at 1500 Hz for later off-line analysis.

Three-dimensional kinematic data from the head, trunk, lower and upper limbs was collected using a 6-camera infrared Hawk system sampling at 120 Hz (Motion Analysis, Santa Rosa, CA). Excursion of center of mass (COM), COP, head and ankle angular displacement were calculated in the sagittal plane. Responses were compared using paired t-tests with significance at $p<0.05$.

D. Experimental Protocols

Three protocols were employed:

1) Visual and Base of Support Rotation. Rotation of the visual scene and the base of support were combined to explore how visual perception affects responses to instability. Seventeen subjects stood quietly on the platform. After 15 sec of quiet stance, the platform tilted 5^0 in dorsiflexion at 30^0/sec and then returned to a neutral position. There were 3 tilts with random inter-tilt intervals within each 70 sec trial. The projected virtual environment (Fig. 1, right) either remained dark or rotated pitch upward at 30^0/sec around the talo-crural axis or around the interaural axis. Area of the TA muscle activity was examined because it is the primary actuator for recovery of balance following an upward tilt of the base of support. RMS of the COM, COP, and ankle angular displacement were calculated over an 8 sec period following the tilt perturbation and normalized to the same time period when in the dark.

2) Vibration at the feet. Seven subjects stood quietly on the dynamic platform. A vibratory noise stimulus was applied at the soles of both feet with six (3 per foot) DC vibrator disks embedded in open-type footwear. Subjects wearing the vibrating footwear stood on both a hard surface and on foam placed on the force plates for 65 sec with eyes closed. During 65 sec of the trial, the vibration stimulus was off, above the threshold of perception (AV), or sub-threshold for perception of vibration (SV). RMS, range, and ellipse area of COM and COP were calculated over the trial period and normalized to each subject's initial position. Approximate Entropy (ApEn), a regularity statistic developed from nonlinear dynamics [26-30], was used to quantify the regularity or predictability of the COP response across the period of the trial.

3) Galvanic Vestibular Stimulation (GVS). Four subjects received 0.5mA of GVS at 0.25 Hz for 15 seconds. Two subjects were immersed in a virtual scene that oscillated in the roll plane at frequencies of 0.25, 0.10, or 0.13 Hz for 80 seconds. Then 20 sec of 0.5mA sinusoidal GVS at 0.10 Hz was combined with a virtual scene (Fig. 1, left) that had been oscillating at 0.25 Hz for 35 sec. The GVS was removed and the scene continued to oscillate for an additional 20 sec. These were then reversed so that sinusoidal GVS was given at 0.25 Hz while the virtual scene oscillated at 0.10 Hz. COP and head angular displacements were calculated for periods 20 sec prior to GVS, 20 sec with GVS, and 20 sec after GVS.

III. RESULTS

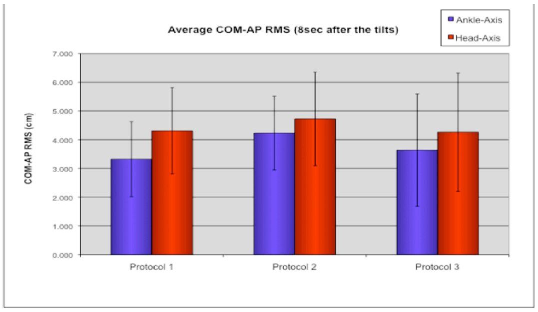

Fig. 2. Average ± SD of COP RMS in the a-p plane.

A. *Visual Scene and Base of Support Rotation*

Significantly greater TA EMG activity and ankle angles were exhibited in all subjects for three different orders of presentation: 1) when visual rotation at the head followed visual rotation at the ankle (p<0.17); 2) when visual rotation at the ankle followed visual rotation at the head (p<0.06); and 3) when visual rotation at the head followed visual rotation at the head (p<0.01). Mean RMS values of COM and COP were also significantly greater when the visual field was rotated about the axis at the head compared to the axis at the ankle for all presentation orders (Fig. 2).

B. *Adding Vibration at the Feet*

COM responses on a foam surface were larger and deviated further from the subject's initial position than on a hard surface (Fig. 3). The addition of sub-threshold vibratory noise to the soles of the feet, even though the subjects did not consciously perceive the vibration, reduced the differences in response to the two surfaces (Fig. 3, upper right).

Sub-threshold noise produced significantly larger excursions of the COP, but with increased regularity of the response on both surfaces (i.e., a lower ApEn). These results imply that application of sub-threshold noise enhanced sensory information at the foot thereby structuring the postural sway response. The changes observed suggest that the addition of stochastic resonance to the system produces sub-cortical excitation and will not place increased demands on the performer's attention for postural control.

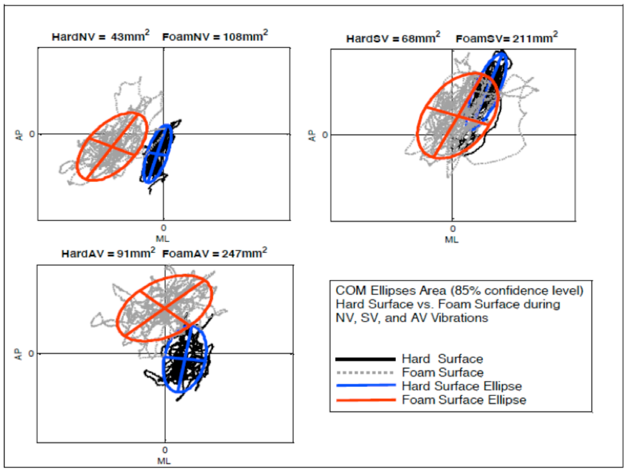

Fig. 3. COM Ellipse area at 85% confidence level for a subject standing quietly on hard and foam surface during no vibration (top left), sub-threshold (top right), and above threshold (bottom left) vibration. The two axes of the ellipse are eigenvalues of the covariance matrix between AP and ML sway.

We have also been using this vibration paradigm to improve balance in patients with stroke. A backwards shift of COM and COP significantly decreased following 10 sessions of standing on a sway-referenced platform while receiving vibration to the soles of the feet (Fig. 4) suggesting improved orientation to vertical.

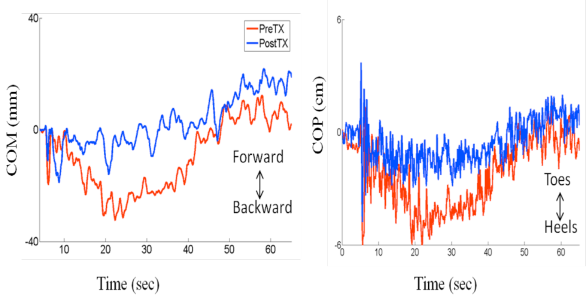

Fig. 4. COM (*left)* and COP (*right*) responses across the pre-training (red) and post-training (blue) trial periods.

C. *Sinusoidal Galvanic Vestibular Stimulation*

As expected from prior experiments [25], exposure to a moving visual field, both prior to and after application of GVS, produced responses at the head and COP that were significantly correlated with the frequency of the visual field oscillation (Fig. 5, left and right). When we combined visual motion with GVS, the FFT of head angular displacement revealed responses at both the GVS and visual scene frequencies (Fig. 5, center). The previous 0.25 Hz response of the COP was shifted down towards 0.2 Hz.

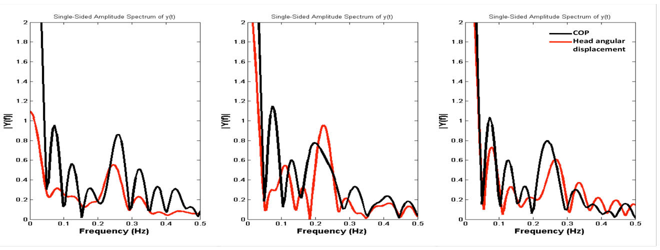

Fig 5. Frequency responses of head angular displacement (red) and COP (black) during 20 sec of 0.25 Hz scene rotation (left), 0.1 Hz GVS and 0.25 Hz scene rotation (center), and post-GVS with 0.25 Hz scene rotation (right).

IV. DISCUSSION

Coupling of the visual and motor system plays a critical role in the vast repertoire of healthy, adaptive motor behavior [31]. In complex environments, characteristics of multimodal stimuli are incorporated into postural behaviors and reflect accommodations made by the central nervous system (CNS) during natural movement. Thus, purposeful postural behavior depends very much on the array of incoming signals.

Our results suggest that both the site of delivery and specific attributes of the sensorimotor environment are important for delivery of therapeutic interventions. The concern about processing demands is particularly important when dealing with patients with neurological impairment such as stroke or Parkinson's disease. The introduction of stochastic resonance made the postural response more structured so that it was less disturbed by unreliable inputs. Increasing intensity of visual-vestibular conflict by rotating the world around the head, increased spatial disorientation but also increased generalized excitation of the system. Presentation of a well-defined vestibular input resulted in accommodation to more complex demands.

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