Using Immersive Technology for Postural Research and Rehabilitation

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Posture has traditionally been examined by isolating individual control pathways to determine their specific contributions. However, if these pathways are responsive to functional contexts, then their responses may differ when the system is receiving simultaneous inputs from multiple pathways. Thus, we may never fully understand how the central nervous system (CNS) organizes behaviors in the real world from studies conducted in the minimized environment of the laboratory. The consequence of this is that when findings from the laboratory are applied to therapeutic intervention, the intervention may not be appropriate for all circumstances and will not fully meet the needs of the patient. We have united an immersive dynamic virtual environment with motion of a posture platform to record the biomechanical and physiological responses to combined visual, vestibular, and proprioceptive inputs. The virtual environment possesses content, contrast, and texture so that we can examine postural responses as they might occur in a complex, real-world environment. In this paper we specifically describe the factors guiding our choices of virtual technology and present data from young adults, elderly adults, and an individual with bilateral labyrinthine loss to demonstrate how multimodal inputs influence their postural response organization. Significant implications for future experimental and rehabilitation protocols are also discussed.

Key Words: Virtual reality—Posture—Motion analysis—Elderly—Labyrinthine deficit.

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In the everyday world, multiple modalities of potentially discordant stimuli are encountered. On a busy street, we are exposed to visual stimuli that may be transient but that occur at various intervals and in several directions with respect to our motion. But the visual system has largely been downplayed as a contributor to postural control because it is believed to be a slower system, and because when vision was removed during a study (either by closing the eyes or by placing subjects in a darkened room) no significant changes in postural reactions have been observed (Keshner, Allum, & Pfaltz, 1987; Nashner & Berthoz, 1978; Vidal, Berthoz, & Millanvoye, 1982). When the effects of visual signals were studied in a more dynamic fashion (Dichgans & Brandt, 1978; Dichgans, Mauritz, Allum, & Brandt, 1976; Lestienne, Soechting, & Berthoz, 1977), however, the quiet stance of subjects was highly correlated to the frequency and amplitude of the visual scene, and subjects often became unstable. In one of our earlier studies we briefly tested such a situation (Keshner & Kenyon, 2000). Subjects were asked to walk within a room with a virtual environment (VE) projected at a constant velocity in roll that was uncorrelated with the parameters of their locomotion. We observed that the subjects were forced to either alter the organization of their locomotion pattern or lose their balance while walking. Thus, in natural environments rather than an experimentally controlled environment, visual signals may have a greater impact on the postural orientation of an individual.

This finding could have significant impact on studies of motor control and on rehabilitation interventions. In the past, postural responses have been examined through isolating individual control pathways in order to determine their specific contribution. However, if these pathways are re-

FIG. 1. Dynamic image presented in the VEPO laboratory to a subject standing on the translating sled. Subject is wearing shutter glasses (Crystal Eyes; StereoGraphics Inc.) in order to perceive the stereo image.

sponsive to functionally relevant contexts, then their responses may well be different when the system is receiving simultaneous inputs from multiple pathways. Thus, we may never fully understand how the CNS organizes behaviors in the real world from studies in the minimized environment of the laboratory. The consequence of this is that when findings from the laboratory are applied to therapeutic intervention, the intervention may not be appropriate for all circumstances and will not fully meet the needs of the patient.

We have attempted to resolve this insufficiency by developing the Virtual Environment and Postural Orientation (VEPO) laboratory. This laboratory combines biomechanical and physiological measurements with an experimentally controlled immersive wide field-of-view (FOV) visual environment (Fig. 1). Subjects stand on a platform that can linearly accelerate in the anterior-posterior direction. A 6 degrees of freedom force plate (AMTI, Watertown, MA) provides measurements of reac-

tion forces and moments exerted on the base of support from which center of pressure (COP) is calculated. Three-dimensional (3D) kinematic data from the head, trunk, and lower limb is collected using 3D video motion analysis. The platform is placed 90 cm in front of a screen on which the virtual image is projected via a stereo-capable projector mounted behind the back-projection screen. In the following sections we will describe more specifically the factors guiding our choices of virtual technology and present data from several subjects tested in this laboratory.

DEVELOPMENT OF DYNAMIC STEREO IMAGERY IN THE LABORATORY

Currently, there are four forms of VE: head-mounted display (HMD), augmented, fish tank, and projection-based (see Sherman & Craig, 2002, and Stanney, 2002, for a review). A totally immersive VE system is the HMD where the subject sees

only the computer-generated image and the rest of the physical world is blocked from view. Augmented VE systems often use HMD technology (e.g., Nomad, Microvision Inc.; Glasstron, Sony Inc.), but recently a projection-based augmented system (PARIS) was developed (Foxlin, 2002). In such systems both the computer-generated images and the physical world are visible to the subject. Here the computer world is overlaid on the physical world. In the so-called fish tank VE, the stereo images are produced on a monitor in front of the subject (Arthur, Booth, & Ware, 1993). These systems have limited FOV and space in which one can interact with the scene. Consequently, the resulting FOV is smaller than that found in other VE systems and, therefore, the accompanying pixel visual angle is smaller (i.e., better). These systems lend themselves to the use of haptic devices in the performance of manual tasks (Komerska, Ware, & Plumlee, 2002). In the projection-based VE that we have chosen to employ, the computer-generated imagery is back-projected on a screen or wall that is in front of the user much like that in a theater (Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992). We use back projection instead of front projection to ensure that the projected scene is not obscured by the subject's body.

The VE system used in the VEPO laboratory is a direct application of the CAVE technology in both hardware and software implementations. Whereas the CAVE is a multiwalled VE system, the VEPO laboratory consists of one wall and one projector (Czernuszenko et al., 1997). The wall in our system consists of back projection material measuring 1.2 × 1.6 m. An Electrohome Marquis 8500 projector throws a full-color stereo workstation field (1,024 × 768 stereo) at 120 Hz onto the screen. A dual Xenon processor PC with an nVidia Quadro4 900XGL graphics card creates the imagery projected onto the wall. The field sequential stereo images generated by the PC are separated into right- and left-eye images using liquid crystal stereo shutter glasses worn by the subject (Crystal Eyes; StereoGraphics Inc.). These glasses limit the subject's horizontal FOV to 90° of binocular vision and 55° for the vertical direction. The correct perspective and stereo projections for the scene are computed using values for the current orientation of the head supplied by the position sensor (Flock of Birds; Ascension Inc.) attached to the stereo shutter glasses (head). Consequently, virtual objects retain their true perspective and position in space regardless of the subject's movement. The total display system latency measured from the time a subject moves to the time the resulting new stereo

image is displayed in the environment is 26–44 ms. The stereo update rate of the scene in our laboratory is 60 Hz, which is half the rate at which we sample the head data (120 Hz).

In the VEPO laboratory, the visual experience of the subjects is that of being immersed in a volume filled with 3D objects at various distances. The environment appears as the inside of a room with columns and a distant horizon (Fig. 1). The virtual objects move about the subject according to the protocol of the experiments. Since the stimuli represent objects at different distances, the velocity of a particular object projected onto the retina is a function of its distance from the subject. Therefore, although the subjects perceive the scene as moving as a single physical unit, on the retina each object within the scene has its own individual velocity based on its distance from the subject.

The choice of a projection-based VE system was based on several factors, the most important of which were patient comfort, FOV, and cost. The factors that we compromised on were image brightness, contrast, and pixel visual angle. Both brightness and contrast are better in an HMD than in a projection-based system. Even when the resolutions of both are the same, because the FOV of the HMD is usually less than the field of regard (i.e., the size of the wall) of the projection-based system, the luminance of the HMD will usually be greater. One of the major drawbacks of HMD systems, however, is the bulky and sometimes heavy display system. The use of such a system with patients can limit the number and type of patient that will tolerate the device, and these systems may affect the movement dynamics (Keshner, Hain, & Chen, 1999). The head gear worn by patients in our projection system is only that of the stereo glasses, which are much like wearing exaggerated sunglasses. These glasses are lightweight and can fit over any prescription glasses that the subject might be wearing. Also, although these glasses restrict the subject's FOV to about 90° horizontally, this is usually larger than many HMD systems can offer. In general, HMD systems can only cover about a 50°–60° FOV for a reasonable cost.

Another problem in the VE is the latency required to generate a new image. In an HMD, the projection screens are not fixed in space but to the head; thus the computer-generated image has larger and more significant image changes with every head movement (Foxlin, 2002). The latencies inherent in the updating of the new visual image are manifested in HMD systems as a swimming of the image seen by the subject. The probable effect

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of the swimming image is that a higher number of subjects experience motion sickness using HMD than projection-based systems (Cobb, Nichols, Ramsey, & Wilson, 1999). In our projection-based system, a great deal of similarity exists from one image to the next with head movement. For example, a picture fixed to a wall is on the wall whether you are looking at it or not. The only image modification visible with head rotation is due to changes in stereo projection. This produces less image motion and reduces the swimming of the image. To date, of the 200 subjects who have used the projection-based system, we have had only one subject complain of motion sickness.

USING THE VIRTUAL ENVIRONMENT FOR RESEARCH AND REHABILITATION

There is significant evidence that dynamic visual inputs induce body motion during quiet stance in both healthy (Previc & Donnelly, 1993; Previc, Kenyon, Boer, & Johnson, 1993) and labyrinthine deficient (Kotaka, Okubo, & Watanabe, 1986) individuals, yet the traditional approach to studying postural reactions has been to have subjects stand with their eyes closed or with a served but static visual field (Keshner et al., 1987; Nashner & Berthoz, 1978; Vidal et al., 1992). Studies with visual field motion have demonstrated large center of pressure changes, with the most robust postural changes in the roll and pitch planes (Ferman, Collewijn, Jansen, & Van den Berg, 1987; Previc, 1992) and at frequencies below 0.2 Hz (Brooks & Sherrick, 1994; Howard & Childerson, 1994; Lestienne et al., 1977).

Motion of the visual field will affect more than sway measured at the base of support, however. Velocity and frequency of visual field stimuli has been correlated with segmental velocities (Dichgans et al., 1976; Dijkstra, Schoner, & Gielen, 1994; Keshner & Kenyon, 2000; Kunkel, Freudenthaler, Steinhoff, Baudewig, & Paulus, 1998; Kuno, Kawakita, Kawakami, Miyake, & Watanabe, 1999; Masson, Mestre, & Pailhous, 1995); muscle electromyographic amplitudes (Dietz, Schubert, & Trippel, 1992); and the direction of gaze (Gielen & van Asten, 1990). Our previous study in the VE (Keshner & Kenyon, 2000) demonstrated that during quiet stance when exposed to rotations of either a complex or simple stereo visual scene in pitch and roll, the upper body responded to visual-vestibular signals, whereas the ankle responded to proprioception and changes in ground reaction forces. Therefore the application of VE technology to dynamic postural research is both a necessary and valid approach for exploring the underlying control mechanisms. Questions relevant to rehabilitation concerns can also be explored within the VE. In our research we are examining how a dynamic visual field (i.e., with stereo and content) might affect posture and spatial orientation. We have extended our research to examine the effects of the moving visual environment with a moving base of support rather than during quiet stance. Thus, subjects are first exposed to an immersive visual environment followed by perturbations at the base of support.

METHODS

Subjects

Four healthy young adults (aged 21–26 years), two healthy elderly adults (aged 76–78 years), and a patient with labyrinthine deficit (44 years) gave informed consent according to the guidelines of the Institutional Review Board of Northwestern University Medical School to participate in this study. The healthy subjects had no history of central or peripheral neurological disorders or problems related to movements of the spinal column (e.g., significant arthritis or musculoskeletal abnormalities) and a minimum of 20/40 corrected vision (subjects could wear their eyeglasses with the stereo goggles). Vestibular integrity was tested in each healthy elderly subject with the Dynamic Illegible "E"-test (Longridge & Mallinson, 1987). Clinical reflex tests (Achilles tendon and Babinski test); sensory tests to determine whether proprioception, light touch, and deep pressure were within normal limits; and Rhomberg tests were also performed on the patient and healthy elderly subjects by an otoneurologist. The patient was diagnosed with idiopathic bilateral vestibular loss and was 6 years post-onset of symptoms. He had a vestibulo-ocular reflex gain of 0.28 to sinusoidal yaw rotations (0.32 Hz) in the dark. Both elderly subjects participated in a daily exercise program and the patient with labyrinthine deficit was a marathon runner. One elderly subject reported that she had fallen two to three times in the previous year. All subjects were naive to the VE.

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Procedures

Subjects stood on the posture platform (sled) with their hands crossed over their chest and their feet together. The scene either rotated ±20° about the pitch or roll axis at 0.1 Hz, or translated ±6 m/second in the fore-aft direction. Sinusoidal translations of the sled were ±10 cm in the anterior-pos-
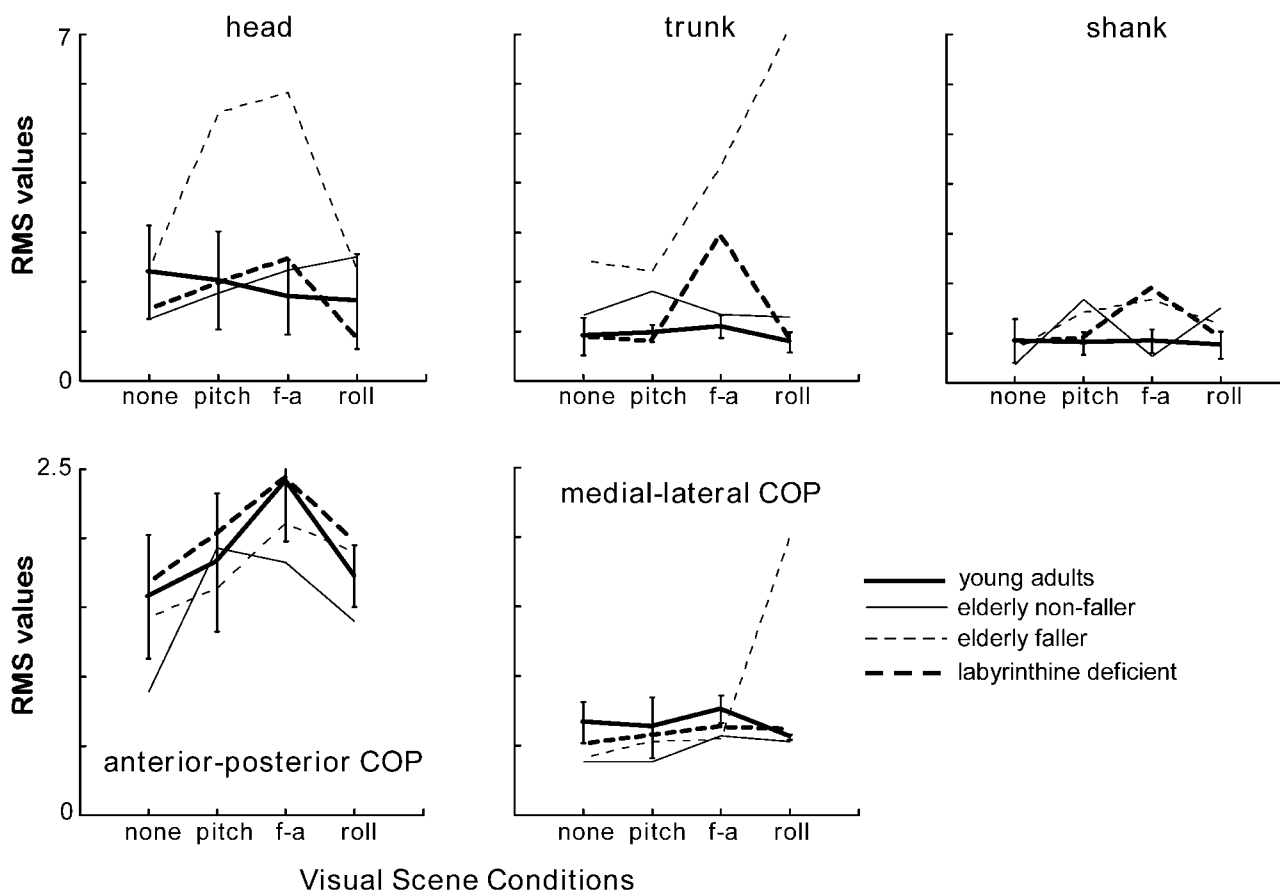
FIG. 2. Root mean square (RMS) values of head, trunk, shank excursion, and anterior-posterior and medial-lateral center of pressure (COP) excursions to sinusoidal sled translations without movement of the visual scene (none) and with pitch, fore-aft, and roll motion of the scene. The mean and standard deviations across the four young adults are also plotted on the bold solid line. Data was taken 50 ms after the start of the trial and plotted for a 60-second period.

terior direction at 0.25 Hz. Each trial lasted 140 seconds with 20 seconds of sinusoidal visual scene motion before and after the sled moved.

Data Collection and Analysis

Three-dimensional kinematic data from the head, trunk, and lower limb were collected at 135 Hz using 3D video motion analysis (Optotrak, Northern Digital Inc., Ontario, Canada). *X-Y-Z* coordinates of each anatomical marker and the sled position signal were collected. Segmental angles were calculated with respect to an inertial coordinate system fixed on markers placed on the sled at the neutral position (preperturbation). Infrared markers placed near the lower border of the eye socket and the external auditory meatus of the ear were used to calculate head angular position relative to the earth vertical. Markers placed at C_7 and the tubercle of the iliac crest were used to calculate trunk angular position relative to earth vertical, and ankle angular position was the angle between the lateral condyle and the lateral malleolus.

A 6 degrees of freedom force plate (AMTI, Watertown, MA) sat on top of the posture platform and recorded the triaxial forces and moments of the ground reaction from which COP was calculated. Root mean square (RMS) values were calculated for the COP and segmental angles to examine changes in response magnitude. Power and magnitude squared coherence (Gerald & Wheatley, 1999) of the segmental and COP response at each stimulus frequency was calculated following a fast Fourier transform analysis. Paired *t* tests were performed on the RMS of the responses of the young and elderly adults.

RESULTS

RMS values for each segment and anterior-posterior sway (COP) were most affected by visual scene motion in fore-aft and roll (Fig. 2). When the sled moved but there was no motion of the scene,
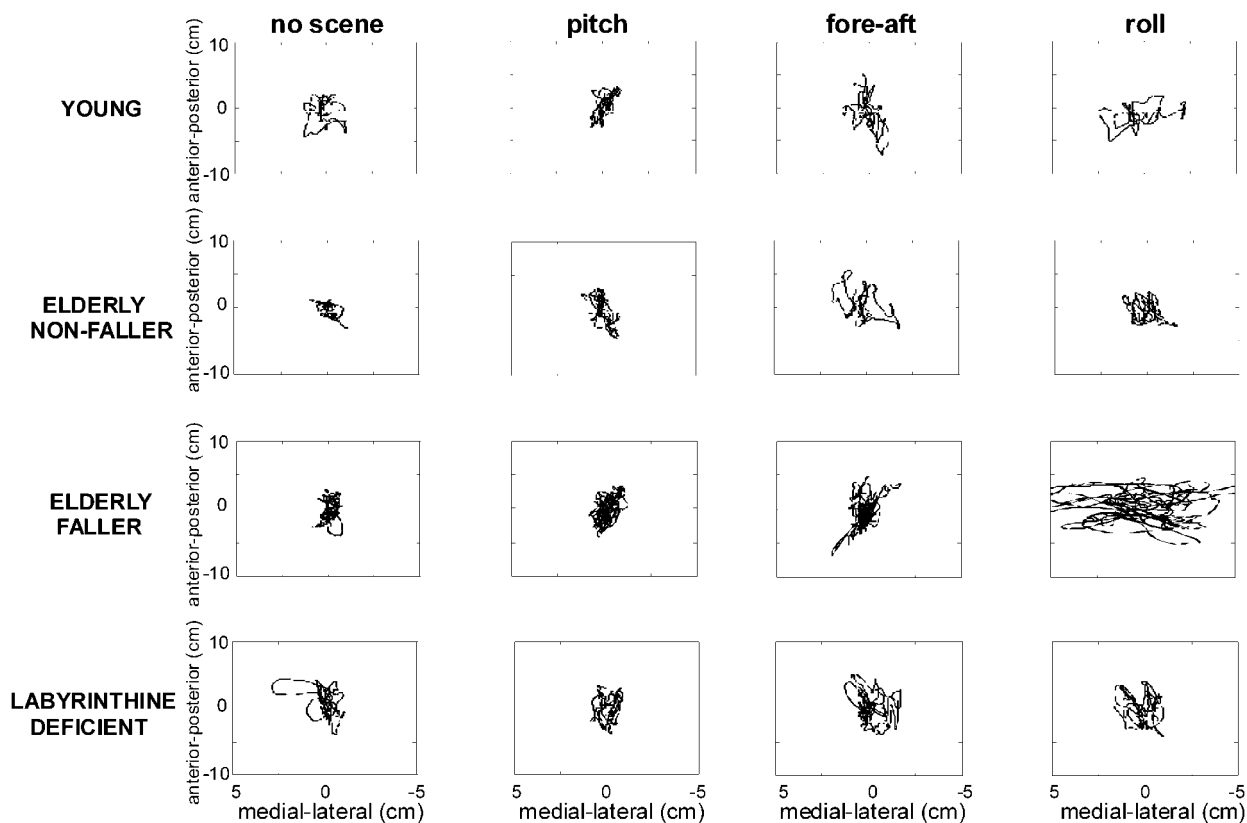
FIG. 3. Anterior-posterior (*y*-axis) and medial-lateral (*x*-axis) center of pressure (COP) responses during sinusoidal sled translation (no scene) and combined sled and visual scene motion in pitch, fore-aft, and roll are plotted for one young adult, two elderly adults, and the labyrinthine deficient adult. Data was taken 50 ms after the start of the trial and plotted for a 60-second period.

the pattern of sway reflected the motion of the sled—moving no more than ±5 cm in the anterior-posterior direction (Fig. 3). With pitch motion of the scene, the anterior-posterior excursion did not change, but young adults exhibited an increase in medial-lateral excursion ($t(3) = 3.707, p < 0.02$). With fore-aft motion of the scene, RMS values of anterior-posterior sway were significantly greater than with no motion of the scene in the young adults ($t(3) = 23.00, p < 0.05$). With roll motion of the scene, anterior-posterior excursions were significantly larger than in those trials with no motion of the scene in both the young ($t(3) = 2.28, p < 0.05$) and elderly adults ($t(1) = 20.46, p < 0.02$). Only the elderly subjects demonstrated a significant effect of visual roll motion on the RMS values for medial-lateral sway ($t(1) = 6.14, p < 0.05$), probably as the result of a very large response from the elderly faller (Fig. 3). RMS values for sway of the labyrinthine deficient subject did not differ from that of the healthy young adults.

When only the sled moved, power of the anterior-posterior sway responses was much greater than medial-lateral sway and was dominated by sled

frequency of 0.25 Hz (Fig. 4). When the visual scene also moved, power at the sled frequency increased and responses at the visual scene frequency (0.1 Hz) emerged. The elderly faller also exhibited a larger medial-lateral component during visual motion in roll.

Our results suggest that the dynamics of the visual field may differentially influence nontransient postural parameters. We have now used this approach to identify how the subject with labyrinthine deficit used the visual information during postural instability. Previous studies indicated that labyrinthine deficient individuals become more sensitive to visual inputs with vestibular loss (Bronstein, 1995a, 1995b; Furman & Jacob, 2001; Guerraz, Gianna, Burchill, Gresty, & Bronstein, 2001; Guerraz, Thilo, Bronstein, & Gresty, 2001). Although some patients with bilateral labyrinthine loss can recover fairly normal-looking gait, they still exhibit ataxia when visual information is obscured (Glasauer, Amorim, Vitte, & Berthoz, 1994; Pozzo, Berthoz, Lefort, & Vitte, 1991) or in environments with conflicting or disorienting vi-
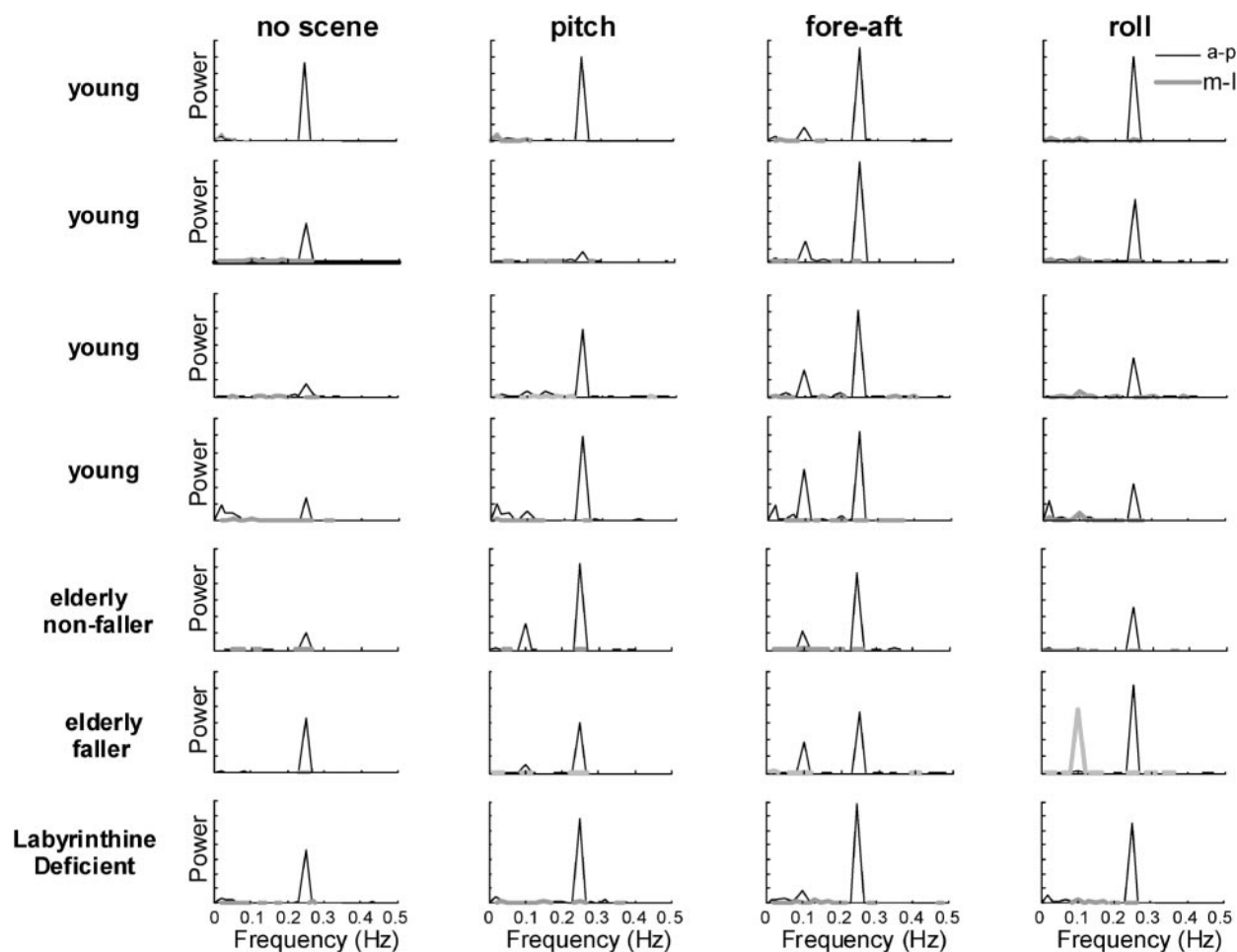
FIG. 4. Power plots of anterior-posterior (black line) and medial-lateral (grey line) center of pressure (COP) for each subject were calculated over a 60-second period, starting 50 seconds after trial onset for sled motion only (no scene) and combined sled and visual scene motion in pitch, fore-aft, and roll. Data for each subject was normalized to that subject's largest response across all conditions.

sual stimuli (Bronstein, 1995a, 1995b; Guerraz, Yardley, et al., 2001c).

We have created a sensory conflict situation by presenting 0.1 Hz fore-aft sinusoidal motion of the visual field concurrent with 0.25 Hz fore-aft sinusoidal motion of the base of support. Two 110-second trials were presented, one with the sled motion alone and one with combined sled and scene motion. In the first half of the trial the subject attempted to counter the visual stimulus with his head and trunk while his ankle was matched to the frequency of the sled. Then he changed his segmental organization so that all three segments were moving synchronously and with the motion of the sled. Although the visual stimulus exerted much greater power with combined inputs, the sled stimulus also exerted greater power over the head and trunk with a combination of visual and base of support motion (Fig. 5). Coherence with the

visual frequency dramatically decreased in all three segments over the period of the trial (0.99–0.34 in the head; 0.97–0.38 in the trunk; 0.92–0.48 in the ankle), suggesting that he chose to ignore the externally imposed visual frequency so that he could respond primarily to the inputs ascending from the sled motion and, most likely, his interoceptive feedback. It may be that in order to maintain an upright orientation this subject has learned to suppress or ignore discordant visual inputs. Response magnitudes and power of the visual signal still increased despite this suppression, suggesting a continued influence of visual motion over the response.

DISCUSSION

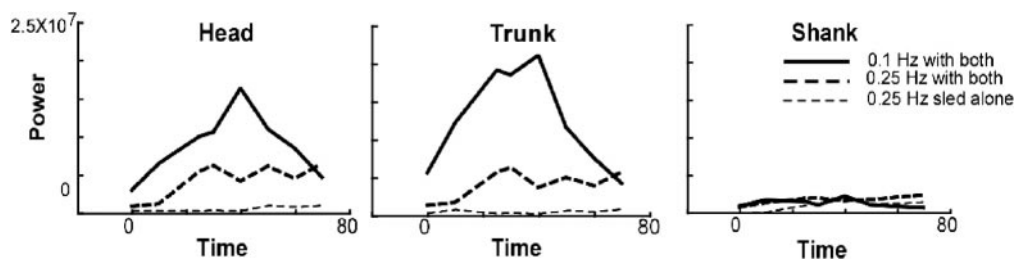Our results suggest that the dynamics of the visual field differentially influenced nontransient

FIG. 5. Power plots of the head, trunk, and shank of the labyrinthine deficient subject are plotted over the period of the trial at the relevant frequencies for sled motion alone and for simultaneous motions (both) of the sled (0.25 Hz) and visual scene (0.1 Hz).

postural parameters and likely increased the potential for postural instability. Individuals with bilateral labyrinthine deficit have been found to demonstrate gradually increasing instability in dynamic environments (Keshner et al., 1987; Redfern & Furman, 1994). Also, elderly subjects have been found to exhibit their greatest instability in the medial-lateral plane (Maki, Holliday, & Topper, 1994; McClenaghan et al., 1995), and this result was exaggerated in our elderly faller by the presence of a visual field moving in the roll plane. We would predict that in the presence of a multimodal dynamic environment, suppression or removal of any one input would influence the outcome of the response. We believe it unlikely that the role of any single pathway contributing to postural control can be accurately characterized in a static environment if the function of that pathway is context-dependent.

These results have significant implications for the continued measurement of postural activity and the important role of the VE in the research and rehabilitation environment. The adaptive nature of the human nervous system makes it imperative that we test and train individuals in conditions as close as possible to those they will encounter during their daily activities. Previous studies examined how abstract images affect posture control (Lestienne et al., 1977). We have found in some cases that a complex, immersive environment may not be any more effective than were the abstract images that were used in the past (Keshner & Kenyon, 2000). However, this may only be true when the subject did not need to interact with his or her environment. Our system allows us to explore the more complex behaviors that are necessary for rehabilitation. The development of the VEPO laboratory has demonstrated that including context, texture, frequency, and complexity can produce more convincing task demands under experimental controls. We want to emphasize that the VE is not a multimillion dollar enterprise, particularly with the advent of the new PC graphics cards, and it could be easily replicated in a clinic and with patients and kept up and running on a continuous basis.

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