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Characterizing Head Motion in 3 Planes during Combined Visual and Base of Support Disturbances in Healthy and Visually Sensitive Subjects

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Abstract

Multiplanar environmental motion could generate head instability, particularly if the visual surround moves in planes orthogonal to a physical disturbance. We combined sagittal plane surface translations with visual field disturbances in 12 healthy (29–31 years) and 3 visually sensitive (27–57 years) adults. Center of pressure (COP), peak head angles, and RMS values of head motion were calculated and a 3-dimensional model of joint motion¹¹ was developed to examine gross head motion in 3 planes. We found that subjects standing quietly in front of a visual scene translating in the sagittal plane produced significantly greater ($p < 0.003$) head motion in yaw than when on a translating platform. However, when the platform was translated in the dark or with a visual scene rotating in roll, head motion orthogonal to the plane of platform motion significantly increased ($p < 0.02$). Visually sensitive subjects having no history of vestibular disorder produced large, delayed compensatory head motion. Orthogonal head motions were significantly greater in visually sensitive than in healthy subjects in the dark ($p < 0.05$) and with a stationary scene ($p < 0.01$). We concluded that motion of the visual field can modify compensatory response kinematics of a freely moving head in planes orthogonal to the direction of a physical perturbation. These results suggest that the mechanisms controlling head orientation in space are distinct from those that control trunk orientation in space. These behaviors would have been missed if only COP data were considered. Data suggest that rehabilitation training can be enhanced by combining visual and mechanical perturbation paradigms.

Keywords

orientation; virtual environment; posture; visual dependence

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Introduction

Neural control of the head and neck depends upon the goal of the movement¹. During postural control, one of the primary goals of the neck is to produce a stable base of support for the mass of the head and the visual and vestibular systems. Most studies of postural control have explored the position of the head only in the plane of the disturbance, assuming that the applied forces will constrain the spatial orientation of the postural response. Complex movements such as gait, however, require that postural stabilization occurs in more than one plane², and the kinematically redundant joints of the neck need to be controlled in all three planes of motion^{3, 4}.

We have reported previously that when both physical and visual disturbances are simultaneously presented, subjects incorporate the frequency characteristics of both inputs into their postural responses⁵. If postural disturbances are presented in more than one orientation in space, we might expect that the stabilization task will also become more spatially complex and produce compensatory motion in more than one rotational plane. With gaze and arm pointing movements, the problem of minimizing orthogonal motion is solved by the nervous system through constraining the rotation vectors to a 2-D surface^{6, 7}. This reduction in the number of rotational degrees of freedom is known as Donders' law. In the head however, Donders' law has been shown to be violated both in monkeys during active gaze saccades⁸ and in humans during active head pointing movements⁹. Previous studies of visual motion alone have demonstrated that there were no directionally specific postural responses orthogonal to the displacement of a visual scene^{10, 11}. The presence or absence of head motion in 3 rotational planes during whole body instability has not yet been studied.

In this study we applied a 3-dimensional model of joint motion¹² to examine compensatory motion of the head with respect to the trunk both when the visual field was stable and when motion of the visual environment occurred in planes other than that of the whole body perturbation. We expected the head to be more unstable in the dark than when a stable visual image was available to assist in orienting the head in space¹³. We hypothesized that if motion of the visual field produced a change in the orientation of the head with respect to the body, then orthogonal head motion would be equal to or greater than that occurring when in the dark. If visual field motion had a directionally specific effect, we predicted that increased head motion would emerge in the plane of the visual motion.

We also examined head motion in three subjects diagnosed with visual sensitivity. These individuals experience dizziness when in visual environments with full field of view repetitive or moving visual patterns¹⁴. Visual sensitivity is often present in patients with a history of peripheral vestibular disorder, but there is a subset of patients with no history of vestibular disorder and who test negative for vestibular deficit on traditional clinical tests. Visual sensitivity is thought to emerge from their inability to adapt to the visual-vestibular conflict that occurs when both the individual and environment are in motion, thereby making identification of the position of the head in space less accurate¹⁴. Greater sensitivity to dynamic visual inputs would interfere with their ability to stabilize the head relative to the trunk. We hypothesized that out of plane head motion in these individuals would be greater than that of healthy subjects when the visual scene was moving. Preliminary data from this population has been published¹⁵.

Methods

Subjects

Twelve healthy young (29–31 yrs) adults (**HS**) and three subjects (27–57 yrs) with a diagnosis of visual sensitivity (**VS**) participated in these experiments. All subjects provided written

consent in accordance with the IRB, Feinberg School of Medicine, Northwestern University. HS were free from musculoskeletal and neurological disorders. Visual sensitivity was diagnosed as a feeling of dizziness or oscillopsia when exposed to full field of view visual motion¹⁴. One VS subject developed sensitivity to visual stimuli with no known etiology (VS1). ENG and MRI of the brain were normal as was her general neurological examination except for extremely poor smooth visual pursuit. Another experienced dizziness when standing up, performing rapid head movements, walking in a dark room, and in busy sensory environments 2 years after treatment with an intravenous antibiotic (VS2). General neurological examination, ENG testing, and rotatory chair testing was normal. The third VS subject (VS3) had migraine associated vertigo and developed visual sensitivity 2 years post onset of BPPV. All VS subjects reported being bothered by elevator and motor vehicle travel, and by complex visual environments such as grocery stores.

Apparatus

Subjects stood barefoot with the feet in parallel and shoulder-width apart on a platform (Neurocom, Inc) that was anterior translated 5 cm at 5 cm/sec. Previously published research describes the hardware and software responsible for generating the virtual environment⁵. In brief, subjects stood approximately 1.25 m in front of a flat screen onto which a virtual environment was back-projected. The virtual environment (scene) 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. For the stereo-imagery, 7 cm spacing between the centers of projection (approximately equal to the average interpupillary distance) was used to produce field sequential stereo images for each eye. Correct scene perspective was continuously updated by motion capture markers providing head position. Total display system latency from the time of a head motion to the time the new image portrayed the movement in the environment was 25 msec. Stereo update rate of the scene (how quickly a new image was generated by the graphics computer in the frame buffer) was 60 stereo frames/sec.

Procedures

Subjects standing on the platform with their arms positioned at their sides (elbows were flexed to 90 deg so that markers on the hip were not blocked) were instructed to stand quietly and look straight ahead at the image. All subjects received, in random order, the platform disturbance in the dark (DARK) and with the image projected as natural motion (NM) where the correct scene perspective was continuously updated by motion capture markers providing feedback about head position. The image was also rotated in upward pitch (PITCH) with a constant velocity (30 deg/sec) of optic flow.

Additionally, HS were recorded when the platform was either stationary or translated in the anterior direction with a synchronized scene translation moving toward the subject at 2 m/sec to resemble real life perception (FORWARD), and when platform translation was combined with a counterclockwise scene rotation (ROLL) at 30 deg/sec. Each trial contained 10 sec of quiet stance before simultaneous triggering of scene and platform motion. Data were collected 10 sec prior to and following onset of the two stimuli.

Data Collection and Analysis

Three-dimensional kinematic data were collected at 120 Hz using the Motion Analysis Hawk system (Motion Analysis, CA). Three non-colinear passive markers per-segment were mounted on the subject's head and trunk using double sided-tape. Placement of head and trunk markers was chosen to minimize problems of marker visibility and facilitate tracking of markers during the experiments. A quiet stance trial was collected, and the mean of 100 frames of these data was used to calculate the head and trunk orientations with respect to the laboratory

coordinate system prior to the perturbation trials. Platform motion was subtracted from linear motion of the head prior to calculating segmental motion.

To describe 3-dimensional motion of head with respect to trunk, we used a joint coordinate system representation¹² (Fig. 1). This representation has been used by others to describe the gross 3-dimensional head-to-trunk movement using marker based systems^{16–18}. Segmental coordinates were derived from three non-colinear passive markers mounted on the subject's head (occipital, right temporal, left temporal) and trunk (T_1 , T_{10} , manubrium). The 3-dimensional sequential rotations defining motion of the head with respect to the trunk (Fig. 1) consisted of a first rotation through an angle ($\theta_{bending}$; the angle between Z_h and e_2) about the head's anterior-posterior axis (X_h -axis or e_1) followed by rotation about the trunk's Y_T axis (or e_2) through $\theta_{flexion/extension}$, the angle between Z_T and e_1 . The final rotation was about a superior/inferior floating axis (e_3) through $\theta_{rotation}$, the angle between e_1 and e_2 . The direction of the floating axis was defined by the direction of the cross product of e_1 and e_2 as shown in Fig. 1. While our choice of the rotational sequence was arbitrary, preliminary examination of the data indicated that calculated amplitudes of the 3-dimensional head-to-trunk orientations were independent of order of rotational sequence. This independence was due to the small angular excursions of the head during the different experimental paradigms (see Woltring¹⁹ for a detailed explanation).

Peak displacement and response area of the head and trunk was calculated in each plane over the first 1000 msec of the trial. RMS values across this 1000 msec period were compared between DARK and every other scene condition for each group (HS and VS) using paired t -tests with a Bonferroni correction at the $p < 0.025$ level and the proportion of variance accounted for (VAF) was calculated. Comparisons between HS and VS subjects were performed with a Mann-Whitney U-test with significance set at $p < 0.05$.

Center of pressure (COP) recordings were collected at a rate of 200 Hz from two AMTI force plates incorporated into the Neurocom Platform. Resultant x and y vectors were calculated as weighted sums from the individual signals. Peak minimum and maximum excursions of the COP were calculated in the sagittal and frontal planes across the first 2000 ms of the trial. Differences between DARK and every other scene condition were examined with t -tests with a Bonferroni correction at the $p < 0.025$ level and VAF was calculated.

Results

Healthy Subjects

COP excursions were significantly greater in the sagittal plane with PITCH than with DARK (Table 1). Angular displacement of the trunk, however, demonstrated no effect of the visual scene motion (Fig. 2). The first response of the head following onset of platform translation was downward pitch (Fig. 2). Magnitudes and directions of head roll and yaw varied across subjects. Onset latencies of head motion following the platform disturbance (mean 120 ± 46 ms) did not significantly differ as a result of scene motion. In the first 1000 msec following onset of platform motion, no significant differences emerged in the peak flexor angle of the head. Peak yaw angles of the head were significantly greater in DARK than with NM ($p < 0.02$; VAF=0.69).

RMS values in the pitch plane were not significantly affected by scene motion (Fig. 3A). No significant difference emerged in the peak flexion angles or RMS values of head pitch whether on a stationary or a translating platform when combined with FORWARD visual motion. The ratio of yaw to pitch on a stationary platform combined with FORWARD visual motion (Fig. 3B) was, however, significantly greater than when on a translating platform with FORWARD visual motion ($p < 0.003$).

Head RMS values in the roll plane were significantly greater in DARK than in NM ($p < 0.02$; VAF=0.72). RMS values were also significantly greater with ROLL than DARK in the roll ($p < 0.025$; VAF=0.54) and yaw ($p < 0.02$; VAF=0.55) planes. Ratios of motion in the 3 planes were suggestive of rotational head motion (roll and yaw) that was greater than sagittal head motion (pitch) in DARK and ROLL (Fig. 3B).

Visually Sensitive Subjects

VS subjects did not exhibit a significant effect of scene motion on their COP excursions. VS subjects did exhibit greater variability than HS in both a-p and lateral sway, and significantly larger COP RMS values than HS in the sagittal plane during DARK and NM (Table 1).

Onset latency of head motion (mean 193 ± 26 ms) was significantly longer in VS subjects than in HS ($p < 0.02$) in each condition tested. Like the HS, the first response of the head in the VS subjects following platform translation onset was downward pitch (Fig. 4). The RMS values of this downward pitch motion appeared to be greater in VS subjects than in HS across all visual scene conditions (Fig. 3A), but were only significant with PITCH ($p < 0.05$). This was likely due to the very large pitch plane responses in VS1 and VS2 (Fig. 4). RMS values of head yaw and roll were significantly greater in VS subjects than in HS with NM ($p < 0.01$). Ratios of out of plane to sagittal plane motion (Fig. 3B) were smaller in VS subjects than HS in DARK, variable with NM, and appeared to increase in PITCH.

Discussion

We have examined how the absence of motion, or the presence of visual scene motion in planes other than physical motion, will influence orientation of the head in space when combined with a linear translation disturbance. Our model of head kinematics revealed significant multiplanar motion of the head which would have been missed had only COP data been considered. If the trunk were the primary mover of the head, then the head with respect to trunk response would have been close to nil and we would assume that the visual scene had little influence on independent motion of the head in space. In most subjects we did observe head motion that exceeded that of the trunk suggesting that distinct pathways may be influencing the position of the head during whole body instability.

When subjects were standing quietly, even in the presence of a visual scene moving only in the pitch plane, there was significant motion in the rotational planes (roll and yaw). When stance was disturbed by platform translations in the sagittal plane, trunk motion was highly constrained to the plane of the perturbing force and head motion in orthogonal planes was minimal relative to pitch. Thus the presence and direction of a physical disturbance did constrain head orientation in space. But head motion orthogonal to the plane of the physical perturbation increased when subjects were standing on the moving platform in the dark or in front of a rotating visual scene. In fact, when sagittal motion of the platform was combined with a rotating visual scene, out of plane motions of the head exceeded even those motions observed in the dark.

It has been shown that subjects exposed to optokinetic stimuli about the roll axis exhibit a significant perception of roll tilt in the direction of the visual stimulus²⁵. Subjects standing in front of a wide field of view virtual environment have been shown to produce a significant tilt of their head and trunk in the direction of the roll motion of the scene^{5, 27}. These results suggest that the presence of a rotating visual field has a stronger influence on position of the head in space than does the feedback generated by linear acceleration of the base of support.

It is not surprising that head motion in each of the three planes was reduced when the scene was providing correct feedback relative to head motion. The horizon in the scene presented

visual signals with a fixed orientation that would assist in precise estimation of the direction of gravity¹³. Our results demonstrated that the quantity of out of plane head motion remained consistent whether the scene was matched to the head, moving forward, or moving in pitch. Three dimensional head motion under these three visual conditions might be consistent because both sagittal and pitch plane visual motion are components of natural motion like gait²⁰. Convergent linear and angular visual flow is constantly used to provide the CNS with motion and orientation information²¹ and suggests that experience with a particular visual environment might influence the ability to maintain a steady orientation in space^{22, 23}.

Although the quantity of head motion in the sagittal plane was consistent in magnitude and direction across all visual conditions, yaw and roll head motions in the dark varied in both magnitude and direction. One explanation is that the vestibular system primarily controls head motion in the sagittal plane and, therefore, motion in this plane was more invariant even in the absence of visual feedback. But this conclusion would be counter to a large amount of literature demonstrating that the vestibular receptors are primarily responsible for signaling multiplanar motions of the head in space^{24, 25}. An alternate explanation is that proprioceptive inputs from the cervical spine were contributing to the orientation of the head in the sagittal plane and, therefore, maintaining a consistent response in that plane even when in the dark²⁶. The role of cervical proprioceptive inputs in head stabilization could be deduced from the response of the visually sensitive subject with a history of vestibular disorder. Unlike the two subjects with no history of vestibular deficit, this individual had a prior opportunity to adapt to unreliable vestibular inputs and now produced very small responses in the sagittal plane suggestive of a reliance on neck proprioceptive inputs to stabilize the head with respect to the trunk.

Even with diminished head with respect to trunk motion in one individual, whole body sway increased in the patient group in the dark and with natural scene motion. More orthogonal head motion was observed whenever the visual field was moving. Orthogonal motion even increased when the visual scene reflected natural visual feedback which should have assisted accurate estimation of head orientation in space^{22, 25}. If their head motion followed the direction of the scene, we could assume that these individuals were simply tracking visual motion. But the direction of the head was compensatory²⁸ for both the physical perturbation and visual scene motion. We conclude that the confluence of larger responses to visual field motion and longer latencies of initial head motion was indicative of a greater reliance on visual feedback to orient in space.²⁹

We have demonstrated that motion of the visual field modified 3-dimensional response kinematics of a freely moving head even while the trunk response was constrained by the direction of a physical perturbation. Emergence of more complex kinematics of the head than of the trunk suggests differential control mechanisms for these body segments. These results have ramifications for rehabilitation interventions such as locomotion training in static visual environments³⁰. Combining visual and mechanical perturbation paradigms would place a greater demand on motor planning for postural stability and spatial orientation behaviors.

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References

1. Keshner EA, Baker JF, Banovetz J, Peterson BW. Patterns of neck muscle activation in cats during reflex and voluntary head movements. *Exp Brain Res* 1992;88:361–374. [PubMed: 1577110]

2. Balasubramaniam R, Riley MA, Turvey MT. Specificity of postural sway to the demands of a precision task. *Gait Posture* 2000;11:12–24. [PubMed: 10664481]
3. Vidal PP, Graf W, Berthoz A. The orientation of the cervical vertebral column in unrestrained awake animals. I. Resting position. *Exp Brain Res* 1986;61:549–559. [PubMed: 3082659]
4. Graf W, de Waele C, Vidal PP, Wang DH, Evinger C. The orientation of the cervical vertebral column in unrestrained awake animals. II. Movement strategies. *Brain Behav Evol* 1995;45:209–231. [PubMed: 7620871]
5. Keshner EA, Kenyon RV, Langston J. Postural responses exhibit multisensory dependencies with discordant visual and support surface motion. *J Vestib Res* 2004;14:307–319. [PubMed: 15328445]
6. Glenn B, Vilis T. Violations of Listing's law after large eye and head gaze shifts. *J Neurophysiol* 1992;68:309–318. [PubMed: 1517824]
7. Hore J, Watts S, Vilis T. Constraints on arm position when pointing in three dimensions: Donders' law and the Fick gimbal strategy. *J Neurophysiol* 1992;68:374–383. [PubMed: 1527564]
8. Crawford JD, Ceylan MZ, Klier EM, Guitton D. Three-dimensional eye-head coordination during gaze saccades in the primate. *J Neurophysiol* 1999;81:1760–1782. [PubMed: 10200211]
9. Admiraal MA, Medendorp WP, Gielen CC. Three-dimensional head and upper arm orientations during kinematically redundant movements and at rest. *Exp Brain Res* 2002;142:181–192. [PubMed: 11807573]
10. van Asten WN, Gielen CC, van der Gon JJ. Postural movements induced by rotations of visual scenes. *J Opt Soc Am A* 1988;5:1781–1789. [PubMed: 3204442]
11. Gielen CC, van Asten WN. Postural responses to simulated moving environments are not invariant for the direction of gaze. *Exp Brain Res* 1990;79:167–174. [PubMed: 2311693]
12. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng* 1983;105:136–144. [PubMed: 6865355]
13. Howard IP, Childerson L. The contribution of motion, the visual frame, and visual polarity to sensations of body tilt. *Perception* 1994;23:753–762. [PubMed: 7845767]
14. Bronstein AM. Visual vertigo syndrome: clinical and posturography findings. *J Neurol Neurosurg Psychiatry* 1995;59:472–476. [PubMed: 8530928]
15. Keshner EA, Streepey J, Dhaher Y, Hain T. Pairing virtual reality with dynamic posturography serves to differentiate between patients experiencing visual vertigo. *J Neuroengineering Rehabil* 2007;4:24.
16. Woltring HJ, Long K, Osterbauer PJ, Fuhr AW. Instantaneous helical axis estimation from 3-D video data in neck kinematics for whiplash diagnostics. *J Biomech* 1994;27:1415–1432. [PubMed: 7806550]
17. Medendorp WP, Melis BJ, Gielen CC, Gisbergen JA. Off-centric rotation axes in natural head movements: implications for vestibular reafference and kinematic redundancy. *J Neurophysiol* 1998;79:2025–2039. [PubMed: 9535966]
18. Moore ST, Hirasaki E, Raphan T, Cohen B. Instantaneous rotation axes during active head movements. *J Vestib Res* 2005;15:73–80. [PubMed: 15951621]
19. Woltring HJ. Representation and Calculation of 3-D Joint Movement. *Human Movement Science* 1991;10:603–616.
20. Hirasaki E, Moore ST, Raphan T, Cohen B. Effects of walking velocity on vertical head and body movements during locomotion. *Exp Brain Res* 1999;127:117–130. [PubMed: 10442403]
21. Cornilleau-Peres V, Droulez J. Stereo-motion cooperation and the use of motion disparity in the visual perception of 3-D structure. *Percept Psychophys* 1993;54:223–239. [PubMed: 8361838]
22. Macneilage PR, Banks MS, Berger DR, Bulthoff HH. A Bayesian model of the disambiguation of gravito-inertial force by visual cues. *Exp Brain Res* 2007;179:263–290. [PubMed: 17136526]
23. Keshner EA, Dokka K, Kenyon RV. Influences of the perception of self-motion on postural parameters. *Cyberpsychol Behav* 2006;9:163–166. [PubMed: 16640471]
24. Green AM, Shaikh AG, Angelaki DE. Sensory vestibular contributions to constructing internal models of self-motion. *J Neural Eng* 2005;2:S164–S179. [PubMed: 16135882]
25. Zupan LH, Merfeld DM. An internal model of head kinematics predicts the influence of head orientation on reflexive eye movements. *J Neural Eng* 2005;2:S180–S197. [PubMed: 16135883]

26. Keshner EA. Head-trunk coordination during linear anterior-posterior translations. *J Neurophysiol* 2003;89:1891–1901. [PubMed: 12686571]
27. Keshner EA, Kenyon RV. The influence of an immersive virtual environment on the segmental organization of postural stabilizing responses. *J Vestib Res* 2000;10:207–219. [PubMed: 11354434]
28. Keshner EA, Woollacott MH, Debu B. Neck, trunk and limb muscle responses during postural perturbations in humans. *Exp Brain Res* 1988;71:455–466. [PubMed: 3416963]
29. Nashner L, Berthoz A. Visual contribution to rapid motor responses during postural control. *Brain Res* 1978;150:403–407. [PubMed: 678978]
30. Dobkin B, Apple D, Barbeau H, Basso M, Behrman A, Deforge D, et al. Weight-supported treadmill vs over-ground training for walking after acute incomplete SCI. *Neurology* 2006;66:484–493. [PubMed: 16505299]

Figure 1.

An anterior-lateral view of the head/trunk with the marker sets/segmental coordinates (left) and joint coordinate system (right) superimposed. The segmental coordinates were derived from the three non-colinear passive markers mounted on the subject's head (occipital, right temporal, left temporal) and trunk (T₁, T₁₀, manubrium). The figure illustrates the calculation used in this study to find three-dimensional angular motion of the head with respect to the trunk (see methods for more detail). The three-dimensional sequential rotations defining the motion of the head with respect to the trunk consisted of a first rotation through an angle ($\theta_{bending}$) about the head's anterior-posterior axis (X_h -axis or e_1) followed by rotation about the trunk's Y_T axis (or e_2) through $\theta_{flexion/extension}$. The final rotation was about a superior/inferior floating axis (e_3) through $\theta_{rotation}$. The direction of the floating axis is defined by the direction of the cross product of e_1 and e_2 .

Figure 2.

Head angular displacement (left column) and trunk angular displacement data (right column) from one healthy subject. Each plot portrays angular displacements in the three planes of motion for each visual and platform disturbance. Each trace on the plot represents either pitch (thin line), or roll (bold black line), or yaw (bold grey line) motion of the head and trunk. Vertical dashed line indicates the time at which the platform and/or scene motion began. The arrow on the top right indicates the direction of each of the three orthogonal planes plotted for head motion.

Figure 3.

A. Center and right plots contain the mean + standard deviation RMS values of head angular displacement for the healthy subjects (HS) and the visually sensitive subjects (VS) in each plane of head motion for DARK, NM, and PITCH scene motion. The plot on the left is the mean + standard deviation RMS values of head angular displacement for HS with ROLL and FORWARD scene motion. **B.** The first plot on the left is the ratio of head motion for HS with a stationary platform with FORWARD scene motion and a translating platform with ROLL and FORWARD scene motions. The second plot from the left presents the mean + standard deviation of the ratio of head motion in the roll plane with respect to the pitch plane (black bar) and in the yaw plane with respect to the pitch plane (gray bar) in the HS for DARK, NM, and PITCH scene motion. The next three plots present the roll with respect to pitch (black bar) and yaw with respect to pitch (gray bar) head motion in each VS subject for DARK, NM, and PITCH scene motion.

Figure 4.

Head angular displacement data for the three visually sensitive subjects. Each plot portrays head motion in the three planes of motion for each visual and platform disturbance. Each trace on the plot represents either pitch (thin line), roll (bold black line), or yaw (bold grey line) motion of the head and trunk. Vertical dashed line indicates the time at which the platform and/or scene motion began. Note the y-axis scale on the left for roll and yaw is the same for all subjects. The y-axis scale on the right for pitch is different for each subject. The arrow on the right indicates the direction of each of the three orthogonal planes plotted for head motion.

Table 1
Mean $\pm$ SD RMS Values of COP in the Sagittal and Frontal Planes

SAGITTAL	DARK	NM	PITCH	FORWARD	ROLL
HS	0.43 $\pm$ 0.1 *	0.65 $\pm$ 0.5	0.56 $\pm$ 0.2	0.75 $\pm$ 0.5	0.49 $\pm$ 0.1
VS	2.67 $\pm$ 2.1 *	3.25 $\pm$ 1.8 *	2.62 $\pm$ 1.7		
FRONTAL					
HS	0.36 $\pm$ 0.2	0.47 $\pm$ 0.1	0.43 $\pm$ 0.2	0.51 $\pm$ 0.4	0.42 $\pm$ 0.2
VS	1.58 $\pm$ 2.0	1.69 $\pm$ 2.1	1.58 $\pm$ 1.9		

* Significant differences between VS and HS ($p < 0.05$).