Original Contribution

The influence of an immersive virtual environment on the segmental organization of postural stabilizing responses

E.A. Keshner[a,*] and R.V. Kenyon[b]

[a]*Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Chicago, IL 60611, USA*
[b]*Department of Electrical Engineering and Computer Science, The University of Illinois at Chicago, Chicago, IL 60607, USA*

We examined the effect of a 3-dimensional stereoscopic scene on segmental stabilization. Eight subjects participated in static sway and locomotion experiments with a visual scene that moved sinusoidally or at constant velocity about the pitch or roll axes. Segmental displacements, Fast Fourier Transforms, and Root Mean Square values were calculated. In both pitch and roll, subjects exhibited greater magnitudes of motion in head and trunk than ankle. Smaller amplitudes and frequent phase reversals suggested control of the ankle by segmental proprioceptive inputs and ground reaction forces rather than by the visual-vestibular signals. Postural controllers may set limits of motion at each body segment rather than be governed solely by a perception of the visual vertical. Two locomotor strategies were also exhibited, implying that some subjects could override the effect of the roll axis optic flow field. Our results demonstrate task dependent differences that argue against using static postural responses to moving visual fields when assessing more dynamic tasks.

Keywords: Sway, stabilization, vision, stereoscopic

*Corresponding author: Emily A. Keshner, Sensory Motor Performance Program, Rehabilitation Institute of Chicago, Room 1406 – E809, 345 East Superior Street, Chicago, IL 60611, USA. Tel.: +1 312 238 2228; Fax: +1 312 238 2208; E-mail: eak@northwestern.edu.

1. Introduction

Studies of postural control have often defined the influence of vision by its presence (eyes open) or absence (eyes closed). Generally, visual information was thought to be redundant unless vestibular or somatosensory inputs were lost as well [10] because removing vision by closing the eyes during platform disturbances does not significantly alter the postural response [21,33, 39]. But studies of dynamic visual inputs during quiet stance indicated that motion of the peripheral visual field induced body motion [35]. When a moving visual surround was fixed with respect to the subject's motion during quiet sway [1,2,33], greater sway amplitudes appeared. When spatial orientation and static postural sway were examined in the presence of a looming visual environment [5,18,29], visual control was dominant in the lower (0.1 Hz) frequency range [12]. Changes in the velocity and frequency of visual field motion have been shown to induce postural readjustments [13,29–31,37], with the most robust postural changes elicited in the roll and pitch planes [14,34]. A multivariate model of sway [25] indicated that both somatosensory and visual information make a unique contribution to the control of whole body posture.

Actual postural readjustments relative to visual disturbances remain poorly described. In most studies, postural instability has been defined as an increase in static sway obtained through center of pressure measures at the feet [3]. Buchanan and Horak [6] examined segmental organization of postural responses, but relied only upon eyes open and closed as the visual influence and related segmental organization to the frequency of platform translation. Even so they reported differential controls of the head and trunk and of the lower limbs as did Keshner et al. in an earlier study [23]. Only Kuno et al. [24], when examining the relation between body

sway and optokinetic vection using a head-mounted display, reported that large magnitudes of body sway were adjusted primarily at the hip and head-neck joints.

We have begun to examine the effects of a 3-dimensional stereoscopic scene on segmental stabilization using the technology of virtual reality or a virtual environment (VE). VEs are used to generate 3-D stereoscopic virtual scenes that elicit a strong sense of presence in the observer. Although this technology is rapidly being developed for both commercial and industrial purposes, little research has been performed to determine how an environment in which the subject perceives himself to be immersed will affect the perceptual and motor behaviors of the individual user. The virtual images are perceived to be at arm length from the performer, thus, we are able to explore the effects of near visual field motion on postural stabilization.

To understand the extent to which 3-D stereo VE conditions could affect postural behavior we performed three separate experiments using two types of visual imagery produced by a VE. The first set experiments paralleled some of the first postural experiments performed to examine the role of visual motion in postural reorganization [11,17]. These experiments used a cloud of random dots that moved in sinusoidal and constant velocity motion. Another set of experiments was performed to understand how more complex realistic imagery might affect postural reorganization. These experiments used a three-dimensional complex texture mapped visual scene, which moved according to both sinusoidal and constant velocity profiles. By presenting two different visual scenes, one with complex content and another with simple content, we were able to determine whether a less complex visual content that could be generated by slower computers would be equally effective. The final experiment examined the influence of rotating visual fields on locomotion behavior.

2. Methods

2.1. Subjects and procedures

Eight healthy young adults (25–34 yrs) volunteered with informed consent to participate in these experiments. Three subjects participated in Experiment I and three subjects participated in Experiment II. Two subjects from Experiment I and two additional subjects participated in the walking experiments. All but one subject was naive to VEs. The experimental protocol took a total of 20 minutes to execute per subject.

Subjects stood in the center of the VE with their arms at their sides and their feet together. At the start of each experiment, subjects were asked to make voluntary sway movements in the pitch and roll planes for comparison purposes. During the static sway trials, the subjects were instructed to maintain erect posture with respect to the perceived gravity vector. Each exposure to the moving visual field was followed by a rest period with eyes closed for approximately one or two minutes. Prior to each walking trial, subjects were instructed to move to the rear of the VE and then, upon command, walk normally forward for a distance of about 7 feet. Then the subject was asked to walk backwards towards his point of origin. Subjects made at least two attempts to walk forward. We limited the number of walking trials so that subjects' responses would have a minimum of learning and adaptation to walking in the presence of the visual scene.

2.2. Apparatus

Subjects were immersed in a three-dimensional, complex texture-mapped, stereoscopic visual scene generated by a VE called the CAVE^{TM}, which is a multi-person, room-sized, high-resolution, 3-D video and audio environment [8,9,20]. The CAVE is a theater $10 \times 10 \times 9$ feet, made up of three rear-projection screens for walls and a down-projection screen for the floor (Fig. 1(A)). Electrohome Marquis 8500 projectors throw full-color stereo workstation fields (1024×768 stereo) at 96 Hz onto each screen, yielding a 3000×2000 linear pixel resolution to the surrounding composite image.

An SGI Onyx II with 3 Infinite Reality Engines creates the imagery projected onto the walls and floor. The field sequential stereo images generated by the Onyx II are separated into right and left eye images using liquid crystal stereo shutter glasses worn by the subject (Crystal Eyes, StereoGraphics Inc.). These glasses limited the subject's horizontal field-of-view to $100°$ 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 attached to the stereo shutter glasses (head). Consequently, the virtual objects retained their true perspective and position in space regardless of the subjects' movement. The total display system latency measured from the time a subject moved to the time the resulting new stereo image was displayed in the environment was 50–75 ms. The update rate of the scene in the CAVE was 48 Hz in both
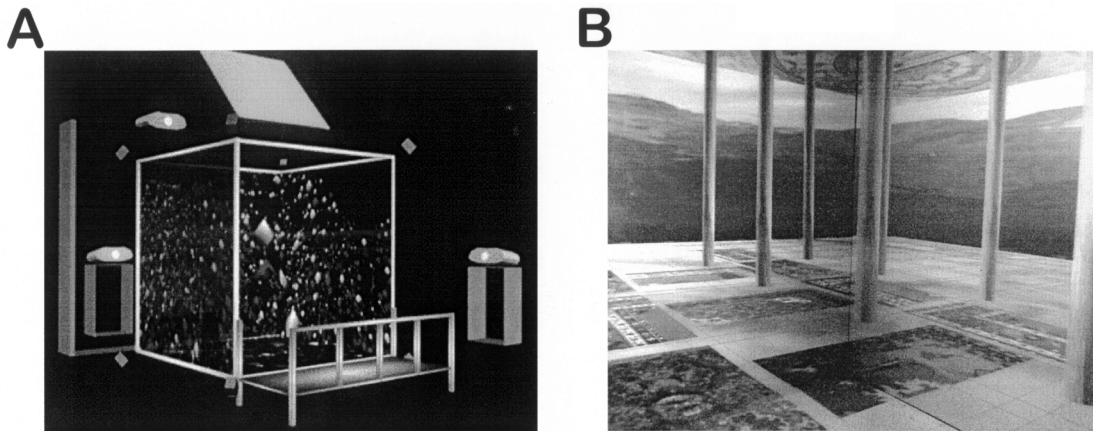
A

B

Fig. 1. (A) An artist's rendering of the CAVE and its components for generating synthetic images. The viewpoint is from outside the CAVE looking in towards the backside of the front wall. The mirror in the foreground reflects light from the projector at the near left to form an image on the front wall. The projectors and mirrors at the right, left and above project to the side walls and to the floor, respectively. The rear wall is open, allowing entry to the CAVE. The objects occupying the volume within the cave shows how the subjects were enveloped by the randomly placed dots that composed the scene in Experiment II. (B) A photograph taken inside the CAVE showing the subjects' view of the interior of The Great Hall of Vection used in Experiment I. The black lines in the scene are due to the seams produced by the joining of the projection screens in the CAVE. Subjects can freely move inside the room with the architectural details behaving properly and in real−time as the person navigates from one point to another.

experiments. The tracker sample rate (and therefore the data sampling rate) was 50 Hz for Experiment I and 60 Hz for Experiment II. During the walking experiments, each subject was presented with the ramp roll or pitch stimulus at the frequency of the experiment in which they were participating.

Orientation of the subject's head, torso, and ankle were tracked with tethered electromagnetic sensors (Flock of Birds, Ascension, Inc.). The 'head' sensor was attached to the stereo glasses. The trunk sensor was placed along the left side of the rib cage and held with a cloth bandage. The "ankle" sensor was not actually placed at the ankle since it would have produced unreliable readings due to the nonlinearities associated with a magnetic sensor so far from the receiver. Consequently, we used angular information from the sensor placed six inches above the left ankle on the shin to represent the angle at the ankle. Nonlinearities within the sensors' 7.5 feet range caused by the metallic objects and electromagnetic fields created by other devices resident in and about the CAVE have been corrected to within 1.5% by using a calibration/correction technique [15].

2.3. Stimuli

Imagery. The visual experience presented to the subjects was that of being immersed in a volume filled with three-dimensional objects at various distances from the subject. During Experiment I, the environment, which we called The Great Hall of Vection, appeared as the inside of a room with columns and a distant horizon (Fig. 1(B)) while for Experiment II, this entire volume was filled with randomly placed dots (Fig. 1(A)). In each case, the virtual objects were moved about the subject according to the protocol of the experiments. Since the stimuli are presented in stereo, the velocity of a particular object projected onto the retina was a function of its distance from the subject. Therefore, even though the subjects perceived the scene as moving as a single physical unit, on the retina each object within the scene had its own individual velocity based on distance from the subject.

Motion profile. Each subject was exposed to both sinusoidal and constant velocity stimuli rotating about the pitch and roll axes. In Experiment I, a 0.1 Hz sinusoid with amplitude of $\pm 18°$ ($\pm 5°$/sec peak to peak velocity) and a constant velocity ramp of $5°$/sec was used. In Experiment II, a 0.5 Hz sinusoid with an amplitude of $\pm 26°$ ($\pm 85°$/sec peak to peak velocity) and a constant velocity ramp of $25°$/sec was used. In both experiments, the roll ramp stimuli rotated in a counterclockwise direction about the line of sight and the pitch ramp stimuli rotated from lower to upper visual fields about an axis going through the subject's ears.

2.4. Data analysis

In each set of experiments, angles at each segment along with the stimulus were plotted relative to time.

Root mean square (RMS) values were calculated for the sinusoidal data. These values were then used to form a ratio to indicate the amount of power at all frequencies with respect to the trunk. In addition, Fast Fourier Transforms (FFTs) were computed from the sinusoidal data and yielded magnitude and phase information on each subjects' response to the stimuli. In Experiment I, a 2048-point FFT was performed which gave us a frequency resolution of 0.025 Hz. Due to the low frequency of the stimulus used in Experiment I, it was necessary to increase the length of the FFT so that there would be enough resolution to identify the peak response reliably. We thought it unwise to perform the same length FFT on Experiment II data because this would have included responses that occurred after the stimulus ceased moving. Thus, in Experiment II, a 1024-point FFT was performed which gave us a frequency resolution of 0.057 Hz. Magnitude data from the FFT's were plotted for each body segment. The phase at the stimulus frequency was recorded and calculated relative to the phase of the stimulus. This was done by subtracting the phase value of the stimulus from the phase response of each subject.

Position data obtained during our walking experiments was plotted on a 3-D graph. The X, Y, Z position data for the head, trunk, and ankle during walking trials were plotted against each other to visualize the movements of the subject's segments during this experiment.

3. Results

3.1. Constant velocity motion

Although velocities of visual scene motion differed greatly between subjects S1–S3 in Experiment I (5°/sec) and subjects S4–S6 in Experiment II (∼ 25°/sec), their response behaviors and dynamics were similar. When asked to move voluntarily in the pitch or roll direction, all subjects flexed and extended at the hip so that the trunk and head moved synchronously and there were small rocking motions at the ankles (see inset of Fig. 2). When subjects were asked to stand quietly and the visual environment was rotated at a constant velocity in the pitch plane, the primary response was a rapid shift of the head and trunk in the upward direction (S1–S4 in Fig. 2) while the ankle produced a smaller, oscillating motion about the initial position. A rapid downward motion of the head and trunk followed the rapid upward shift while the stimulus was still ongoing. In the other two subjects (S5 and S6), upward motion was more gradual and observed in the ankle as well, and even more so in the ankle and trunk than in the head of S6.

The ratio of the RMS values of segmental position across time should illustrate the relative extent of motion of one segment with respect to another (Table 1). During constant velocity rotations in pitch, the motion of the trunk was about 1.5 to 2 or more times greater than that of the ankle, whereas the trunk and head tended to be more of a 1 : 1 relationship or the trunk moved less than the head (S2 and S4). These patterns suggest that the visual scene dominated motion at the upper body, but that this motion could easily be compensated in the spine or at the hip so that the ankle did not have to compensate greatly for the induced instability.

When the visual environment was rotated with a constant velocity in roll, subjects drifted in the counterclockwise direction of the stimulus (Fig. 2) while producing oscillations at each segment. Similar patterns of motion at all three segments suggest that subjects S4, S5, and S6 were locking their hips and moving as a rigid rod from the ankle to the head. In S2 and S3 the ankle exhibited little shift in position, but the trunk and head suggested a sway pattern initiated at the hip rather than the ankle. S1 differed from the rest in the group by producing an immediate, rapid counterclockwise shift in the trunk with a rapid return while the head and ankle oscillated mostly about the initial position.

RMS values in roll with a constant velocity stimulus (Table 1) indicate that the head traveled more than the trunk in all subjects. The trunk and ankle relationship was more variable, however. In S2 and S3 the large ratio of trunk to ankle motion suggests large lateral bending motions at the waist and, possibly, hips. In S4 and S5, the approximately 1 : 1 relationship between the trunk and ankle suggest a more rigid whole body pendulum led by motion of the head. Larger displacements of the head and ankle in S1 and S6 suggest that these subjects attempted to stabilize by shifting their hip in the clockwise direction as the head and ankle oscillated in the counterclockwise direction of the visual scene.

3.2. Sinusoidal motion

Sinusoidal motion of the two visual scenes occurred at different frequencies (0.1 Hz for S1–S3; 0.5 Hz for S4–S6) but at similar velocities (85°/sec and 90°/sec, respectively). The primary difference in the response patterns of the two groups appeared in the frequency

Table 1
Ratio of trunk to head and trunk to ankle root mean square values

		Pitch Ramp	Roll Ramp	Pitch Sine	Roll Sine
S1	trunk/head	1.24	0.72	0.49	0.96
	trunk/ankle	2.70	0.69	0.98	0.91
S2	trunk/head	0.34	0.80	0.33	0.75
	trunk/ankle	1.69	6.32	1.43	1.51
S3	trunk/head	0.83	0.70	0.91	0.96
	trunk/ankle	1.76	3.62	1.15	3.11
S4	trunk/head	0.60	0.71	0.80	0.67
	trunk/ankle	2.12	1.06	1.31	0.65
S5	trunk/head	0.99	0.62	0.84	0.82
	trunk/ankle	1.44	1.20	0.82	0.82
S6	trunk/head	1.17	0.56	0.41	0.54
	trunk/ankle	1.32	0.76	1.95	0.90

relation between segmental and stimulus motion. FFT analyses (Fig. 3) revealed that at 0.1 Hz (S1–S3) each segment was dominated by the frequency of visual scene motion. At 0.5 Hz (S4–S6), frequency related oscillations, related to the stimulus frequency, overlay a lower frequency postural drift.

Although each of the segmental responses exhibited peaks of varying amplitudes that were related to the stimulus frequency, intersegmental behavior did not consistently follow the sinusoidal pattern of the predominant frequency (Fig. 4). In pitch, two of the subjects (S3 and S5) attempted to maintain a sinusoidal relation with the stimulus in all segments. The other four subjects (S1, S2, S4, S6) followed the stimulus for varying intervals and then exhibited a sudden downward drop, mostly at the head, followed by a steep upward motion. Three of the subjects (S1, S2, and S6) had much greater magnitudes of head than trunk and ankle motion (Table 1). In the other three subjects, head and trunk responses were close to unity. In all of the subjects, trunk motion was either equivalent to, or 1.5 times greater than the ankle.

RMS values close to one for all segments might suggest that subjects were moving as a rigid inverted pendulum, and indeed this pattern was suggested in the response behaviors of S3, S4, and S5. An analysis of phase relations between each segment and the stimulus (Table 2) revealed, however, that the contiguous phase relations between body segments that would describe a rigid inverted pendulum were only observed in S3. In all other subjects except S2, the head and trunk were closely in phase with each other but the phase of the ankle differed by as much as 100° (S5).

In roll, the 0.1 Hz sinusoidal pattern of the visual scene was much more evident in the response behaviors of S1–S3 (Fig. 4). Each of these subjects exhibited small (< 30°) phase differences between each segment and the stimulus and between their head, trunk,

and ankle (Table 2). Variability between the behaviors emerged in the response magnitudes. The similar phases and 1 : 1 RMS ratios (Table 1) in S1 suggest a rigid inverted pendulum pattern. In S2 and S3, however, the trunk moved 1.5 to 3 times greater than the ankle, respectively, suggesting large compensations at the hip rather than the ankle. In all three subjects, actual magnitudes of motion about the ankle were similar (Fig. 4) from which we infer that the ankle had a limited compensatory range in this plane of motion.

The 0.5 Hz stimulus did not dominate the roll responses of S4–S6. In S4, small oscillations at the stimulus frequency in the head were superimposed upon lower frequency, large amplitude drift of each segment initially in the clockwise direction, or opposite that of the visual scene. S5 and S6 maintained the stimulus related oscillations in the head and trunk for several cycles and then exhibited sudden larger shifts of each segment in the direction opposite the visual scene. For each of these subjects, larger RMS responses occurred in the head and ankle than in the trunk (Table 1) suggesting a lateral curving of the trunk in response to the motion in the roll plane. Response phases (Table 2) of S6 suggest that the segmental reorganization pattern occurred simultaneously, but both S4 and S5 exhibited phase reversals at the ankle that suggest the ankle was compensating for changes in the other segments rather than for motion of the visual scene.

Results from the FFT support observations in the raw data where drift is displayed as a peak at low frequencies. Larger components at the stimulus frequency are found in roll than in pitch, mostly in the head and torso.

3.3. Walking during constant velocity motion

Two subjects from Experiment I (S1 and S3) and two additional subjects (S7 and S8) were tested while walking. The two additional subjects observed the random
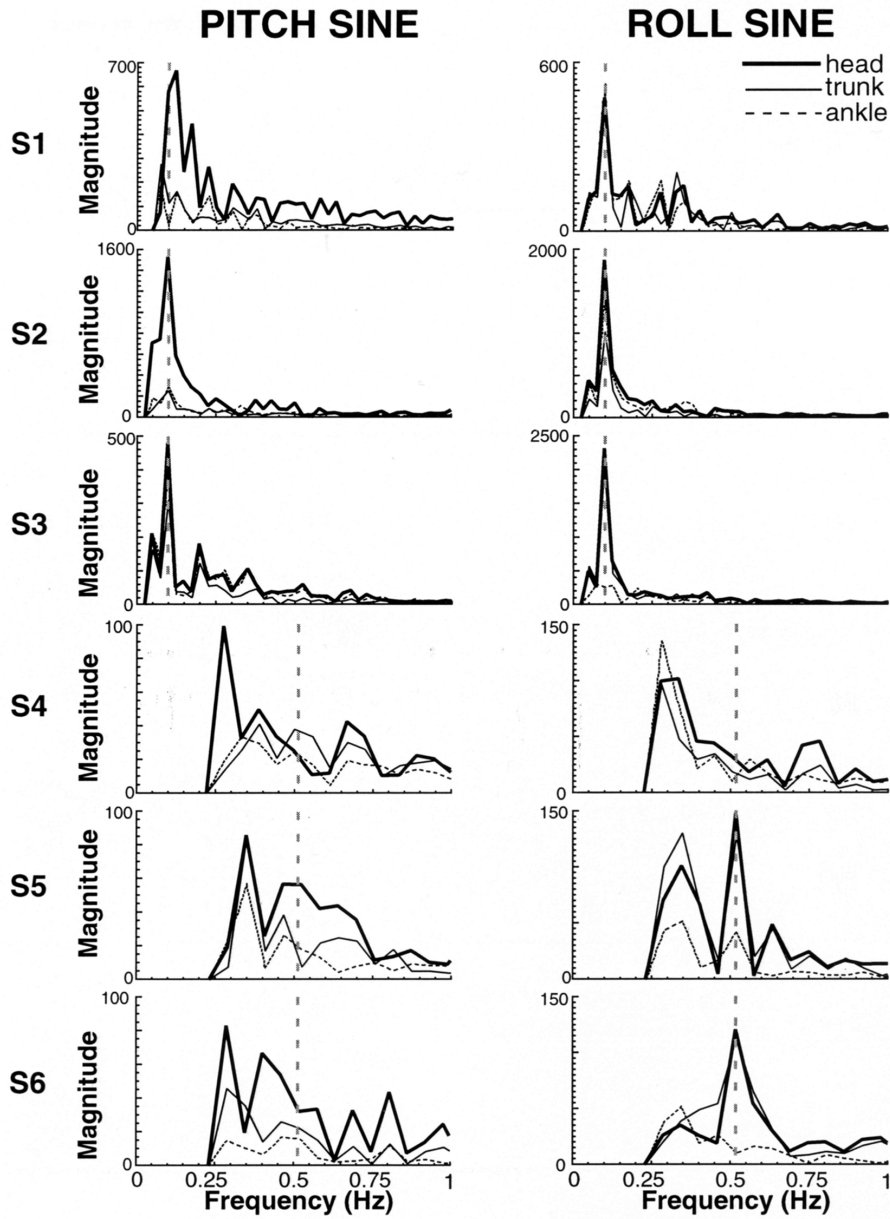
Fig. 3. Results of the FFT analysis of pitch and roll responses to sinusoidal motion of the visual scene. S1–S3 received a 0.1 Hz stimulus while S4–S6 received a 0.5 Hz stimulus (indicated by the vertical dashed line on each graph).

Table 2
Phase angles of each segment with respect to visual scene motion

	Pitch Sine			Roll Sine		
	Head	Trunk	Ankle	Head	Trunk	Ankle
S1	−4°	−5°	−26°	5°	18°	21°
S2	−20°	−61°	−34°	6°	−20°	4°
S3	−87°	−75°	−79°	−13°	−19°	−32°
S4	−43°	−50°	−124°	86°	3°	−24°
S5	−119°	−144°	−18°	−3°	−8°	84°
S6	111°	108°	58°	150°	128°	101°

dot pattern experienced by all subjects in Experiment II. The relationship between the head, trunk, and ankle while walking forward during constant velocity motion of the visual scene in the counterclockwise direction is represented as 3-dimensional behavior in Fig. 5. In each case the left leg was the only one instrumented and, therefore, the movement of the "ankle" represents the motion of this limb. For all subjects the three segments appear to be moving uniformly in space.

All of the subjects stated that they knew they were being pulled off balance and were unable to counteract the destabilizing force, but they compensated for this instability by exhibiting two different strategies. With each visual image one subject (S1 and S7) exhibited a normal step length, taking only two or three steps to cover the seven-foot distance which would be a normal gait for this distance. It is of interest that the lateral shift in position for these subjects took place with the second step and not the first (Fig. 5). In each case, the subject's first step was straight ahead and the second step was to the left regardless of which foot was placed first. One subject who made the first step with the left foot then made the second step by crossing the right leg over the left leg in order to move to the left.

The resulting behavior caused these subjects to translate to the left in the direction of the stimulus (top two graphs in Fig. 6). When queried about the amount of translation that they produced during the walking trials, subjects responded that they recognized they were moving off center. In fact, these subjects were three feet to the left of center at the end of their trial. The other subject in each group (S3 and S8) walked with short, vertically projected steps, taking approximately seven or eight steps in the seven feet traveled. Looking from the top down (bottom two graphs in Fig. 6), we can see that these subjects exhibited an increased frequency of medial-lateral sway of the head and trunk as though they were rocking over each foot as they stepped forward. These subjects reported that they were only focused on not falling over.

4. Discussion

The purpose of this study was to explore the effect of an immersive dynamic visual field on segmental postural stabilization. Previous studies [11,13,34,36,38] have reported that subjects standing erect in a positive gravitational field perceive a shift of the gravitational vertical when presented with roll motion of the visual surround. This altered perception is believed to be

the result of a visual-vestibular interaction whereby the otolith signal from the actual gravitational vector and the visual system's motion signal combine to produce the perception that one is being tilted opposite to the direction of visual scene rotation. Thus, the typical compensatory response to a rotating visual field is to tilt in the direction of visual scene motion. When subjects observe the world to be moving (e.g. in a counterclockwise direction) they perceive that it is they who are moving in the opposite direction (i.e. clockwise) and compensate for the perceived tilt by tilting in the direction of the visual environment (i.e. counterclockwise). This perception of tilt can be altered to one of spinning about the line of sight by changing the signal strength (e.g. when in microgravity) or directional information (e.g. when in a supine position) of the otoliths [19,27, 28,43].

We have observed that both sinusoidal and constant velocity motion of the visual surround generate a postural reorganization. In both planes subjects tended to respond more with the head and trunk than with the ankle. In roll, although the magnitude of motion was greater in the head and trunk than in the ankle, all segments had similar phases and oscillatory frequencies suggesting that subjects were responding as a simple pendulum limited only by the constraints of the base of support. In pitch, however, the head and trunk were linked in magnitude and phase whereas the ankle tended to produce small compensations and was largely out of phase with the upper body.

Large magnitude tilts of the head and neck may represent an attempt to diminish the visual-vestibular mismatch resulting from the absence of head acceleration combined with the dynamic visual signal. But if the vestibular system influenced the head and neck alone, we would expect the compensatory action to stop at the neck. Instead, we observed equal or greater tilts in the trunk that would suggest a predominant influence of visual-vestibular signals on trunk postural reactions as well [23]. Much smaller compensations and phase reversals occurred at the ankle suggesting that the ankle was compensating for inputs other than the visual flow field. In addition, a low frequency drift underlying the segmental oscillations in response to the higher sinusoidal frequency of the visual flow field implied the existence of two separate controllers for the segmental responses. Thus, in this plane, the upper body appeared to be responding to visual-vestibular signals with changes at the hip while the ankle may have been responding more to segmental proprioceptive inputs and inputs arising from changes in ground reaction forces. Sepa-
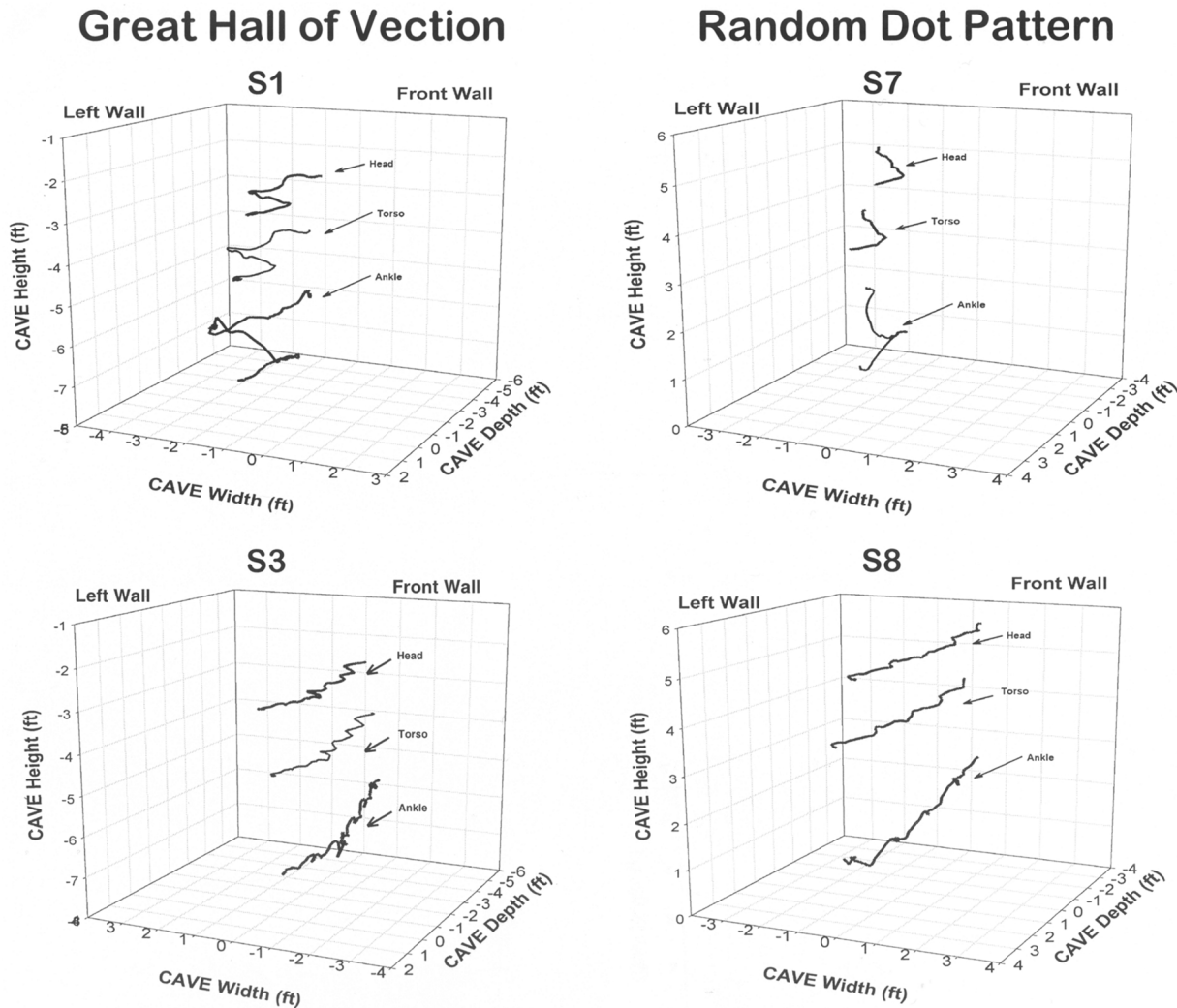
Great Hall of Vection

Random Dot Pattern

Fig. 5. 3-D graphs of four subjects during locomotion showing the relationship of the head, trunk, and ankle motions. The gait patterns produced by the subjects walking from the rear of the CAVE to the front wall are shown. In each case the left leg was the only one instrumented and therefore the movement of the "ankle" represents the motion of this limb. The slight rise in the ankle data when close to the front of the CAVE is due to the magnetic sensor nonlinearity at this extreme distance from the transmitter.

rate controllers for upper body and lower limb postural responses have been suggested in earlier studies [23, 24], and a recent study of patients with labyrinthine and neurological disorders revealed that otolithic and somatosensory signals can convey different and sometimes conflicting messages about verticality [4].

In previous studies with a dynamic visual surround, center-of-pressure was often the only measurement and it was assumed that subjects responded only to the optic flow field. But center-of-pressure measures actually reflect a summation of the body's segmental actions. Our results suggest that relying only on measures from the base of support may conceal the complex control

processes involved in responding to the dynamic visual surround. Although the common goal is to maintain a vertical orientation, postural controllers may set limits of motion at each body segment rather than be governed solely by a perception of the visual vertical.

In the traditional paradigm used to investigate this visual-vestibular interaction on posture, the subject remains stationary and one can see compensatory postural changes in the subject's body orientation. When the subject has been able to transition from a static control strategy to moving within the disorienting environment [26,37], large differences in vertical perception and locomotion organization became apparent. When
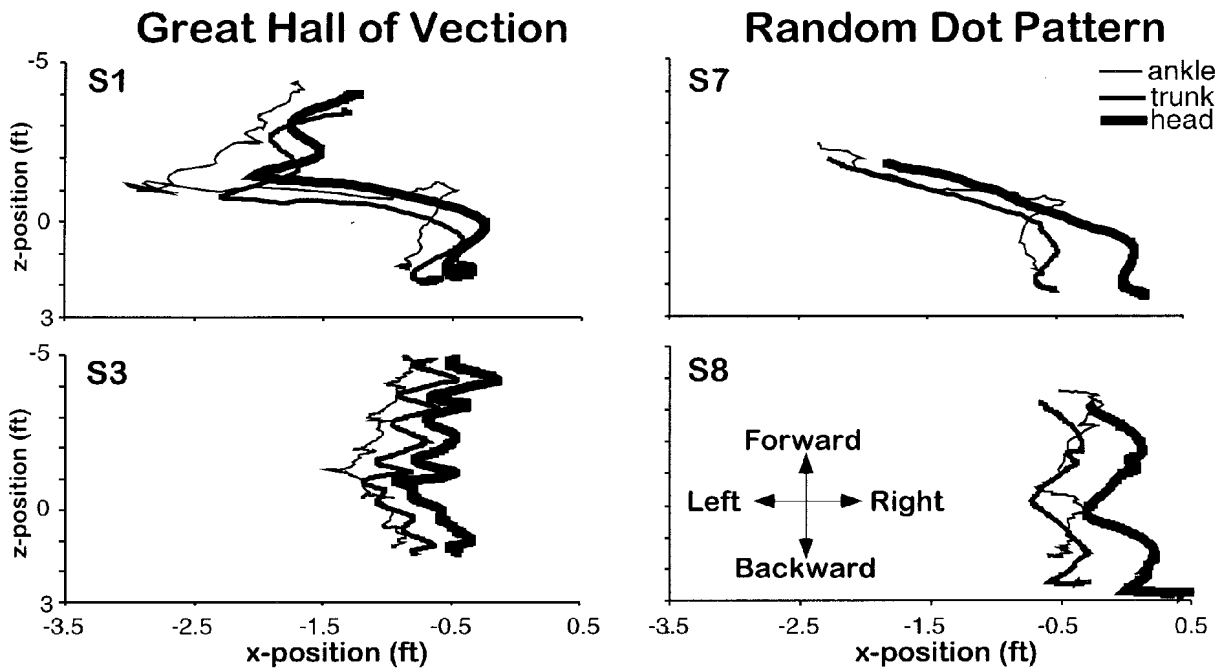
Fig. 6. A top-down view of the same four subjects presented in Fig. 5 demonstrates the two distinct locomotion patterns while moving forward during a constant velocity roll stimulus. The top two graphs illustrate the more natural gait pattern and the bottom two graphs illustrate the gait pattern with a shortened step length. Each gait pattern was exhibited by one subject receiving each visual scene.

actively moving through the environment, strong proprioceptive and tactile feedback information that is signaling a stable base of support from the lower limb during locomotion combines with otolith signals so that the CNS weights the correct perception of vertical more heavily. Subjects are actively receiving feedback from the ground reaction forces indicating that the world is stationary and stable, thus in this case, one might expect the effects of the dynamical visual information to be reduced.

In our dynamic visual environment, some subjects were able to override the effect of the optic flow field. By altering the normal locomotor pattern, subjects were able to counteract the effects of the destabilizing visual stimulus, and correspondingly, the altered perception of vertical. By shortening their steps and increasing flexion at the ankle, the subjects may have exerted a cognitive control over their locomotion that may be focused on increasing their awareness on both the sensory signals and their motor output. This locomotor pattern was reminiscent of the gait observed in elderly fallers [42] or subjects that have been walking with reversing prisms [16]. The more cautious gait may serve to heighten proprioceptive feedback as well as lessen the destabilizing impact of ground reaction forces and the amount of time spent in single stance. Subjects

who exhibited a more natural gait pattern were probably producing an automatic locomotor response with force and time parameters controlled by the spinal segmental levels of the CNS but spatially organized (direction and speed) by the visual-vestibular interaction [37]. Interestingly, the content of the visual scene did not determine response strategy selection (each subject receiving the random dot pattern exhibited a different strategy), thus this paradigm can be used in laboratories with less advanced technologies than those reported here.

Prior to the advent of virtual environment display technology, experiments using complex realistic computer-controlled imagery to study visual information processing/motor control linkages during walking have been difficult. Even now, the type of technology principally employed in this paradigm requires that the subjects wear a head-mounted display [40] or walk on a treadmill [7]. But head mounted displays can add significant weight to the subject's head and may alter the normal stabilizing responses expected during postural instability [22]. Treadmill devices have been found to alter the forces during mid- and late-stance and may produce different control strategies than if the subject walked overground [41]. Observation of our subjects exposed to the visual rotation stimuli in

the CAVE found that the responses were qualitatively similar to those observed and published in the literature. The novel information that we have shown here is how the different body segments respond in maintaining posture during the visual stimuli exposure. In addition, our recordings of subjects walking while undergoing exposure to the disorienting visual stimuli provides new insights into the strategies available to the postural control system during gait. These results demonstrate dramatic task dependent differences in the assessment of visual-vestibular responses from which we infer that the use of static postural responses to moving visual fields may not be appropriate for assessing more dynamic tasks that subjects perform in their everyday living experience. Future assessments of patients should address their progress with both static and dynamic tasks and motor behaviors that more closely match that performed everyday.

Acknowledgements

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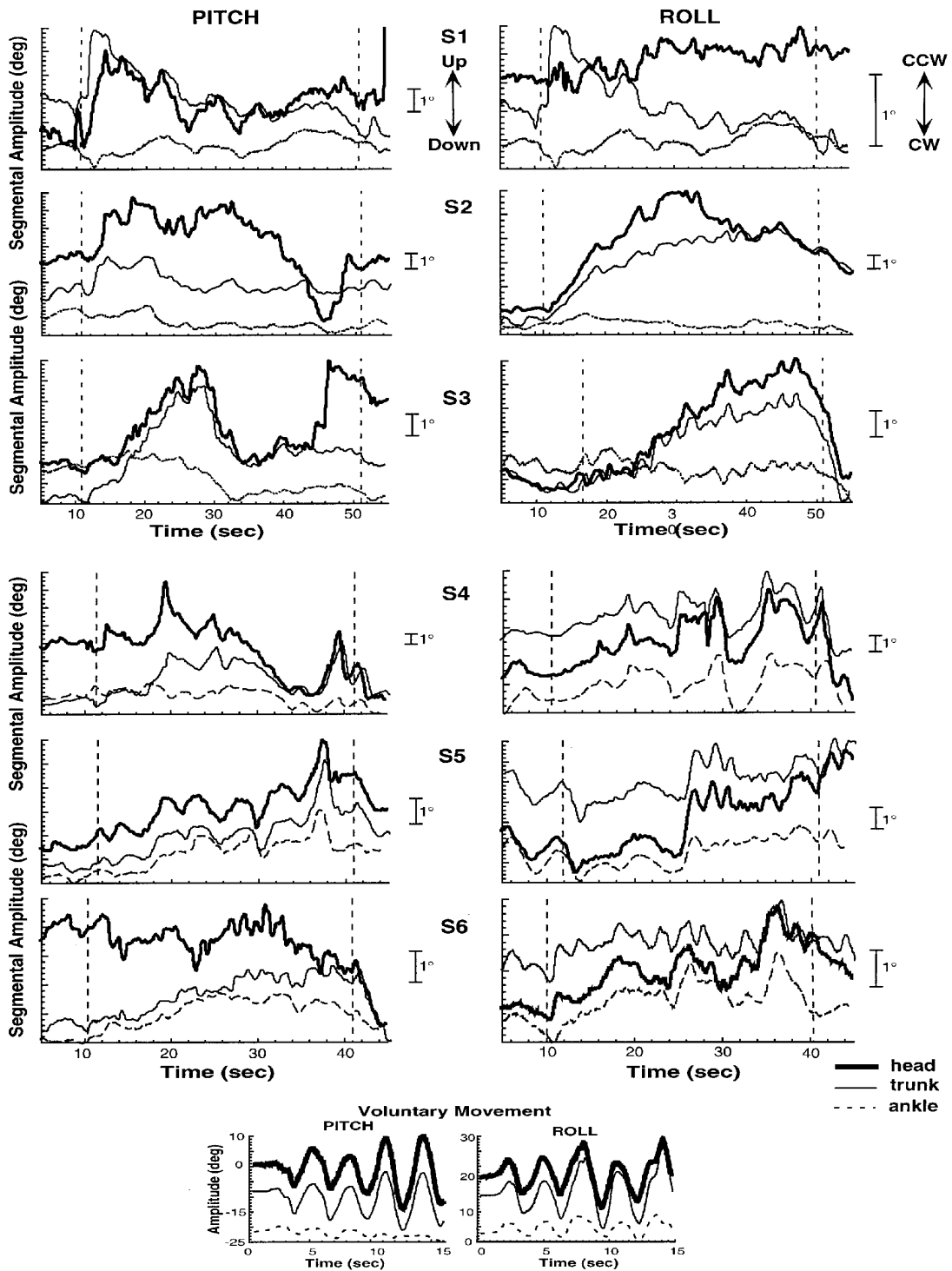
Fig. 2. Relative amplitudes of head, trunk, and ankle orientation in space for each subject are plotted relative to time in pitch and roll and with voluntary pitch or roll motion of one subject during constant velocity motion of the visual environment. Upward movements represent motion in the direction of the environment. The vertical dashed lines indicate the start and termination of the visual scene motion. The baseline of each segment has been shifted so that they may be plotted on the same graph. The small black bar to the right of each graph indicates 1° of segmental motion.
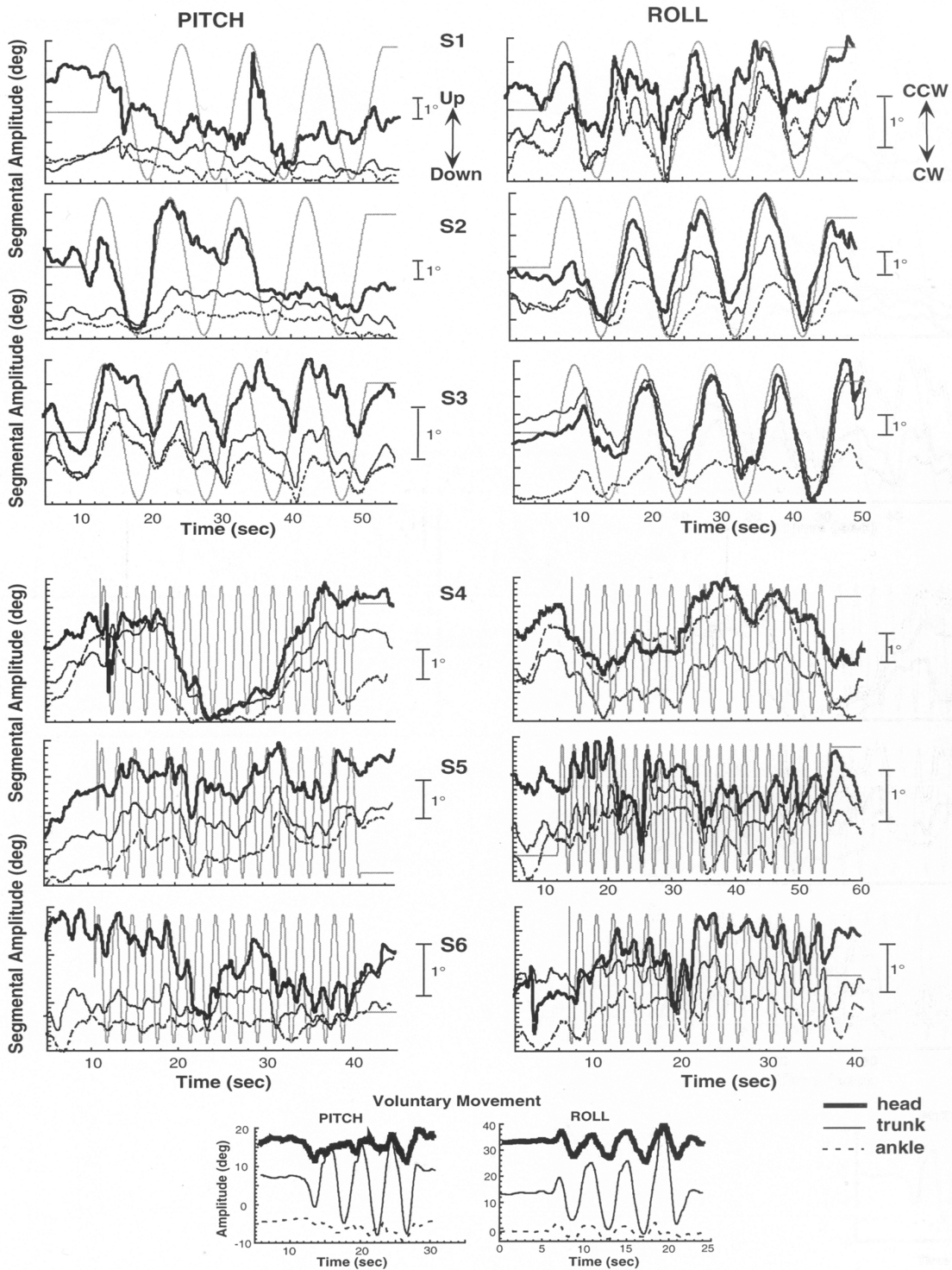
Fig. 3. Relative amplitudes of head, trunk, and ankle orientation in space for each subject are plotted relative to time in pitch and roll, and with voluntary pitch or roll motion of one subject during sinusoidal (±9°) motion of the visual environment. The gray background lines in each graph represent motion of the visual scene. The baseline of each segment has been shifted so that they may be plotted on the same graph. The small black bar to the right of each graph indicates 1° of segmental motion.