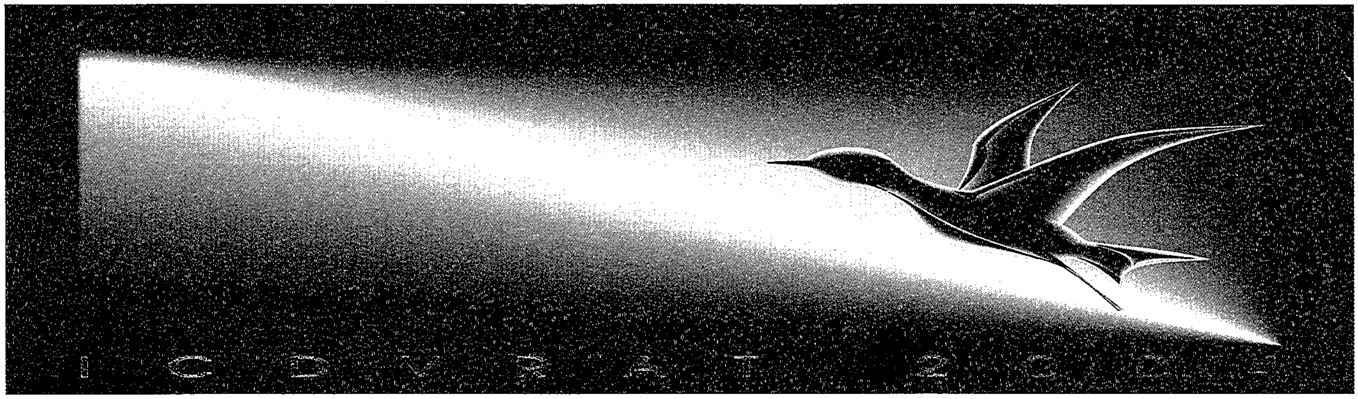

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Employing a virtual environment in postural research and rehabilitation to reveal the impact of visual information

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ABSTRACT

We have united an immersive virtual environment with support surface motion to record biomechanical and physiological responses to combined visual, vestibular, and proprioceptive inputs. We have examined age-related differences during peripheral visual field motion and with a focal image projected on to the moving virtual scene. Our data suggest that the postural response is modulated by all existing sensory signals in a non-additive fashion. An individual's perception of the sensory structure appears to be a significant component of the postural response in these protocols. We will discuss the implications of these results to clinical interventions for balance disorders.

1. INTRODUCTION

In an effort to understand how the central nervous system (CNS) controls motor performance in humans, scientists have endeavoured to reduce the complexity of the system to a single pathway of control and a single measurable output. However, data from this approach are not robust because the CNS is very plastic and will alter its responses and control parameters over time and with specific parameters of a task. Thus, if the task is to walk from one location to the next with the eyes closed, we are not necessarily learning about the role of vision in locomotion, but about how the CNS will adjust its responses when vision is not available. In fact, the visual system has been downplayed as a contributor to postural control because it has a longer reaction time than somatosensory inputs and because when removed, either by closing the eyes or by darkening the room, no significant changes in automatic postural reactions have been observed (Buchanan and Horak, 1999; Keshner et al, 1987; Nashner and Berthoz, 1978). But in natural rather than experimentally controlled environments, visual signals may have a greater influence on postural orientation than expected from laboratory studies. Using a virtual environment (VE), we tested such a situation (Keshner and Kenyon, 2000). Subjects were asked to walk while viewing a virtual representation of a room that rotated at a constant velocity about the visual axis of the subject. The roll motion of the room was uncorrelated with the parameters of their locomotion. We observed that subjects either altered the organization of their locomotion pattern or lost their balance while walking. Thus, when findings from the laboratory are applied to therapeutic interventions, the intervention may not be appropriate for all circumstances and will not fully meet the needs of the patient.

The impact of visual information on movement planning is particularly relevant to studies of postural control because maintaining posture is a multimodal process. During movement we are simultaneously exposed to visual inputs, information from the ground, and somatosensory signals from our own body that may be transient or sustained and that occur at multiple frequencies and in multiple directions with respect to our motion. The performer may choose to suppress responses to irrelevant or conflicting sensory information, thereby simplifying the control process. However, if conflicting inputs are not suppressed, but can instead

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influence and modify the weighting of all other sensory inputs, then response parameters must accommodate even inappropriate sensory signals. The consequence of this, particularly in the elderly (Peterka et al, 1990), is that the performer may not detect, or may not plan a response that will match, the most imperative stimulus parameters and a fall will occur.

We have attempted to resolve this insufficiency by developing the Virtual Environment and Postural Orientation (**VEPO**) laboratory. Although this laboratory continues to evolve (Keshner and Kenyon, 2004), all of our studies combine biomechanical and physiological measurements with an experimentally controlled immersive wide field-of-view visual environment. We present a series of studies here in which we examined the relative weighting of visual and physical stimuli on the postural response in both healthy young and elderly adults. A subsequent study in which we compare the effects of mental calculation to those of searching for a visual target presented against a moving visual field is also presented. We presented subjects with sinusoidal inputs so that predictive mechanisms were also be engaged. Thus we have used the VE to keep all inputs activated and have observed that rather than shifting from one signal to another, subjects incorporated characteristics of all inputs into their segmental responses. Adding the virtual environment to the traditional posture laboratory permits the exploration of more complex motor behaviours, and should expose modifications in motor behavior that take place with impairment or disorders of the system thus supporting the development of appropriate rehabilitation interventions.

2. METHODS

2.1 Development of the Virtual Environment and Postural Orientation Laboratory

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 theatre (Cruz-Neira et al, 1992). We use back-projection instead of front-projection to insure that the subject's body does not cast a shadow on the projected scene. Our laboratory consists of one wall of back projection material measuring 1.2 m x 1.6 m. An Electrohome Marquis 8500 projector (Electrohome Ltd., Kitchener, Ontario CA) throws a full-colour stereo workstation field (1280x1024 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. Field sequential stereo images generated by the PC are separated into right and left eye images using liquid crystal stereo shutter glasses (Crystal Eyes, StereoGraphics Inc., San Rafael CA). These glasses limit the field of view to 90° in the horizontal and 55° in the vertical direction. The correct perspective and stereo projections for the scene are computed using coordinates for the current orientation of the head supplied by an infrared motion analysis system. For this we have used both the Optotrak (NDI, Ontario, Canada) and the Motion Analysis (Motion Analysis Corp., Santa Rosa CA) systems. Consequently, virtual objects retain their true perspective and position in space regardless of the subjects' 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 20-30 ms. The *stereo* update rate of the scene is 60 Hz which is half the rate at which we sample the head data (120 Hz).

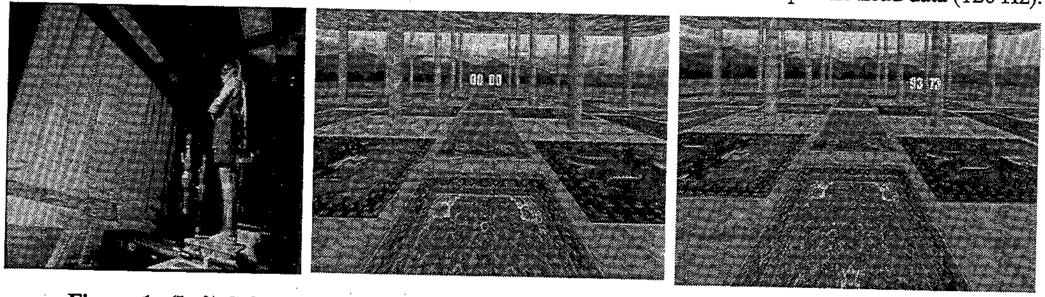

Figure 1. *(Left) Subject wearing stereo shutter glasses stands on the posture platform in front of the back projection screen. The virtual image with a projection of the stationary no-calculation task (centre) and the randomly moving calculation task (right).*

2.1.1 Scene Characteristics. The scene consisted of a room containing round columns with patterned rugs and painted ceiling (Fig. 1). The columns were 6.1 m apart and rose 6.1 m off the floor to the ceiling. The rug patterns were texture mapped on the floor and consisted of 10 different patterns. The interior of the room measured 30.5 m wide by 6.1 m high by 30.5 m deep. The subject was placed in the centre of the room between two rows of columns. Since the sled was 64.8 cm above the laboratory floor the image of the virtual room was adjusted so that its height matched the sled height (i.e., the virtual floor and the top of the sled were coincident). Beyond the virtual room was a landscape consisting of mountains, meadows, sky and clouds.

The floor was the distance from the subject's eyes to the virtual floor and the nearest column was 4.6 m away. The resolution of the image was 7.4 min of arc per pixel when the subject was 40 cm from the screen. The view from the subjects' position was that objects in the room were both in front of and behind the screen. When the scene moved in fore-aft, objects moved in and out of view depending on their position in the scene.

2.1.2 Experimental Protocols. A linear accelerator (sled) that could be translated in the anterior-posterior direction was controlled by D/A outputs from an on-line PC. The sled was placed 40 cm in front of the screen on which the virtual image was projected (Fig. 1). Both healthy young (20-38 years) and older (58-78 years) adults have been tested in this apparatus. Subjects were exposed to a ±15.7 cm/sec sinusoidal translation of the sled in the anterior-posterior direction at 0.25 Hz (±10 cm excursion). A ± 3.8 m/sec sinusoidal fore-aft motion of the computer generated stereo image was presented at 0.1 Hz (±6.1 m excursion) either separately or combined with the sled motion. Each trial lasted a total of 205 sec.

In a second study, the visual scene was translated in fore-aft at 0.1 Hz without a secondary task (scene only) and the sled was anterior-posterior translated (0.25 Hz) while the subject's eyes were closed (sled only). Then, while the sled and visual field were translating in fore-aft, pairs of numbers were projected directly in front of the subject (stationary) or moved randomly within the visual field (moving) (Fig. 1). Subjects were instructed to press a button whenever a stationary or moving pair of zeros appeared (no-calculation) and to press one of two buttons when the difference between the stationary or moving numbers was equal or not equal to 4 (calculation).

2.1.3 Data Analysis. Three-dimensional kinematic data from the head, trunk, and lower limb were collected at 120 Hz by an infrared motion analysis system. Segmental excursions of the head with respect to the trunk, the trunk with respect to the shank, and the shank with respect to the sled were calculated. Center of mass (COM) of the head, trunk, and shank were also calculated. Power of the response at each stimulus frequency was derived using a 40 sec sliding window following a fast Fourier transform analysis. Differences between the populations and across conditions were calculated using Wilcoxon matched-pairs signed rank tests and Wilcoxon rank sums tests.

3. RESULTS

3.1 Responses to Visual Field Motion in Young Adults

We know that when the support surface (i.e., the sled) moves but the world appears stationary, subjects will either ride along with the motion of the sled or compensate for that motion by moving in the opposite direction (Buchanan and Horak, 1999). This indeed was the result we observed in our subjects. Segmental output was reasonably consistent across the whole period of the trial (Fig. 2) and response frequencies peaked at the frequency of stimulus input. When only the visual scene moves but the support surface remains stationary, subjects can choose to ignore the apparent motion of the visual world because both the vestibular and somatosensory systems would signal an absence of physical motion (Dichgans et al, 1972). Some of our subjects could suppress the response to visual motion, but others responded to it, mostly by moving their trunk and head in the direction of the visual scene as would be expected when there is a visual-vestibular conflict (Dichgans et al, 1972).

When both the sled and visual scene were moving, there was a conflict between the visual and the other sensory systems because of the spatial and temporal discordance in the two stimuli. Now it became more difficult to suppress responses to motion of the visual world and subjects responded in one of two ways. Either they locked their segments together and responded as an inverted pendulum, or they incorporated both the frequency of the sled and the frequency of the scene into their segmental responses, often with an associated increase in segmental response amplitude (Fig. 2). The increased power observed in this condition could not be obtained simply by summing the effects of the trials with single frequency inputs. Power of the response increased around 60-80 sec into the trial, similar to a response we may expect if a subject was experiencing vection - the sensation of self-motion through the visual system (Hettinger et al, 1990). With vection, the optical flow pattern creates a compelling illusion of self-motion that is not corroborated by the inertial forces transmitted through the vestibular sense organs.

We have employed a Principal Component Analysis (PCA) to determine the overall weighting of the inputs from the sled and the scene (Fig. 2). For most subjects, the relative weighting of each input fluctuated across a trial, but some subjects exhibited a strong preference for either the sled or the scene. For example, S1 in Fig. 2 had a stronger, more consistent response to the scene motion than to sled motion. S3 demonstrated the opposite effect. Both subjects weighted the two signals relatively equally when presented with the both at the same time. S2, on the other hand, did not respond strongly to either input either when presented singly or in a combined fashion. Contributions of each body segment to the overall response strategy were observed primarily in the trunk and shank.

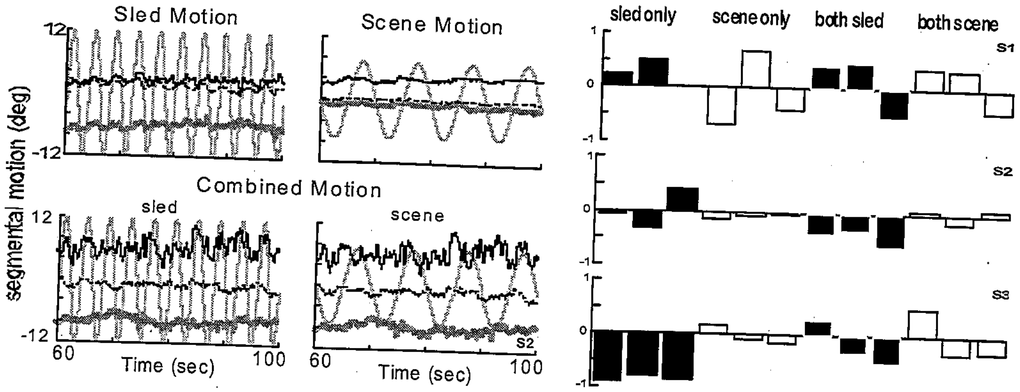

Figure 2. *(Left) Relative excursions of the head re trunk (bold grey line), trunk re shank (black line), and shank re sled (dotted line) in a young adult subject plotted over a 40 sec period of the trial for each condition The same data in the combined condition is overlies sled and scene (thin grey lines) motion. (Right) Overall weighting of the input variables (sled = filled bars; scene = open bars) derived from the PCA for 3 young adults. Each bar of each condition represents a subsequent non-overlapping 40 sec time period. The direction of each bar indicates the relative phase between the response and the input signal.*

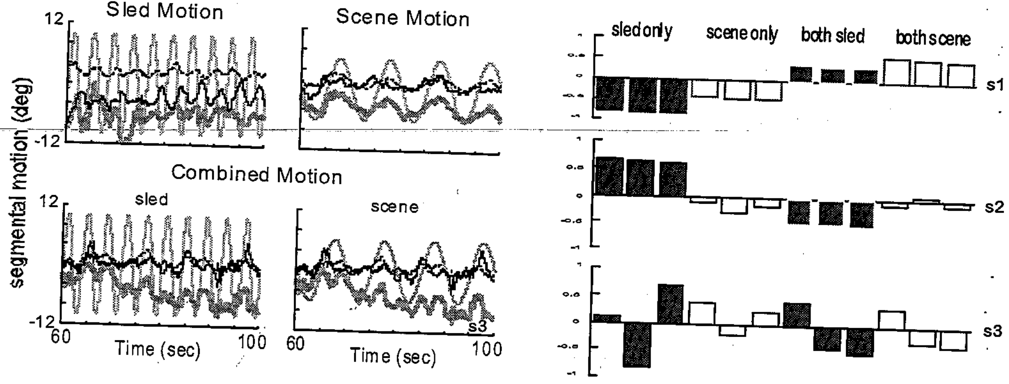

Figure 3. *(Left) Relative excursions of the head re trunk (bold grey line), trunk re shank (black line), and shank re sled (dotted line) in a 67 year old subject plotted over a 40 sec period of the trial for each condition The same data in the combined condition is overlies sled and scene (thin grey lines) motion. (Right) Overall weighting of the input variables (sled = filled bars; scene = open bars) derived from the PCA for 3 elderly adults. Each bar of each condition represents a subsequent non-overlapping 40 sec time period. The direction of each bar indicates the relative phase between the response and the input signal.*

3.2 Responses in Elderly Adults

Maintaining balance with either sled or scene motion was a challenge to the elderly subjects, and some subjects were unable to complete the trials when the two stimuli were combined. When only the sled moved, these subjects tended to exhibit a response of the trunk that was compensatory to the motion of the sled and a response of the shank that matched the direction of the sled (Fig. 3) from which we infer that they were bending at the hip. When only the scene moved, the elderly subjects were more affected by motion of the visual scene than were the younger adults. This was demonstrated by large responses of the head with respect to the trunk in the direction of scene motion (Fig. 3). This sensitivity to visual motion carried over into the combined protocol where the elderly subjects exhibited clear motion of all body segments in the direction of the visual scene motion. Greater equivalency of the two input signals emerged in the PCA results (see S1 and S3 in Fig. 3) in both the trials with a single input and in the trials with combined inputs.

3.3 Tracking a visual target

Differential weighting of sensory inputs suggests that an individual's perception of the stimulus array might influence their response. To further explore how visual attention modifies balance reactions, we asked both young and elderly subjects to perform a visual tracking task while the full field of view was translated fore-aft. When asked to focus on either a stationary or moving target, no differences were observed between the young and older adults. In both groups, button press latencies for identifying the correct number calculation were shorter during the non-computation tasks than during the computation tasks indicating that the task did convey an attentional load in both groups.

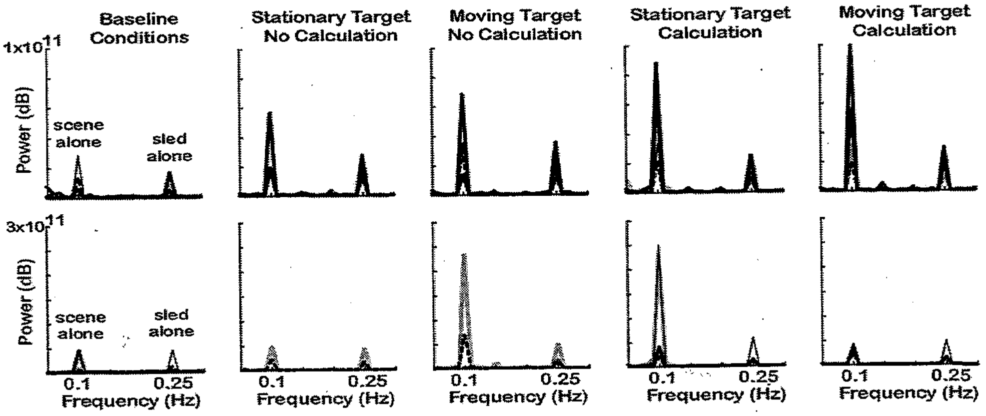

Figure 4. *Power derived from fast Fourier transforms performed on the COM response of the head for five young (top row) and four older (bottom row) adults with each visual task (each line is the response of one subject). Note the greater magnitude of the power scale for the older adults.*

When we examined the COM response at each body segment, we found that all subjects responded predominantly at the input frequencies of the sled (0.25 Hz) and the visual scene (0.1 Hz), but power of the response was much greater in the elderly subjects overall (Fig. 4). For both groups, power of the head increased only at the frequency of the visual scene when combined with the focal task. In the young adults, power at 0.1 Hz increased for the head when the visual target was moving, and increased even more when calculation was required whether the target was stationary or moving. For both groups, power at the head was significantly greater during the stationary calculation task than during the stationary no-calculation task ($p <$ 0.01), although of the four elderly subjects, only two exhibited any real differences. The magnitude of head excursion also increased with a stationary calculation task when compared to the stationary no-calculation task ($p < 0.001$). Older adults exhibited greater head angular displacements than the young adults during the moving target tasks, but similar COM displacements suggest that they were using different kinematic strategies for head stabilization.

4. CONCLUSIONS

The results presented here argue that postural responses to motion of the visual field are strongly potentiated by the presence of both physical motion and an additional visual task. Either support surface or visual field motion alone produced marginal responses in most subjects, but the response to visual stimulation was dramatically enhanced when these inputs were combined, perhaps because the visual inputs were incongruent with those of the physical motion. Also, adding the calculation task to the combination of visual scene and support surface motion reduced the typically stabilizing effect of a stationary visual target (Strupp et al, 2003).

With single inputs, some subjects consistently selected a single segmental strategy. With multiple inputs, most subjects produced behaviours that fluctuated between the two stimuli. A non-additive effect occurred in the energy of the response with combined inputs in that the magnitude of the response kinematics greatly increased. Segmental kinematics in the older adults were more affected by visual scene motion than the young adults, implying that instability observed in elderly adults may be due to an inability to minimize their responses to inappropriate or irrelevant inputs. The dependence of the elderly subjects on stabilizing their posture by flexing at the hip also suggests that their more rigid and unstable trunk (Allum et al, 2002; Wu, 1998; Keshner, 2004) would be less capable of minimizing disturbances to the position of the head in space.

Segmental responses to visual field motion were also strongly potentiated when the visual field motion was combined with physical motion suggesting that there are greater consequences of engaging in a cognitive task when there are multimodal demands on posture (Jamet et al, 2004). During functional activities, postural control is a continuous process and an integral component of any activity we engage in. Our current results demonstrate that individual perception of the sensory structure was a significant component of the postural response. Previous results from our laboratory (Keshner and Kenyon, 2000; Keshner et al, 2004) have revealed time dependent properties in the postural control system. We suggest that a constant recalculation of the stimulus flow is required to appropriately tune the response to the environmental context. In elderly adults, the inability to actively suppress continuous regulation of the visual environment could result in a miscalculation between the required postural responses and relevant environmental demands.

These results have significant implications for the continued measurement of postural activity and the important role of the virtual environment 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. Our system allows us to explore more complex behaviours that are necessary for rehabilitation (Keshner and Kenyon, 2004). We believe that application of VE technology to dynamic postural research is both a necessary and valid approach for exploring underlying control mechanisms and questions that are relevant to rehabilitation.

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5. REFERENCES

J H Allum, M G Carpenter, F Honegger, A L Adkin and B R Bloem (2002), Age-dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man, *J. Physiol.*, **542**, pp. 643-663.

J Buchanan and F Horak (1999), Emergence of postural patterns as a function of vision and translation frequency, *J. Neurophysiol.*, **81**, pp. 2325-2339.

C Cruz-Neira, D J Sandin, T A DeFanti, R V Kenyon and J C Hart (1992), The CAVE automatic virtual environment, *Communications*, **38**, pp. 64-72.

J Dichgans, R Held, L R Young and T Brandt (1972), Moving visual scenes influence the apparent direction of gravity, *Science*, **178**, pp. 1217-1219.

L J Hettinger, K S Berbaum, R S Kennedy, W P Dunlap and M D Nolan (1990), Vection and simulator sickness, *Military Psychology*, **2**, pp. 171-181.

M Jamet, D Deviterne, G C Gauchard , G Vancon and P P Perrin (2004), Higher visual dependency increases balance control perturbation during cognitive task fulfillment in elderly people, *Neurosci. Lett.*, **359**, pp. 61-64.

E A Keshner (2004), Head-trunk coordination in elderly subjects during linear anterior-posterior translations, *Exp Brain Res.*, DOI: http://dx.doi.org/10.1007/s00221-004-1893-2.

E A Keshner, J H J Allum and C R Pfaltz (1987), Postural coactivation and adaptation in the sway stabilizing responses of normals and patients with bilateral peripheral vestibular deficit, *Exp. Brain Res.*, **69**, pp. 77-92.

E A Keshner and R V Kenyon (2000), The influence of an immersive virtual environment on the segmental
ation of postural stabilizing responses, *J. Vestib. Res.*, **10**, pp. 207-219.

er and R V Kenyon (2004), Using immersive technology for postural research and rehabilitation,
e Technol., (in press).

er, R V Kenyon and J Langston (2004), Postural responses exhibit intra-modal dependencies with
ant visual and support surface motion, *J. Vestib. Res.*, **14**, (in press).

Nashner and A Berthoz (1978), Visual contribution to rapid motor responses during postural control, *Brain Res.*, **150**, pp. 403-407.

R J Peterka, F O Black and M B Schoenhoff (1990), Age-related changes in human vestibulo-ocular reflexes: Sinusoidal rotation and caloric tests, *J. Vestib. Res.*, **1**, pp. 49-59.

M Strupp, S Glasauer, K Jahn, E Schneider, S Krafczyk and T Brandt (2003), Eye movements and balance. *Ann. N. Y. Acad. Sci.*, **1004**, pp. 352-358.

G Wu (1998), Age-related differences in body segmental movement during perturbed stance in humans, *Clin. Biomech.*, **13**, 300-307.