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Field of view and base of support width influence postural responses to visual stimuli during quiet stance

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Abstract

We explored the destabilizing effect of visual field motion as the base of support (BOS) and the field of view (FOV) were narrowed. Visual field motion was achieved using an immersive virtual environment (scene) that moved realistically with head motion (natural motion) and translated sinusoidally at 0.1 Hz in the fore-aft direction (augmented motion). Natural motion was presented in stereo while augmented motion was presented in both stereo and non-stereo. Subjects viewed scene motion under wide (90° and 55° in the horizontal and vertical directions) and narrow (25° in both directions) FOV conditions while standing flatfooted (100% BOS) and on two blocks (45% and 35% BOS). Head and whole body center of mass (COM) and ankle angle root mean square (RMS) were determined as were head, whole body, and shank COM FFTs. During natural motion, the primary effect emerged in the head RMS which was significantly smaller with a 35% BOS and the wide FOV compared to the narrow FOV. However, the primary effect of augmented motion emerged in the power analysis of head and whole body COM which significantly increased with the wide FOV for a 35% BOS compared to 100% BOS. Statistical analysis indicated an effect of BOS on depth perception for head and whole body RMS; however, post hoc comparisons revealed no significant differences between stereo and non-stereo augmented motion. We conclude that reducing the BOS increased reliance on peripheral visual information to stabilize the head in space even when the augmented visual motion promoted postural instability.

Keywords: Posture; Virtual reality; Vision; Base of support; Sensory re-weighting

1. Introduction

The growing popularity of virtual reality in laboratory and clinical settings has promoted the study postural control during precisely controlled movement of the visual environment. In subjects wearing head mounted displays providing full visual field motion, Tossavainen et al. [1] report increased levels of postural sway. Increases in postural sway are also observed in subjects experiencing movement of the virtual environment while wearing stereo shutter glasses that limit the horizontal and vertical fields of view (100° × 55°) [2,3] demonstrating that movement of the visual environment can influence postural control even under moderately reduced field of view conditions. Individuals experiencing simultaneous visual field motion and discordant somatosensory input demonstrated increased attendance to visual information for postural control suggesting an increased weighting of visual information when sensory feedback modalities were in conflict [4]. To better understand which properties of imposed visual information (i.e. stereovision and field of view) influence postural control when stability is compromised, we have investigated postural responses to moving scenes created within a virtual environment when subjects are standing on short beams to reduce the size of their base of support.

Previously, it has been shown that reducing the stability of the support surface increases the reliance on visual

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information for the control of posture [5–7]. In a recent study, Mergner et al. [8] reduced the stability of the support surface by applying small lateral tilts to the support surface, and subjects experienced these tilts while viewing anterior–posterior sinusoidal motion of a virtual environment. Under this unstable support surface condition, Mergner et al. [8] also found an increase in the use of visual information for the control of posture and suggested that instability in the support surface heightened the subject's use of the visual environment as a reference for postural orientation.

Both the parameters of stereovision and field of view have been shown previously to have significant effects on the postural response. Kawakita et al. [9] report that when subjects experience sinusoidal translation through a virtual environment consisting of a random-dot pattern, peripheral information dominates the visual contribution to postural control. However, it has also been demonstrated that both central and peripheral visual field motion result in postural compensations [10]. These data demonstrate that the influence of visual information on postural control may be due to both the pattern of optic flow information and the portion of the field of view in which it is observed [11]. Under conditions of postural instability with unreliable proprioceptive information and absent peripheral vision, central field of view information may become more heavily weighted for postural control. In this study, we hypothesize that standing on a reduced base of support and viewing visual motion with a narrow field of view will result in postural destabilization equivalent to that occurring while viewing visual motion with a wide field of view.

Another important component of natural visual stimulation is the presence of depth perception. Some studies examining the effects of depth perception on postural control have shown few differences between the presence of stereo and non-stereo vision [12,13]. But there is evidence that stereo information enhances a feeling of self-motion when viewing a moving visual display [14], and, consequently, adjustments have to be made in order to maintain postural control. Further, Kelly et al. [15], indicated that, when standing on one foot, cues to depth could alter the perception of subjects' self-motion and, consequently, influence postural control. In this study we test the hypothesis that decreasing postural stability by reducing the base of support will produce differences between stereo and non-stereo visual information on postural control.

2. Methods

2.1. Subjects

Ten healthy adult volunteers (four male, six female) naïve to virtual environments participated in the study. Subjects were between the ages of 20 and 39 years and had no known musculoskeletal or neurological disorders which may have impacted their performance. All subjects were informed of the procedures and provided written consent in accordance with the Institutional Review Board of Feinberg School of Medicine, Northwestern University.

2.2. Apparatus and procedures

The virtual environment and the hardware and software responsible for its generation have been previously reported elsewhere [2]. In brief, subjects viewed a virtual environment projected via a stereo-capable projector onto a 1.2 m × 1.6 m back-projection screen. The environment 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 painted ceiling (Fig. 1A). Beyond the virtual room was a landscape consisting of mountains, meadows, sky and clouds. For all trials, field sequential stereo images of the environment were separated into right and left eye images using liquid crystal stereo shutter glasses worn by the subject (Crystal Eyes, StereoGraphics, Inc.). For the trials with stereo-imagery, 7 cm spacing between the centers of projection was used to produce images for each eye [approximately equal to the average interpupillary distance (IPD)]. In the trials without stereo imagery, the two projections were generated from centers with identical

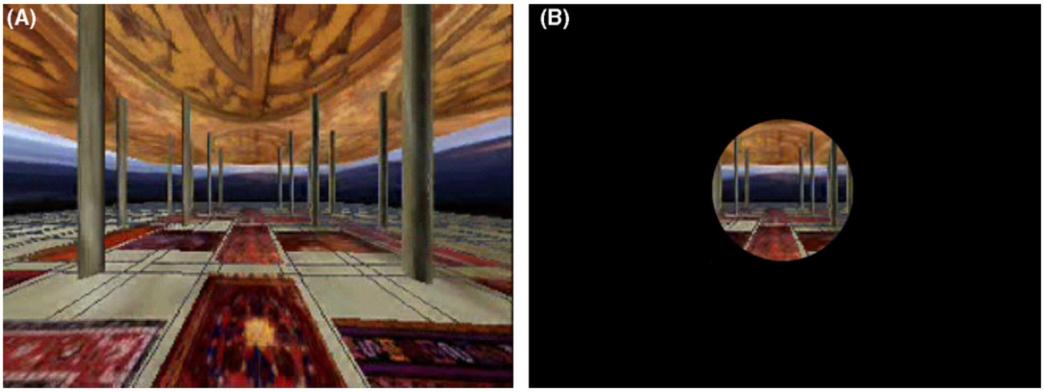

Fig. 1. Wide (A) and narrow (B) views of the virtual environment. For the wide condition, subjects' FOV was 100° in the horizontal direction and 55° in the vertical. For the narrow condition, FOV was 25° in both directions.

viewpoints (i.e. the IPD equaled 0 and the center was located between the two eyes). This ensured that the luminance of the images and field of view (FOV) conditions were the same in stereo and non-stereo conditions since the subjects used the shutter glasses in each condition. The shutter glasses limited the subject's horizontal FOV to 100° of binocular vision and 55° for the vertical FOV. The correct perspective and stereo projections for the scene were computed using values for the current orientation of the head (6 df) supplied at 120 Hz by reflective markers (Motion Analysis) attached to the stereo shutter glasses (head). Consequently, virtual objects retained their true perspective and position in space regardless of the subjects' movement.

Subjects stood comfortably with the feet in parallel and shoulder-width apart and with their upper arms at their sides and bent approximately 90° at the elbows. Subjects were asked to maintain an erect posture while standing barefoot in the middle of the virtual environment. During quiet stance, optic flow was generated either in response to the movements of the head only (natural motion) or in response to movements of the head plus a visual forcing function motion (augmented motion). The visual forcing function drove the scene sinusoidally in the fore-aft at 0.1 Hz an additional ±2.44 m at ±2.96 m/s, a velocity shown to be sufficient to induce postural responses [2,16]. Subjects experienced these visual conditions while standing on each of three sizes of the BOS: 100%, 45%, and 35% of foot length in the AP direction (from heel to toe). Two FOV conditions were also presented, a wide FOV (100° horizontal and 55° vertical) and a narrow FOV (25° in both directions) (Fig. 1). Reduction of the FOV was accomplished by attaching apertures with a diameter of 1.08 cm (viewing holes cut into black cards) over the lenses of the stereo goggles. In all, subjects completed 18 trials of standing while experiencing combinations of the visual motion, BOS, and FOV conditions. Trials lasted a total of 140 s with the translating visual stimulus starting after 10 s of quiet stance and ending 10 s prior to completion of the trial. Trial conditions were presented in random order.

2.3. Data collection and analysis

Reflective markers were attached bilaterally on the second metatarsophalangeal joint, lateral malleolus, lateral epicondyle of the tibia, greater trochanter of the femur, acromion process, lateral epicondyle of the humerus, styloid process of the ulna, second metacarpophalangeal joint, and zygomatic arch. Markers were also placed on C7 and on L4/L5 joint of the spine. A six camera Motion Analysis (Motion Analysis, Inc.) system was used to capture joint motion at 120 Hz. Commercial software (Kintrak, Inc.) was used to generate a 13-segment biomechanical model of the body for determining COM motion during the standing trials. COM for the head, trunk, and shanks over the course of the trial were derived from previously reported equations [17]. Right and left ankle joint kinematics were determined as the angle between the foot and shank. All data were low-pass filtered using a fourth order Butterworth digital filter at 4 Hz.

For the majority of subjects (6 out of 10), a 65% reduction in the BOS combined with augmented visual motion resulted in their having to take a step in order to keep from falling. To eliminate the effects of stepping on the analysis of postural stability, within each 140 s trial, a 60 s window of continuous stance occurring between the initial and final 10 s was selected and used for analysis. For 5 of the 10 subjects, it was possible to analyze an analogous 60 s period of stance (from 45 to 105 s) for all trials. For the other subjects, a 60 s period was selected either prior to or following a step, and an attempt was made to use the same time window for all trials for each subject. (For example, if a subject stepped 85 s following the beginning of the trial, the window for analysis could be from 20 to 80 s and, if possible, the window for every trial from that subject would be from 20 to 80 s.) However, it was not possible to use the same period of time across all trials for four of the subjects, and, consequently, it is possible that some of the variability in the results reflects data sampled at different periods of the trials.

For all kinematic data, the mean value of 20 s window of data was subtracted for every 5 s of data. Root mean square (RMS) values were determined for the anterior–posterior linear displacement of the head and whole body COM and the angular displacement of the ankle joints. Head and whole body RMS data were then normalized by each subject's foot length. Power of the head, whole body, and shank COM over the course of the trials was determined using a fast Fourier transform (FFT) calculated in Matlab 7.0 (Mathworks, Inc., 2004) using the "FFT" and "conj" routines. FFTs for the head, whole body, and shank COMs were performed only on trials with augmented visual motion (both stereo and non-stereo) in order to characterize the COM responses to a driven visual scene; natural scene motion which had no forcing function was not included. Consequently, a $2 \times 2 \times 3$ (stimulus by FOV by BOS) ANOVA with repeated measures was performed on the FFT data. A $2 \times 3 \times 3$ (stimulus by FOV by BOS) ANOVA with repeated measures included RMS data from both the augmented visual motion and the natural vision conditions. For both analyses a significance level of $p < 0.05$ was used. When appropriate, Bonferroni post hoc comparisons were made to determine differences among the factors. All statistical analyses were executed using SAS statistical package (SAS Institute, 1999).

3. Results

3.1. Responses to reduction of the BOS are affected by FOV

A number of significant interactions emerged in these results. We hypothesized that reducing the BOS would increase the effect of augmented visual motion on postural sway as measured by RMS of the COM and RMS of the ankle angles regardless of whether the scene was presented with the narrow or wide FOV. Results pertaining to this hypothesis are as follows. Augmented visual motion did not significantly affect postural sway when viewed through the narrow FOV. A significant three-way (stimulus by BOS by FOV) interaction, as seen in Fig. 2, showed that there were no differences between the natural and the augmented motion conditions for any of the BOS conditions with the narrow FOV; however, viewing the augmented motion with the wide FOV while standing on the 35% BOS, resulted in greater RMS magnitudes of head COM [$F(4,36) = 3.87$, $p < 0.011$] and left and right ankle angle [$F(4,36) = 3.92$, $p < 0.01$; $F(4,36) = 2.96$, $p < 0.033$, respectively]. These significant three-way interactions revealed that when standing on the 35% BOS head COM RMS was significantly lower when viewing natural visual motion with a wide FOV compared to augmented visual stimuli [$t(1,36) = 9.89$, $p < 0.001$ for the stereo and $t(1,36) = 7.18$, $p < 0.001$ for the non-stereo conditions]. Furthermore, when standing on the 35% BOS, viewing natural visual motion with a wide FOV also lead to reduced head COM RMS compared to when viewing natural motion with a narrow FOV[$t(1,36) = 4.47$, $p < 0.011$]. Standing on the 35% BOS with a wide FOV also revealed differences in ankle angle RMS which was reduced in the natural visual motion condition compared to *only the stereo* augmented

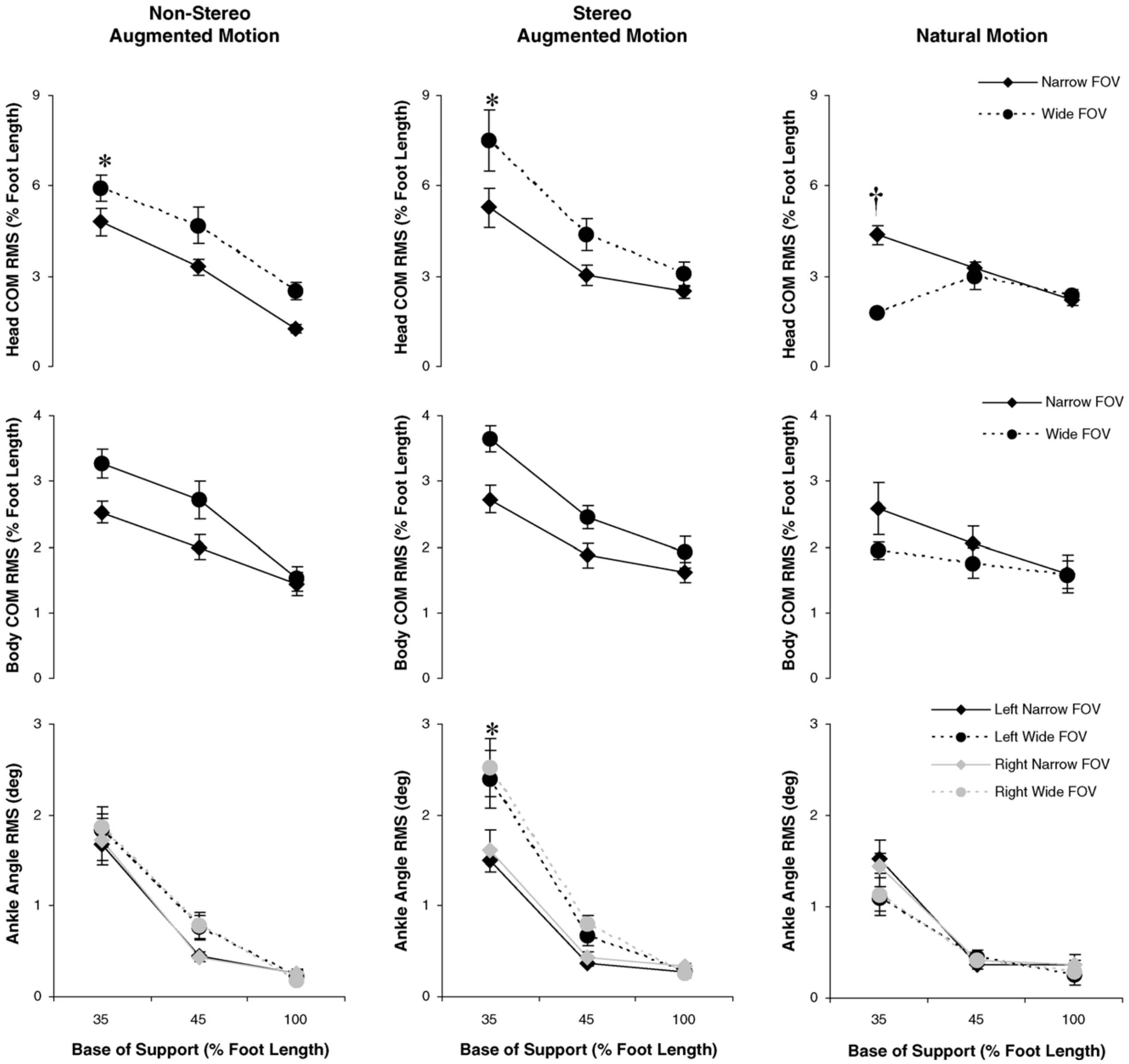

Fig. 2. Head and whole body COM and ankle angle RMS means and standard errors for each of the three visual motion conditions: augmented motion presented in non-stereo and stereo and natural motion. Subjects viewed the virtual scene in each of the three BOS conditions with a wide (circle and dashed) or narrow (diamond and solid) FOV. Left (black) and right (gray) ankle angle RMS are depicted separately. †Significant difference between the wide FOV and the narrow FOV ($p < 0.05$). *Significant difference between natural and augmented RMS with a wide FOV ($p < 0.05$).

visual condition [$t(1,18) = 5.15$, $p = 0.01$ for the left and $t(1,18) = 5.32$, $p < 0.001$ for the right]. In contrast, head COM and ankle angle RMS when standing on the 45% and 100% BOS did not differ among visual motion conditions for either the narrow or wide FOV.

Regardless of the size of the BOS, the wide FOV combined with augmented movement of the visual scene led to increased whole body COM RMS, a significant stimulus by FOV interaction [$F(2,18) = 10.74$, $p < 0.001$] (Fig. 2). Compared to natural visual motion, whole body COM RMS was increased in the stereo and non-stereo conditions [$t(1,18) = 5.91$, $p < 0.001$ and $t(1,18) = 4.81$, $p < 0.003$, respectively] when viewing with a wide FOV. When viewing with a narrow FOV, whole body COM RMS did not differ among the visual conditions.

A two-way BOS by FOV interaction also emerged for power of the whole body COM in response to visual scene movement as a wide FOV led to increased response to the visual stimuli when standing on a reduced BOS surface [$F(2,18) = 3.64$, $p < 0.048$] (Fig. 3). The whole body COM power at 0.1 Hz was 5.1 times greater with the wide FOV compared to the narrow FOV only when standing on the 35% BOS [$t(1,18) = 4.64$, $p = 0.003$].

3.2. Responses to reduction of the BOS are affected by the presence of stereo

Our second hypothesis was that the effect of a reduced BOS will be influenced by the presence of stereovision. The significant stimulus by BOS by FOV three-way interaction

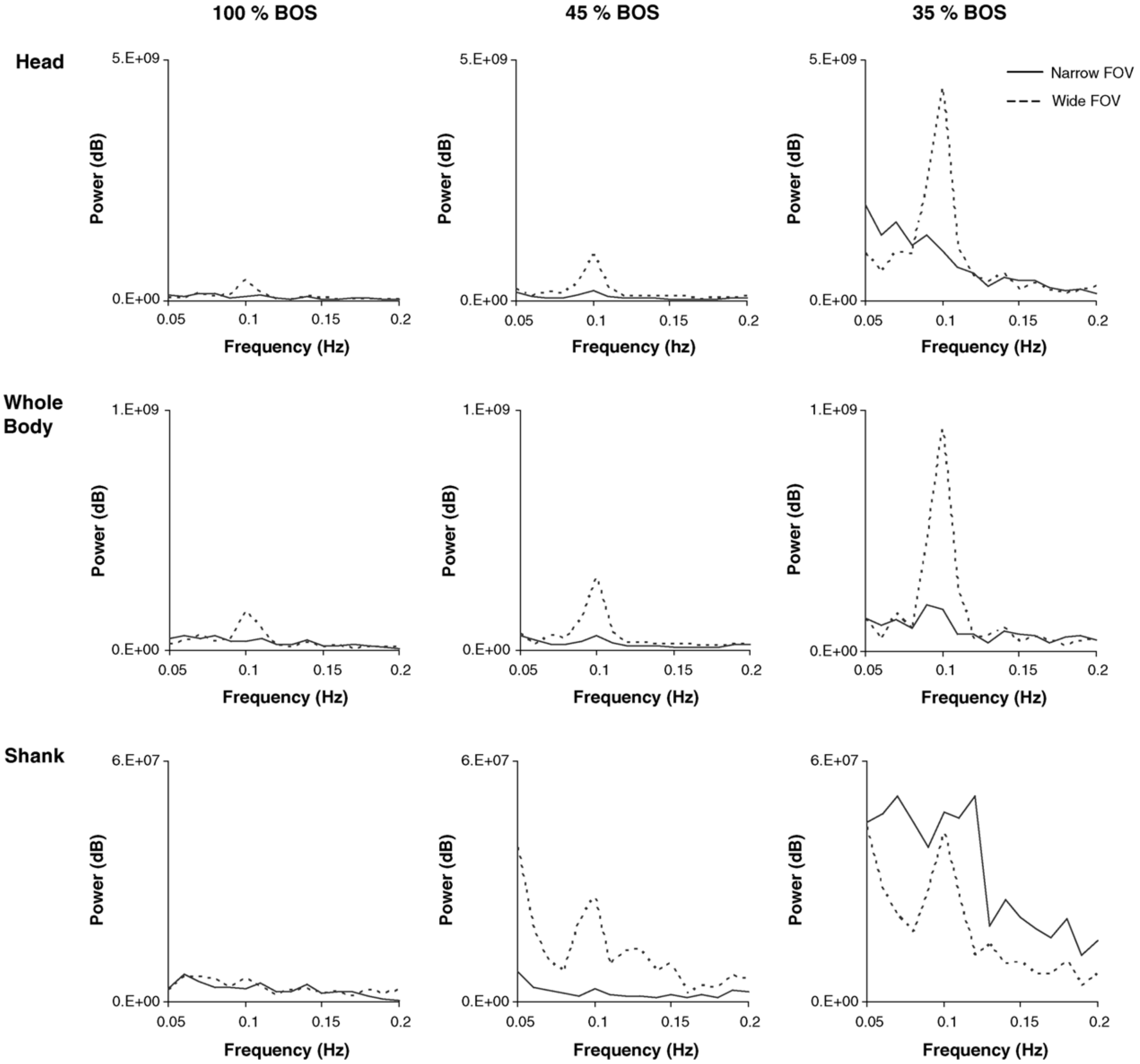

Fig. 3. Average head, whole body, and shank COM power for each of the three BOS conditions when the augmented visual motion was imposed on a stereo virtual scene. Subjects viewed the motion with the narrow (black line) and wide (dashed) FOV. For the whole body COM, significant differences between the wide and narrow FOV conditions were achieved only for the 35% BOS. Shank COM power, in contrast was greater for the wide FOV compared to the narrow regardless of the size of the BOS.

[$F(4{,}36) = 3.87$, $p < 0.011$] that emerged for the head COM RMS revealed that the effect of stereovision was partially determined by the FOV and the BOS (Fig. 2). With the wide FOV and stereovision, RMS of head COM was significantly increased when standing on the 35% BOS compared to the 45% BOS [$t(1{,}36) = 5.42$, $p < 0.001$].

All other COM measures were affected by the interaction between BOS and stereovision regardless of the size of the FOV, however. Displacement of the whole body COM increased as a result of standing on a reduced BOS and viewing a stereo augmented visual scene, a significant stimulus by BOS interaction [$F(4{,}36) = 3.72$, $p < 0.013$] (Fig. 2). With stereo augmented motion, whole body COM RMS was significantly greater for the 35% BOS than the 45% BOS [$t(1{,}36) = 5.39$, $p < 0.001$]. For the head COM, power at 0.1 Hz (Fig. 3) was 4.6 times greater on the 35% BOS compared to the 45% BOS [$t(1{,}18) = 3.67$, $p < 0.027$] and 10.8 times greater than the response to the 100% BOS [$t(1{,}18) = 4.25$, $p < 0.008$] when subjects were provided with augmented visual motion in stereo, a significant stimulus by BOS interaction [$F(2{,}18) = 3.84$, $p < 0.041$]. Thus, the head became more frequency dependent with stereovision but only increased its motion with the wide FOV. Power of the whole body COM was unaffected by the presence or absence of stereovision. The presence or absence of stereovision had no effect on ankle motion aside from the previously mentioned reduction in ankle angle RMS observed between the natural visual motion and the stereo augmented motion when standing on the 35% BOS with a wide FOV.

4. Discussion

In this study we explored how augmenting motion of the visual surround with a wide and narrow FOV and the presence or absence of stereovision influenced postural sway induced by narrowing the BOS. Our primary finding was that subjects relied more on visual feedback to stabilize posture when standing on the most reduced BOS with the wide FOV both when the scene responded naturally to the subjects' movements and when visual motion was augmented. Our observation of increased power at the frequency of the visual input supports the hypothesis of a greater reliance on visual inputs when mechanically unstable. This increased reliance on vision could have been advantageous to the control of posture when the reduced support surface was inducing instability and the visual surround moved appropriately in response to head movement. Using a moving room paradigm where the support surface and visual surround could be moved separately, Lishman and Lee reported the strong influence of vision on the experience of self-motion during stationary stance even when visual information conflicted with other sensory information [5]. Similarly, we found that when visual motion was much greater than the subject's own motion, such as in the augmented visual motion conditions, subjects were unable to fully suppress the effects of visual field motion despite its negative impact on their ability to maintain postural stability as indicated by the increased levels of head and whole body COM RMS.

These findings are consistent with other research suggesting an increase in reliance on vision for postural control with instability [5–9] and may signify a shift of sensory weighting from somatosensory to visual feedback [18]. In some respects this potential shift in sensory weighting resembles that of subjects experiencing the Sensory Organization Test of the Neurocom Equitest System [19] in conditions where proprioceptive information is specifically altered through manipulation of the BOS. For this study we believe that sensory reweighing may be a response to the perception of support surface instability [8] and may also be a functional compensation for a reduced BOS which limits ankle torque production by reducing the moment arm available to the ankle stabilizing muscles and might also alter proprioceptive information. Trimble and Koceja have shown that reducing the BOS decreases the gain of the afferent discharge of the ankle stabilizers to suppress short latency reflex responses [20] used to compensate for the altered mechanics of a smaller BOS [21]. Such reduction would prevent an inappropriately large reflex from further promoting instability, but information from the proprioceptors could still provide accurate information about the characteristics of the support surface. Perception of the support surface reduction or instability may promote more heavily weighted vision to ensure postural stability.

The presence of the narrow visual FOV was not as compelling as the wide FOV even when postural instability was magnified by a reduced BOS. The small effect with the narrow FOV may have been due to the design of our visual environment. It is assumed that narrowing of the FOV in this study removed lamellar visual information in the peripheral visual field so that subjects were exposed primarily to radial expansion of the central visual scene. In our study, the narrow FOV consisted primarily of large objects with no definable borders (e.g. the floor, the ceiling, and the mountainous view in the distance [Fig. 1]). Pillars from the temple were still viewable, but they also were distant from the subject. While it has been shown that radial expansion in the central visual field can sufficiently suggest movement of the body [22], the expansion of such distant objects may have even reduced the effectiveness of central visual field motion [23]. Consequently the radial expansion and the lamellar flow in the central visual field may have been insufficient to induce postural responses even under conditions of a reduced BOS.

Finally, reports of the effects of non-stereo and stereo visual information on postural control are varied. Differences in body sway when viewing a static display with one or both eyes open have been minimal suggesting that non-stereo information alone is sufficient for postural control [12,13]. Research by Palmisano [14] and Kawakita et al. [9], on the other hand, suggests that constant forward translation of a computer generated environment more effectively induces whole body movement when presented in stereo. Our results to stereovision were conflicting. There seemed to be an effect of a stereo field when we increased mechanical instability with a reduced BOS, but postural sway was not significantly more influenced by the stereo presentation compared to the non-stereo. The contribution of stereovision to depth perception may have been small compared to other non-stereo cues to depth, such as shading, perspective, looming, and motion parallax [24]. Lord and Menz, in contrast, reported differences between non-stereo and stereovision on postural control in the elderly when standing on compliant foam surfaces [25]. However, the effects of stereovision observed in that study could be partially attributed to the inclusion of elderly subjects who are more dependent on visual information for postural control than young subjects during sway referencing [2]. Because it is possible that the effect of stereovision may be related to dependence on the visual field for postural control and that this dependence may be variable even within a young, healthy population [26], our inability to observe a consistent contribution of stereovision may be a reflection of heterogeneity in our group of subjects.

With the emergence of virtual reality as a viable tool for scientific investigation [1,27] and rehabilitation [28,29], questions about which properties of virtual reality influence postural control have yet to be resolved [30]. This study suggests that presentation of an augmented visual stimulus in the wide field of view strongly impacts postural control when stability is compromised. Further studies need to be performed to understand the extent to which the effect of these properties can be generalized to the postural control when the augmented motion is changed (i.e. a stimulus is provided in a different direction or at a different frequency) or objects embedded in the scene change the environmental context.

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