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RESEARCH NOTE

Visual motion combined with base of support width reveals variable field dependency in healthy young adults

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Abstract We previously reported responses to induced postural instability in young healthy individuals viewing visual motion with a narrow (25° in both directions) and wide (90° and 55° in the horizontal and vertical directions) field of view (FOV) as they stood on different sized blocks. Visual motion was achieved using an immersive virtual environment that moved realistically with head motion (natural motion) and translated sinusoidally at 0.1 Hz in the fore-aft direction (augmented motion). We observed that a subset of the subjects (steppers) could not maintain continuous stance on the smallest block when the virtual environment was in motion. We completed a posteriori analyses on the postural responses of the steppers and non-steppers that may inform us about the mechanisms underlying these differences in stability. We found that when viewing augmented motion with a wide FOV, there was a greater effect on the head and whole body center of mass and ankle angle root mean square (RMS) values of the steppers than of the non-steppers. FFT analyses revealed greater power at the frequency of the visual stimulus in the steppers compared to the non-steppers. Whole body COM time lags relative to the augmented visual scene revealed that the time-delay between the scene and the COM was significantly increased in the steppers. The increased responsiveness to visual information suggests a greater visual field-dependency of the steppers and suggests that the thresholds for shifting from a reliance on visual information to somatosensory information can differ even within a healthy population.

Keywords Posture · Virtual reality · Vision · Field dependency · Sensory re-weighting

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Introduction

During upright stance, visual motion increases postural sway (Lishman and Lee 1973; Kawakita et al. 2000; Guerraz et al. 2000) and is further destabilizing when subjects stand on an unstable support surface (Keshner et al. 2004). In a previous study (Streepey et al. 2006), we induced instability by manipulating the size of the base of support (BOS) on which an apparently homogenous group of young, healthy subjects stood while viewing visual motion produced in our virtual reality laboratory. We believed that increasing instability would increase the subjects' reliance on peripheral vision and stereo cues to depth. An unexpected outcome was that a distinctive sub-group (five steppers) of our 15 subjects needed to step repeatedly from the smallest BOS (35% of foot length) when viewing a moving virtual environment. In the absence of scene motion, however, the steppers successfully maintained stance on the smallest BOS. One potential explanation for this phenomenon is that within the same population some individuals rely more heavily on visual information for postural control than others (Kitamura and Matsunaga 1990; Isableu et al. 1997, 2003; Golomer et al. 2005). We have now performed additional analyses comparing this group of steppers with our more successful group for conditions where the steppers could stand for the required amount of time (i.e., with 100 and 45% BOS) to test the hypothesis that an increased dependence on visual field information in the steppers would emerge as increased postural sway when viewing movement of the visual field even when stability was not as severely compromised.

Methods

Fifteen (7 male, 8 female) healthy adult volunteers (21–51 years old) participated in the original study (Streepey et al. 2006). Subjects were free from musculoskeletal and neurological disorders. All subjects were informed of the procedures and provided written consent in accordance with the Institutional Review Board of Northwestern University Medical School.

Previously published research describes the hardware and software responsible for generating the virtual environment (Keshner et al. 2004) as well as the experimental protocol used in this study (Streepey et al. 2006). 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 trials with 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. In trials without stereo imagery, two projections were generated from centers with identical viewpoints (i.e., the interpupillary distance equaled 0). Shutter glasses (Crystal Eyes, StereoGraphics Inc.) limited the subject's horizontal and vertical FOV to 100° and 55° of binocular vision.

Subjects stood barefoot with the feet in parallel and shoulder-width apart under three BOS conditions: 100, 45, and 35% of foot length in the anterior-posterior direction (from heel to toe). Reduction of the BOS was achieved by having the subjects stand on an adjustable 5 cm high wooden beam. Two modes of visual motion were provided: (1) natural motion where the correct scene perspective was continuously updated by motion capture markers providing head position and (2) augmented motion orientation where natural motion was combined with a visual forcing function which drove the scene sinusoidally in the fore-aft direction at 0.1 Hz an additional ±2.44 m at ±2.96 m/s. The total display system latency from the time of a subject's head motion to the time the new image showed the movement in the environment was 25 ms. Visual motion was viewed with a wide (100° horizontal and 55° vertical) field of view (FOV) and a narrow FOV (25° in both directions). The FOV was reduced by attaching apertures with a diameter of 1.08 cm (viewing holes cut into black cards) over the lenses of the stereo goggles. Subjects experienced in random order each of 18 possible BOS, FOV, and visual motion (augmented in stereo, augmented in non-stereo, natural in stereo) combinations. 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.

Reflective markers were attached bilaterally on the second metatarsophalangeal joint, lateral malleolus, lateral epicondyle of the tibia, greater trochanter, acromion process, lateral epicondyle of the humerus, styloid process of the ulna, second metacarpophalangeal joint, and zygomatic arch. Markers were also placed on C-7 and on L4/L5 joint of the spine. Marker motion was captured at 120 Hz using a six-camera Motion Analysis system (Motion Analysis, Inc.) and low-pass filtered at 4 Hz using a fourth order Butterworth digital filter. Center of mass (COM) for the head, trunk, and both shanks was derived from previously reported equations (Winter 1990) using commercial software (Kintrak, Inc.). Right and left ankle angles were determined as the angle between the foot and shank segments.

Steppers were defined as individuals who could not sustain 60 s of continuous stance on the 35% BOS in the presence of augmented visual motion with a wide FOV. Of our 15 subjects, 5 subjects were categorized as steppers (3 male, 2 female; 32.2 ± 10.9 years old) with the other 10 being categorized as non-steppers (4 male, 6 female; 28.1 ± 6.1 years old). The difference in age between the two groups was not significant. When confronted with augmented visual motion while standing on the 35% BOS, the steppers generally displayed greater amounts of postural sway which

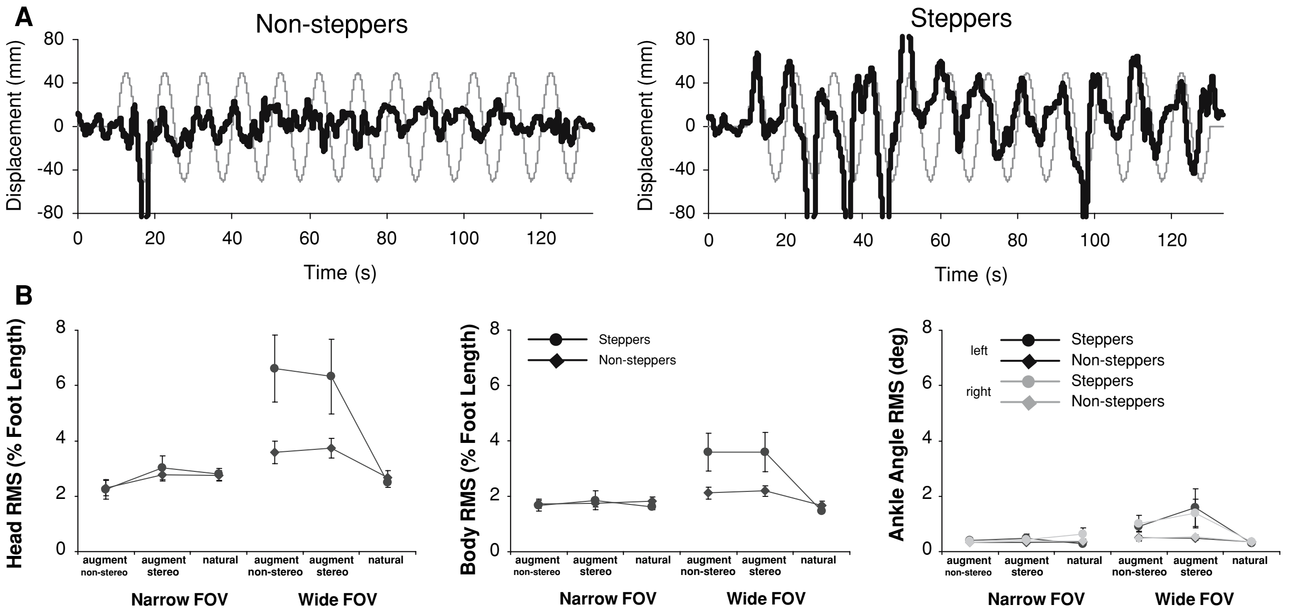

Fig. 1 **a** Representative whole body COM trajectories (*thick, black*) and augmented visual motion forcing function (*thin, gray*) plotted over the course of 140 s for the steppers and non-steppers when standing on the 35% BOS and viewing stereo augmented visual motion. Motion exceeding ±80 mm resulted in stepping regardless of subject grouping. The amplitude of the visual motion (±2.44 m) has been scaled to fit the plots. **b** Repeated stepper (*circle*) and non-stepper (*diamond*) head and whole body COM and ankle angle RMS averages and standard errors for each of the three visual motion conditions: stereo augmented motion, non-stereo augmented motion, and natural motion. Right (*gray*) and left (*black*) ankle RMS data are shown. When viewing visual motion with a wide FOV compared to a narrow FOV, RMS in the steppers increased while RMS for the non-steppers changed little

contributed to their inability to maintain continuous stance (Fig. 1a). The first step off from the 35% BOS took place between 2 and 37 s following scene movement onset (average delay to a step was 17 ± 13.4 s). It was not uncommon for non-steppers to take a step within this time-span. However, upon reestablishing themselves atop the 35% BOS, they were then able to maintain a minimum of 60 s of stance. Steppers were more likely to step backwards from the 35% BOS than the non-steppers (92% of the steppers' steps were in the backwards direction versus 77% for the non-steppers). Because the steppers could not sustain continuous stance on the 35% BOS in the presence of the visual motion, these trials were not used in analysis.

For the 100 and 45% BOS trials, 60 s of continuous stance were selected for analysis (Streepey et al. 2006). The mean value of a 20 s window of data was subtracted for every 5 s of data. In the anterior-posterior direction, root mean square (RMS) values were determined for the head and whole body COM linear displacement and for the ankle joint angular displacement using the following formula:

$$\mathrm{RMS} = \sqrt{\frac{\sum (\bar{x} - x_i)^2}{N}}$$

where $\bar{x}$ is the mean displacement and x_i is the instantaneous displacement. To characterize the COM responses to the augmented scene, power of the head, whole body, and shank COM was determined using a fast fourier transform (FFT) calculated in Matlab 7.0 (Mathworks, Inc., 2004) for trials with augmented visual motion (both stereo and non-stereo); natural scene motion which had no forcing function was not included in FFT analysis.

For trials with visual motion, time lags between augmented stimulus and the head, trunk, whole body, and left and right shank COMs were computed using a method similar to one employed by Buchanan and Horak (2001). Cross-correlations between a segments' COM and the augmented motion were determined at zero lag and as the data were shifted forward and backward in time steps of 0.083 s with respect to each other. The maximum time shift in either the forward or backward direction was limited to 10 s, the amount of time necessary for the 0.1 Hz augmented stimulus to complete one cycle. The head, trunk, and left and right shank COM time lags used in analysis corresponded to the maximum cross-correlation value over the course of one cycle.

To examine differences in postural control between the steppers and non-steppers standing on the 100 and

45% BOS, multi-factorial ANOVAs (group × scene × FOV × BOS) with repeated measures were used. A level of $P < 0.05$ was used to determine significant main effects and interactions. When significant main effects and interactions were found, Bonferroni post hoc comparisons were made.

Results

Regardless of whether the BOS was 100 or 45%, viewing augmented motion with a wide FOV had a significantly greater effect on the head [$F(4,26) = 8.04$, $P < 0.001$] and whole body [$F(4,26) = 5.64$, $P < 0.003$] COM RMS of the steppers than of the non-steppers, a group by FOV by scene effect (Fig. 1b). RMS values in the non-steppers did not change with width of the FOV. Steppers, however, increased both their head and whole body COM RMS when viewing either stereo or non-stereo augmented motion with a wide FOV compared to a narrow FOV. Furthermore, the head COM RMS of the steppers was significantly greater than that of the non-steppers when viewing augmented motion with a wide FOV, and steppers also tended to have greater trunk COM RMS. The steppers also had significantly greater left and right ankle angle RMS when viewing only stereo augmented motion with a wide FOV [$F(4,26) = 3.44$, $P < 0.03$ and $F(4,26) = 6.29$, $P < 0.002$, respectively] (Fig. 1b).

For trials where only augmented visual motion was presented, a wide FOV significantly increased power at 0.1 Hz for the head [$F(1,13) = 20.06$, $P < 0.001$], whole body [$F(4,26) = 21.98$, $P < 0.001$, and left and right shank COM [$F(1,13) = 7.57$, $P < 0.02$ and $F(1,13) = 7.81$, $P < 0.02$, respectively] in the steppers compared to the non-steppers (Fig. 2a). In addition, a significant group effect [$F(1,13) = 12.88$, $P < 0.004$] revealed that the lag between the whole body COM and both the stereo and non-stereo augmented scenes was greater in the steppers compared to the non-steppers regardless. FOV was also demonstrated to affect the lag between the augmented scenes and the head [$F(1,13) = 7.21$, $P < 0.02$] and the trunk [$F(1,13) = 5.23$, $P < 0.04$] with the lags being greater in the narrow FOV condition compared to the wide (–2.46 vs 0.076 s for the head and –2.02 vs 0.17 s for the trunk, respectively).

Discussion

Even with evidence for individual preferences for selecting and weighting sensory information (Gurfinkel et al. 1995; Kluzik et al. 2005; Isableu et al. 1997, 2003) to go along with the multiple degrees of freedom available for the maintenance of stance, subtle differences in postural control may go unnoticed as there exist multiple combinations of sensory information and joint coordination patterns that can yield similar postural outcomes. In fact, had our original experimental protocol not included standing on a 35% BOS, there would have been little to differentiate the steppers from the rest of the population other than their having large, but acceptable, responses to visual motion. Only by challenging the task constraints of stance by imposing such a reduced BOS were we able to observe differences in how these combinations impacted the ability to maintain balance without stepping.

Despite maintenance of their balance without having to take a step while standing on the two support surfaces examined here, postural stability was still compromised in the steppers when confronted with wide FOV visual motion that moved with a greater excursion and velocity than their postural sway. That this compromise appeared in the wide as opposed to the narrow FOV condition may be due to the increased lamellar flow in the peripheral visual field which other studies have suggested produces greater compensatory postural responses than central visual field motion (Stoffrengen 1985; Kawakita et al. 2000). The increased instability produced by wide FOV visual motion in the steppers may have resulted from their being more dependent on a visual reference frame for postural control. A traditional method for assessing dependence on visual field information for spatial orientation is to use a static visual test such as the rod and frame test (Isableu et al. 1997, 2003; Kitmura and Matsunaga 1990). Similar to the findings of Kitmura and Masunaga (1990) who observed significant positive correlations between postural sway and field dependence only when subjects viewed a dynamic visual scene, in our current study, no differences were observed between the steppers and non-steppers unless dynamic, augmented motion was provided. This raises the possibility that the steppers were more field dependent than the non-steppers.

It has been reported that, when subjects faced support surface translations, stability could be maintained by increasing postural stiffness and dampening (Peterka 2002), a strategy that would also promote stability when standing on a reduced BOS. Dampening was achieved primarily through the reduction of lag between the stimulus and the response. We found that the whole body COM of the stepper subjects generally lagged the augmented stimulus to a greater extent than the non-steppers. Such a lag may have promoted the increased whole body COM motion observed in the

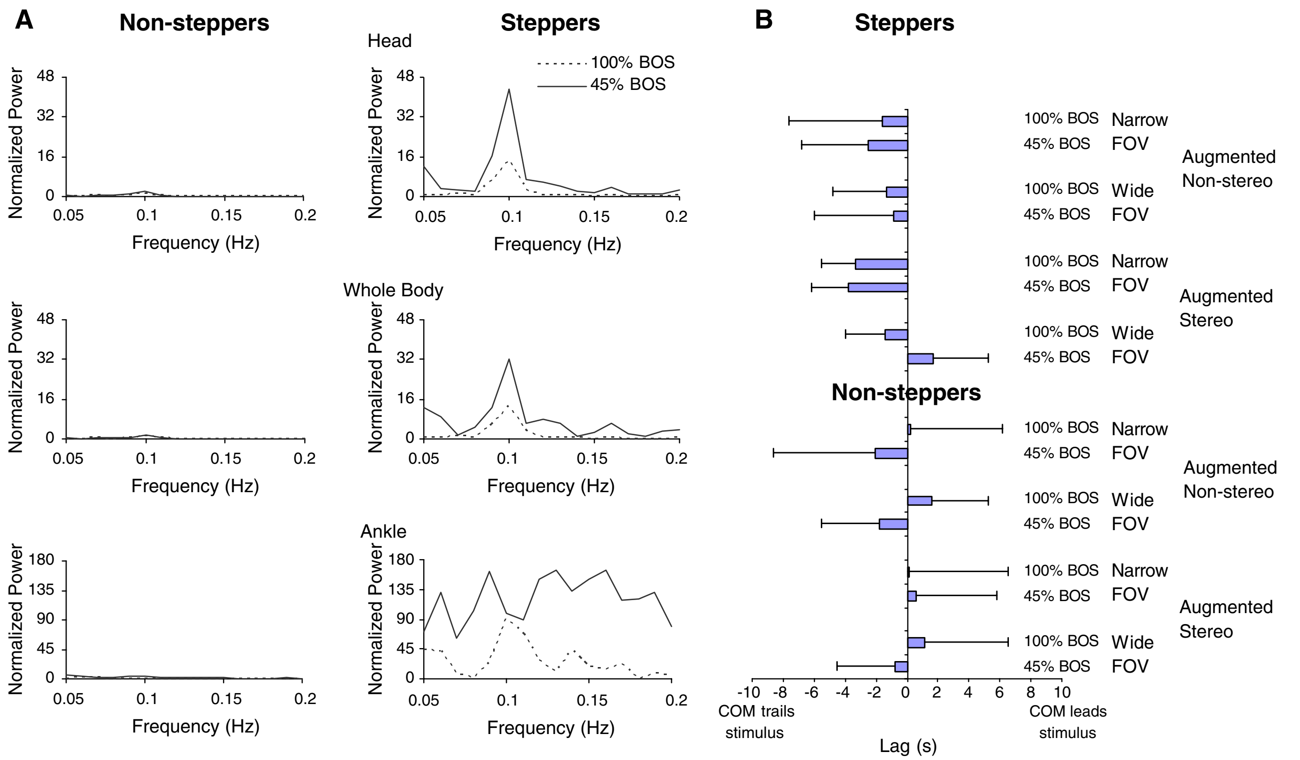

Fig. 2 **a** Average head, whole body, and left shank COM power for the 100% (*dashed line*) and 45% (*black line*) BOS conditions when the augmented visual motion was imposed on a stereo virtual scene and viewed with a wide FOV. Head and whole body COM power in response the visual stimuli; both stereo and non-stereo (not shown) was significantly increased in the repeated steppers compared to the non-steppers. Shank COM was also significantly increased in the repeated steppers although the power spectrum was much broader. **b** Stepper and non-stepper average whole body COM lag with respect to the non-stereo and stereo augmented scene motion. Overall, the motion of the whole body COM trailed that of the augmented motion to a significantly greater extent in the steppers compared to the non-steppers. Manipulation of the FOV and the BOS appeared to have little impact on whole body COM lag

steppers, which would increase the amount of torque needed to maintain stability. In the 35% BOS where the moment arm necessary for generating torque about the ankle is reduced, this increase in demand may have contributed to the increased frequency of the steppers loss of balance. Moreover, these increased lags in the steppers could represent a reduced weighting of graviceptive sensory information, which may dominate cues to verticality during low frequency motion (Peterka 2002).

Peterka (2002) also observed that the amplitude of postural sway in healthy subjects would saturate as the amplitude of visual field motion increased. In vestibular deficient subjects, however, postural sway did not saturate with increased amplitudes of visual motion even though their proprioceptive feedback was intact, suggesting that an intact vestibular system was critical for the non-linear damping of postural sway (Peterka 2002). Our group of steppers had no indications of vestibular dysfunction. We might assume, therefore, that an increased weighting of visual inputs, even in a population of healthy individuals, can inhibit or delay the shift of control from the proprioceptive and/or visual systems to the graviceptive system. Increased responsiveness to visual information may indicate that the thresholds for shifting from a reliance on visual information to a reliance on vestibular information are greater in some individuals. Variable thresholds could be the result of subtle sensory deficits within an otherwise healthy population (Peng et al. 1999), or a shift in the central set point that signals when to alter the response to specific sensory pathways (Maurer et al. 2005).

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