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Visual Sensitivity Modulates Postural Sway in a Virtual Environment in Healthy Elderly and Individuals with Stroke

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Abstract— **We employed a virtual environment to examine the impact of visual sensitivity on postural behaviors in adults with chronic symptoms of stroke. Six adults at least 1 year post-stroke (52-70 yrs) and 6 healthy adults (50-70 yrs) were tested in a Rod and Frame test. They then stood quietly on a platform within a 3-wall virtual environment. The platform was tilted 3° into dorsiflexion while in the dark, with visual motion matched to head motion, or with pitch up and down visual field rotations at 30 and 45 °/sec. While the visual field rotated, the platform was held tilted for 30 sec and then slowly returned to a neutral position over 30 sec. Center of pressure (COP) was recorded and approximate entropy (ApEn) values were calculated and compared with visual error from the Rod and Frame test. No significant differences in visual errors were detected in the Rod and Frame task between the populations. However, in subjects with large visual errors (>8 deg) strong inverse correlations with ApEn values (*r*>-0.7) emerged with either a scene referenced to head motion or matched to the velocity of the platform tilt. ApEn values were typically below 1 indicating that COP responses were mostly predictable and reflecting a single input. This low ApEn with increased visual error suggests that the visual field serves as a meaningful reference for postural stabilization in visually dependent adults. Our results support the use of virtual environments to generate adaptive postural behaviors.**

Keywords- Stroke; aging; visual-vestibular conflict; visual dependence; balance

I. INTRODUCTION

Unlike most animals, humans rely heavily on their sense of vision to orient themselves in the world [1]. It has been suggested that declines in somatosensory, vestibular and muscle function with age contribute to a greater dependence on visual inputs with aging [2-4]. Even in healthy young adults, postural control is highly influenced by optic flow when somatosensory feedback is varying [5, 6], and optic flow has been observed to have a strong influence both on quiet stance on a moving platform and on gait [7]. Although it is generally agreed that visual information is not used in the generation of automatic postural reactions [8, 9], a slowing of the postural reactions with age [10-12] may create a window for the more slowly processed visual inputs to modify the postural response. Visual field motion has been shown to influence postural behaviors within 1-2 sec following a balance disturbance [13], and these early visual responses have been described as automatic, pre-conscious visual processes [2].

Perception of physical motion and orientation in space is derived from the convergence of vestibular, proprioceptive, and visual signals. We observed that in a virtual environment where visual field motion did not match the feedback from externally triggered physical motion, healthy older subjects weight visual and vestibular/proprioceptive signals differently than young adults [14]. Young adults shifted their reliance between sensory pathways and give greater importance to proprioceptive feedback during visual mismatch. Older adults continued to weight vision more heavily even when inappropriate.

Motor impairments following cerebrovascular accident (CVA) are related to poor control of balance and mobility [15-17]. However, large population studies investigating the risk of falling in elderly individuals who were post-stroke revealed that motor impairment alone did not increase the risk of falling. Individuals post-stroke had a three times greater risk of falling when sensory deficits were also present [18]. Dizziness and spinning symptoms were also strong risk factors in this population [19]. We have previously reported that individuals post-stroke are immediately destabilized by optic flow whereas healthy adults have a 40-80 sec delay before the visual vection response becomes apparent [14]. This delay is suggestive of impaired vestibular processing [20] in the patients post-stroke. Patients post-stroke have also been shown to have abnormally large body sway movements to full field visual motion [21], and a reduced ability to resolve sensory conflicts in the presence of conflicting or disorienting visual stimuli, thereby causing inappropriate postural reactions [22].

The goal of this study was to determine whether postural sway was affected by a measure of visual dependency when

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standing balance was disturbed in a virtual environment. We examined center of pressure responses in both healthy adults and adults with CVA during both a transient postural disturbance and throughout the compensatory behaviors following that disturbance while standing in a rotating virtual environment.

II. METHODS

A. Subjects

Six healthy older adults (50-70 yrs), and 5 patients with right hemiparesis and one patient with left hemiparesis following a stroke (52-70 yrs) gave informed consent to participate in this study. Patients were at least one year post-stroke, and all but one had a smaller than 10 deg limitation of ankle range of motion on their affected side. Berg balance measures ranged from 51-55 (maximum is 56) and 2 patients used canes when ambulating.

B. Apparatus

The Rod and Frame protocol is an accepted psychophysical measure of visual dependence [23-26] comprised of a projection screen displaying a luminous frame tilted 22.5° clockwise or counterclockwise from horizontal. For each trial, a luminous rod was positioned 20° or 45˚ from vertical or horizontal and digitally rotated at a speed of 0.5˚/sec within the tilted frame.

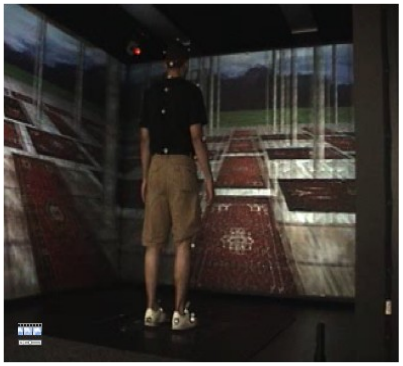

Figure 1. 3-wall virtual environment displayed to subjects standing quietly on the dynamic platform.

A 3-degree of freedom posture platform (Neurocom International Inc., Clackamas OR) with integrated dual triaxial force plates (AMTI, Watertown, MA) sits within a 3-wall virtual reality back projection system. Three transparent 1.2 m x 1.6 m screens are placed 90 cm in front and to the right and left of the platform. The projected image (scene) consists 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 (Fig. 1).

C. Procedures

1) Rod and Frame Protocol: Each subject completed the Rod and Frame test while standing freely in the upright position in the dark. They were instructed to look straight ahead at the projection screen. Subjects verbally instructed the experimenter when they perceived the rod as reaching pure vertical or horizontal. Absolute angular deviations of the rod were calculated as the value of the position given by the subject and visual error was this value subtracted from 90°.

2) Posture Test Protocol: Subjects stood comfortably on the platform with their feet side-by-side at hip width, and with their upper arms at their sides (Fig. 1). Foot position was marked on the platform and reproduced across trials. Subjects were asked to maintain an erect posture in all trials. After 5 sec of quiet stance, the platform was rotated in 3° of dorsiflexion at a constant velocity 30°/sec. The visual field either remained dark (DARK), or was matched to the motion of the head (STILL), or was simultaneously rotated in upward (UP) or downward (DOWN) pitch at velocities of 30 and 45°/sec. Onset of visual rotation and platform movement were synchronized. The platform maintained a 3° tilt for 30 sec, and then slowly returned to the horizontal at a constant velocity of 0.1°/sec over a 30 sec period. The visual field maintained a consistent rotation throughout the 65 sec trial period.

D. Data Analysis

Center of pressure (COP) recordings were collected at a rate of 200 Hz from the two force plates. Resultant vectors in the anterior-posterior (AP) and side-to-side (ML) directions were calculated as a weighed sum from the individual signals from the right and left force plates. The raw COP time series in each direction for each trial was analyzed with Matlab files available on Physionet [27] using a nonlinear regularity statistic known as Approximate Entropy (ApEn). ApEn is a probability statistic based on the logarithmic likelihood that a sample of data will remain within a tolerance window that defines the criterion of similarity (r = 0.2) for subsequent data increments of two data points (m = 2) [28-30]. ApEn values tend to range between 0 and 2, with values closer to 2 indicating more unpredictable motion and, therefore, a more complex response organization [31-34]. Values closer to 0 indicate a higher level of regularity and a system response that is more predictable and less complex. ApEn values for the AP and side-to-side directions were calculated for each trial for each visual condition across two time periods of the trial: 10-30 sec following the tilt (sustained tilt), and over the last 20 sec that the platform returned to a neutral position. A relation between the ApEn values and the visual error on Rod and Frame tested was examined using a Pearson Product Correlation Coefficient in each visual condition.

III. RESULTS

A previous study from our laboratory [4] revealed significantly increased angular deviations on the Rod and Frame test in healthy older adults compared to healthy young adults. However, neither an age nor a population difference was evident in the subjects tested here (Fig. 2). There was a surprisingly wide range of angular deviations from pure visual vertical and horizontal in each population. Mean visual angle error in the healthy adults was 10.5°±7° (ranging from 5 to 21°) and 11.9°±9° (ranging from 1.5 to 22°) in the adults with stroke.

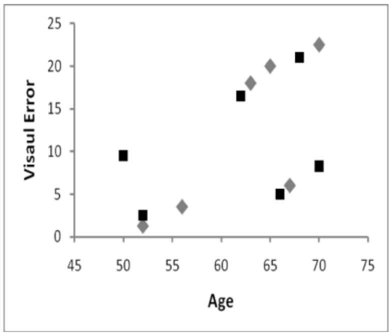

Figure 2. Mean angular deviation from vertical and horizontal plotted against age for each healthy (grey triangles) and stroke (black squares) subject.

A. COP Responses in Healthy Adults

Postural sway behaviors did differ between the two populations during both periods of the 65 sec trial. During quiet stance preceding the onset of the support surface tilt, healthy older adults exhibited very small shifts in either the AP or ML directions (Fig. 3). With the onset of support surface tilt (tilt in Fig. 3), the COP exhibits large deviations in the AP direction indicative of the AP sway taking place. During the sustained tilt and the return of the platform to neutral, responses of the COP remained primarily in the AP direction for this group. The areas of the response were increased relative to quiet sway, and the direction of visual field motion tended to shift COP forces either more forward (down 30) or more backward (up 30) than when in the dark. The only healthy older adults to demonstrate a more diffuse, overlapping response of the COP for all conditions also reported large visual errors in the rod and frame test (2nd and 5th rows in Fig. 3).

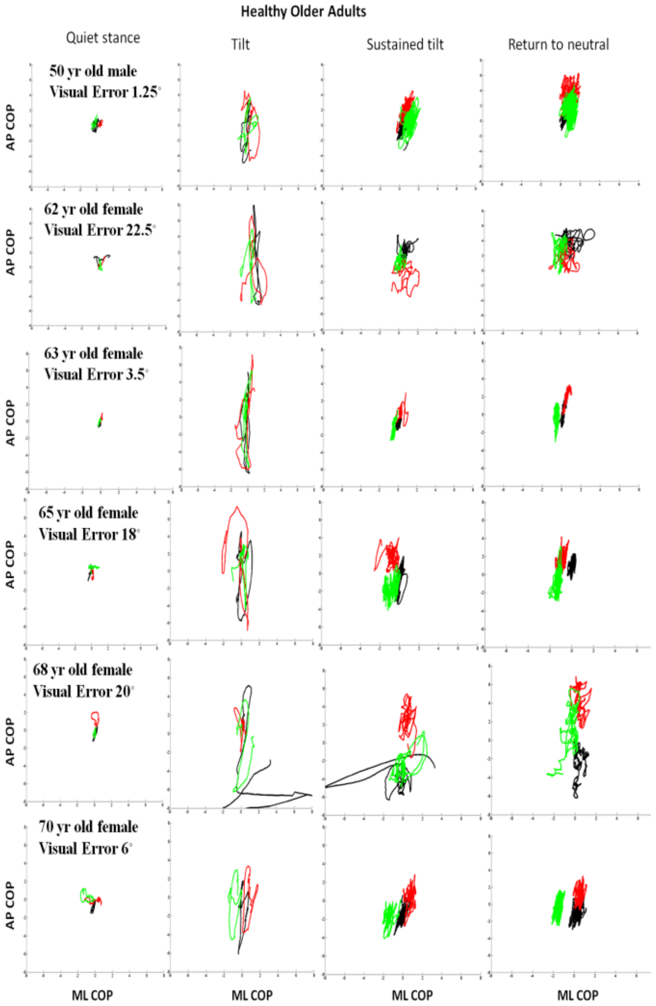

Figure 3. AP COP plotted against side-side (ML) COP for each healthy adult during quiet stance, platform tilt, sustained tilt, and return to neutral. Age, sex, and visual error in the rod and frame task for each subject are identified at the top of each quiet stance plot. Positive y-axis depicts forward motion; negative y-axis depicts backward motion; positive x-axis depicts motion to the right; negative x-axis is motion to the left. Three visual conditions are overlaid in each plot: dark (black), up 30 (green), and down 30 (red).

B. COP Responses in Adults with Stroke

Patients with stroke exhibited more ML activity in their COP responses than did the healthy older adults (Fig. 4). Except for the subject with a large visual angle error (4th row in Fig. 4), there was greater ML activity even in quiet stance. Despite the greater activity in both planes of COP motion, there was a clear distinction between the direction of the COP response during visual motion in the up and down directions compared to the dark. Interestingly, the shifting COP forces occurred both in the ML direction and AP direction with pitch visual field motion producing more shifts of the COP toward the right and left as well as forward and back.

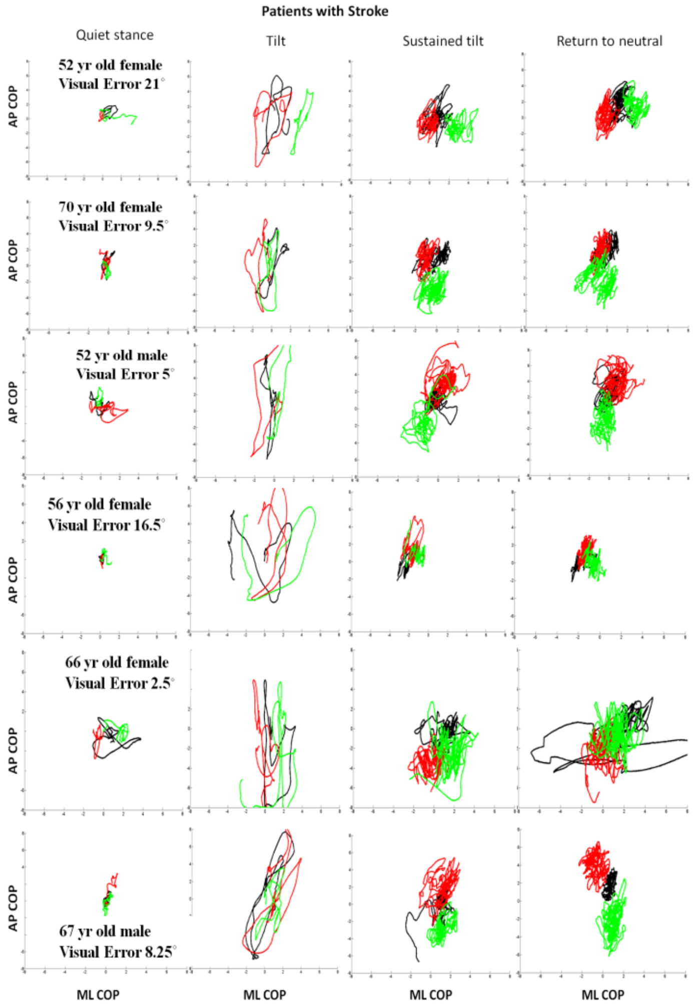

Figure 4. AP COP plotted against side-side (ML) COP for each adult with stroke during quiet stance, platform tilt, sustained tilt, and return to neutral. Age, sex, and visual error in the rod and frame task for each subject are identified at the top of each quiet stance plot. Axis directions are the same as in Fig. 3. Three visual conditions are overlaid in each plot: dark (black), up 30 (green), and down 30 (red).

C. ApEn Calculations

In order to explore the presence of complex multi-sensory processing across the different visual conditions, we measured fluctuations in the COP through the measure of approximate entropy (ApEn). ApEn was calculated in each response plane of the COP for each subject in each condition in order to determine: 1) whether the different visual conditions had a quantitative effect on the COP, and 2) whether there was relationship between the complexity of the COP response and extent of visual dependence revealed through the Rod and Frame test.

ApEn values for the two populations indicated some trends in the periods of sustained tilt and the return to neutral of the support surface (Fig. 5). For both groups, ApEn of the COP in both directions was smaller on the tilted platform when the visual scene was referenced to the motion of the head (STILL in Fig. 5) than when in the dark or during visual field rotation. The effect of the head referenced scene on the ApEn remained for the patients with stroke during the return of the platform to neutral. During the sustained tilt, patients with stroke had lower ApEn values in the ML COP direction but larger or equivalent ApEn values in the AP direction when compared to healthy adults across the visual conditions. When the platform was returning to neutral, patients with stroke had smaller ApEn values than the healthy older adults in the AP and ML directions of COP for almost all of the visual conditions.

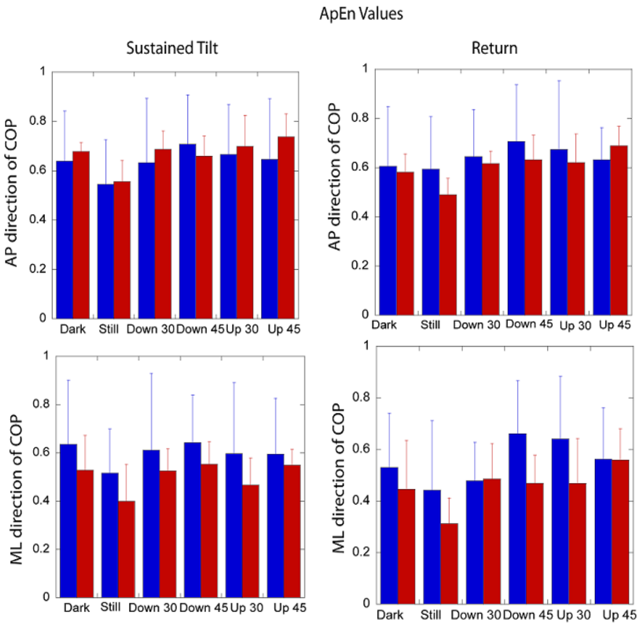

Figure. 5: Average ApEn values with standard deviation error bars for COP in the AP direction (top) and the ML direction (bottom) for healthy adults (blue) and patients with stroke (red) in each visual condition.

The relationship between ApEn values and visual angle error was also examined. Because there were no differences in the range of visual errors between the two populations (Fig. 1), this variable was collapsed and subjects were separated into two groups: those with visual errors less than 8 deg (n = 5) and those with visual errors greater than 8 deg (n = 7). An inverse relationship was observed between the ApEn values during the period of sustained tilt and the visual error. ApEn of the COP was higher in individuals with average visual errors < 8 deg in both the AP (mean ApEn=0.74±0.5) and ML (mean ApEn=0.67±0.7) planes of motion compared to individuals with > 8 deg visual errors in both the AP (ApEn mean=0.59±0.06) and ML (ApEn mean=0.47±0.05) planes (Table 1). A Wilcoxon statistic was used to assess differences between visual conditions. Individuals with < 8 deg of visual error had significantly higher ApEn values in the ML direction during both pitch up rotations than individuals with > 8 deg of visual error (p<0.03). Marginal statistical differences in the ApEn values for the AP and ML directions during pitch down rotations at 45˚/sec and in AP direction for the head referenced visual scene indicated that individuals with smaller visual errors exhibited higher ApEn values than those with larger visual errors (p <0.05).

Table 1: Average ApEn values (standard deviation) for the subjects with visual errors below 8 deg and those subjects with visual errors greater than 8 deg on the Rod and Frame test.

	< 8 deg Error		**> 8 deg Error**	
VISUAL SCENE	AP COP	ML COP	AP COP	ML COP
DARK	0.75 (0.13)	0.70 (0.23)	0.60 (0.12)	0.50 (0.16)
STILL	0.65 (0.10)	0.53 (0.12)	0.48 (0.11)	0.40 (0.19)
DOWN 30	0.78 (0.16)	0.69 (0.30)	0.57 (0.16)	0.48 (0.12)
DOWN 45	0.78 (0.16)	0.71 (0.13)	0.61 (0.10)	0.52 (0.12)
UP 30	0.73 (0.16)	0.71 (0.22)	0.65 (0.17)	0.40 (0.12)
UP 45	0.76 (0.16)	0.69 (0.19)	0.64 (0.19)	0.49 (0.08)

Although this inverse relationship was present even in the dark during the sustained tilt, COP ApEn values were most strongly correlated (*r*>-0.7) with large visual angle errors (>8 deg) when the visual field was either referenced to the head motion (STILL) or moving at the same velocity as the platform (shaded areas in Table 2). During platform return, the inverse relationship between ApEn and visual angle error was strongest in the AP direction for individuals with visual errors greater than 8 deg when the visual scene pitched up at 30˚/sec (*r*=-0.73). In addition, visual error was inversely related (*r* =-0.76) to ApEn in the ML direction for individuals with visual errors less than 8 deg when the visual scene was referenced to the head motion.

Table 2: Correlations between average ApEn values during the sustained tilt and visual error during the Rod and Frame Test

	< 8 deg Error		**> 8 deg Error**	
VISUAL SCENE	AP COP	ML COP	AP COP	ML COP
DARK	-0.42	-0.41	-0.57	-0.13
STILL	-0.56	0	-0.88	-0.23
DOWN 30	-0.35	-0.35	-0.76	-0.72
DOWN 45	-0.16	-0.10	-0.67	-0.51
UP 30	-0.28	-0.39	-0.89	-0.78
UP 45	-0.39	-0.59	-0.44	-0.46

IV. DISCUSSION

Previous studies [23, 24] have reported a relationship between Rod and Frame results and postural sway during quiet stance and traditional clinical tests of instability (e.g., Romberg testing). But the correlation between dynamic postural behaviors with the Rod and Frame protocol, an accepted psychophysical test of visual dependence, has not previously been performed. In these experiments, we have extended this investigation to evaluate the influence of visual field motion on the postural sway and examined the interrelationships between posture, visual information, and visual dependence.

Our subjects were selected because of previous reports in the literature claiming that aging individuals and those with neurological disorders would exhibit greater visual sensitivity [21, 35-38]. Visual sensitivity did not emerge more strongly in either group tested here, but appeared as an individual difference or perceptual style between all of the subjects [39, 40]. In our prior study [4], we demonstrated that both healthy elderly adults and individuals with stroke had significantly greater visual angular deviations on the Rod and Frame test than healthy young adults. But the population in this study is not as well defined since it extends from the fifth to seventh decade. This might explain why we were unable to show a relationship between age and visual angle error.

ApEn values in this study were typically less than one, which would be indicative of some regularity in both planes of COP excursion. Both proprioceptive inputs from the platform and inputs from the visual field have the potential to organize the behavior over the 20 sec time period that we measured. Thus, the increasing regularity of the ApEn values with increasing visual angle error could be indicative of a greater reliance on the visual information or on the proprioceptive information in these subjects. When the visual scene was referenced to the head, thereby supplying a stabilizing visual field effect, ApEn values dropped closest to zero, suggesting that the visually sensitive subjects were using the visual information to stabilize themselves. Strong correlations between ApEn and visual angle error during the platform tilt when the visual scene was moving at the same velocity as the body suggests that vision served as the organizing parameter for this response in people who were visually dependent when the information was meaningful to the postural task. Variations in ApEn values with variations in velocity and direction of the visual field indicates that these individuals were relying more greatly on the varying visual information from each task rather than on the consistent proprioceptive feedback from the support surface.

We conclude that adults exhibiting greater visual dependence rely on visual information to determine their dynamic orientation in space when visual and somatosensory inputs are in conflict [41-43]. Strong correlations between the standard Rod and Frame test of visual dependence and the measures of postural sway within the virtual environment provide support that the behaviors measured within these environments are transferable to the physical world. We would advocate the use of this technology both for assessment and training of adaptive postural behavior.

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