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Postural Adjustments Produced by Moving Visual (Horizontal Optokinetic) Patterns

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Abstract

The effects of horizontal optokinetic stimulation (HOKS) on postural sway were examined in 30 normal subjects aged 20 to 75 years. Fixed-platform posturography was evaluated with the eyes open and closed and during HOKS (20–100°/sec) in the rightward and leftward directions. Forward-backward sway was greater in amplitude than lateral sway under all viewing conditions. Sway amplitude was greater with eyes closed than with eyes open. HOKS significantly enhanced sway amplitude in both directions; however, significant differences occurred only between velocity extremes. Compared to younger subjects, older subjects showed greater forward-backward sway with eyes closed and greater lateral sway during HOKS. HOKS produces a visual cue that conflicts with the other two sensory signals regulating posture (vestibular and proprioceptive systems). Such conflicting visual cues may contribute to serious postural instability and falls in the elderly. The addition of optokinetic stimuli to fixed-platform posturography may enhance its diagnostic value.

Key Words: Age effects, controls, fixed-platform posturography, optokinetic stimulation, vestibular system

Balance is a complex function that is dependent upon sensory input through visual, proprioceptive, and vestibular systems (Nashner and McCollum, 1985). The motor outflow to axial and limb muscles is under reflex control and is modified by continuous multiloop sensory feedback through which vision plays a powerful role. Body sway consists of a combination of forward-backward and lateral motions, largely about the ankle joints. The amplitude and velocity of sway is enhanced in the dark by as much as 50 percent to 65 percent (e.g., Travis, 1945; Edwards, 1946; Barré, 1949; De Haan, 1959; Dichgans et al, 1975). The powerful stabilizing effects of vision are even greater in certain clinical conditions such as neurodegenerative disease (e.g., tabes dorsalis) affecting muscle and proprioceptor afferents (e.g., Frenkel, 1907) or in patients with loss of vestibular function (Tokita et al, 1981, 1989), and the vision effects are age dependent.

Individuals over 60 years of age typically exhibit an increased sway amplitude while standing on a fixed or movable platform (Stelmach et al, 1989; Pyykkö et al, 1990) and show other symptoms (e.g., increased incidence of falls, impaired timing and coordination of antigravity muscles serving balance) suggestive of major age-related changes in the balance system (Woollacott et al, 1986; Pyykkö et al, 1990; Wolfson et al, 1992). Young-old differences are generally exaggerated with increasingly difficult tasks or perturbations (e.g., eyes closed stance is more difficult and shows greater young-old difference than eyes open stance). Finally, the age-related decline in postural control is often confounded by underlying (subtle) diseases (e.g., osteoarthritis) (cf. Alexander, 1994). Few investigators, however, use highly screened older adult control groups for balance studies because such studies might overestimate the balance capabilities of seniors living independently in the community (Stelmach et al, 1989).

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When a subject views a moving visual environment, a conflict is induced between the changing visual input and the stable, geocentric vestibular and proprioceptive cues. Mach (1875) first showed that when observers view a wide-angled display rotating around their line of sight, they feel the body tilting opposite to the moving stimulus (the oculogyral illusion). A sensation of self-rotation also can be produced by rotation of the visual surround about a horizontal or vertical axis (circular vection) (Dichgans et al, 1972; Held et al, 1975), or with linear motion of the visual surround (linear vection) (Berthoz et al, 1974; Lestienne et al, 1977).

In addition to producing subjective sensation of movement, moving visual patterns also produce postural adjustments that have been studied using visual stimuli moving in an anterior-posterior direction (e.g., Lee and Aronson, 1974; Lestienne et al, 1977; Shumway-Cook and Horak, 1986; Horak, 1987) or rotating around the line of sight (Dichgans et al, 1976). These two stimulus protocols are similar in that both produce a stimulus-dependent postural sway that occurs within 0.5 to 2 sec after the onset of the stimulus (Berthoz et al, 1975; Dichgans et al, 1975; Lestienne et al, 1977). They differ only in the direction of evoked sway. Forward-backward sway is evoked with stimuli moving in the forward-backward direction, and lateral sway is induced with torsional stimuli.

The purpose of this study was to generate normative data on postural sway induced by horizontal optokinetic stimulation in subjects standing on a fixed platform. Although substantial data exist on the changes in postural sway with the eyes open and closed, and during forward-backward or torsional visual motion, sway induced by horizontal optokinetic patterns has not been studied and may provide a challenge to the vestibular and proprioceptive systems, thereby extending the diagnostic value of fixed-platform posturography.

METHODS

Fixed-platform posturography was conducted on 30 normal subjects between the ages of 20 to 75 years (41.3 ± 16.6, mean ± SD). All subjects had normal hearing for their age (Brandt and Fozard, 1990) and vision correctable to 20:20. In answering a questionnaire, all subjects reported normal vestibular function.

The custom posturography system (Peak Associates, Pasadena, CA) is shown in Figure 1 and consists of (1) a fixed platform with two independent foot plates with force transducers that resolve the forward-backward and lateral changes in the center of force of a standing subject; (2) a 180° curvilinear projection screen located 1 metre from the subject; (3) an optical stimulator for projection of all moving visual stimuli (Fowler et al, 1993); and (4) a safety support harness to prevent the subject from falling.

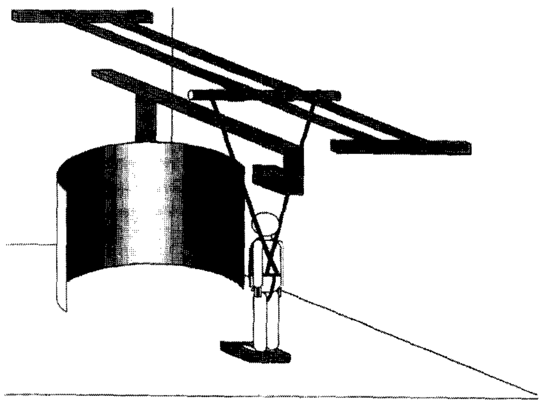

Figure 1 Optokinetically induced postural sway. The subject stands on the balance platform and views the circular screen. A projector located above the subject's head rotates random bars (1° × 8° visual angle) left or right at velocities of 20°/sec, 40°/sec, 60°/sec, 80°/sec, and 100°/sec. The balance platform measures lateral and forward-backward sway.

During the test, the subjects were asked to maintain a relaxed vertical posture, with feet slightly apart and hands at their sides. Postural sway was recorded under the following three conditions: (1) eyes open against a fixed background, (2) eyes closed, and (3) eyes open against a background moving at 20, 40, 60, 80, and 100°/sec in the rightward or leftward directions. The random bar (1° × 8° visual angle) optokinetic pattern, produced by a shadow projector system, covered 180° of the circumference in the horizontal plane and 40° in the vertical plane. Each stimulus trial consisted of a 30-sec period of postural testing during stimulation and a minimum of 30 seconds of rest. Moving visual stimuli were presented binocularly and were randomized to prevent order effects. Subjects were given an alerting task to maintain vigilance and were instructed to look in the direction of the screen.

Postural sway was measured as changes in "center of force," COF(x,y), a time-varying vector defined in the horizontal plane: the x-axis is the bitemporal axis (right ear positive) and the y-axis is the anterior-posterior axis (anterior positive). COF(x,y) was computed as a weighted average of the output from six force transducers (three for each foot plate) as follows: First, the x-y position of each force transducer was measured; because the position of the six sensors on the platform is fixed mechanically, these values are constants. Next, force vectors (A_1–A_6) were computed by multiplying the x-y position of each transducer in the horizontal plane times its output (f_1, f_2, ... f_6), for example, $A_1 = f_1(x_1,y_1)$, $A_2 = f_2(x_2,y_2)$, ... $A_6 = f_6(x_6,y_6)$. Finally, the six force vectors are summed and normalized by dividing by the sum of the individual forces (f_1+ f_2+ .... f_6) to give the resultant force vector:

$$\text{COF}(x,y) = \frac{f_1(x_1,y_1) + f_2(x_2,y_2) + \dots\ f_6(x_6,y_6)}{f_1 + f_2 + \dots\ f_6}$$

Postural sway, registered as movement of the resultant force vector, is a good measure of horizontal variations of the center of gravity, providing that the angular acceleration of the body is small and below 1 Hz, which it generally is in tests of this type (Gurfinkel, 1973). The value of COF(x,y), that is, the forward-backward and lateral sway of the body, was sampled at 200 Hz. These data were transferred to an ASCII file and exported to a spreadsheet program (EXCEL, Microsoft Inc.) for further analysis, including (1) displays of position in the forward-backward and side-to-side dimensions as a function of time, (2) "squiggle plot" display of the forward-backward and lateral center of force over the recording time, and (3) elliptical plots of the ±1 and ±2 standard deviations of the amount of forward-backward and lateral sway during the recording period.

RESULTS

Figure 2 shows the changes in sway amplitude (ordinate) over time (abscissa) in a typical subject during each of the stimulus conditions tested. The top row shows sway with the eyes open and closed, and the remaining rows show sway induced by each of the stimulus velocities (20–100°/sec) to the right or to the left, as indicated. In the two left columns are the lateral sway and in the two right columns are the forward-backward sway. From these responses, it is clear that forward-backward sway exceeds lateral sway. Further, the shifting baseline in these responses indicates that the overall body position is not constant during the stimulation but may change abruptly at times (e.g., see forward-backward sway between 10–14 sec for stimuli moving 80°/sec to the right). Individual sway patterns such as this cause high variability in the group data. A small proportion of subjects (21%) exhibited a rapid tilt away from, and then a slow body tilt in the direction of, the stimulus. Others showed the opposite response, that is, a rapid tilt in the direction of the stimulus and then a slow tilt in the opposite direction (37%), whereas the largest group (42%) exhibited lateral tilt, but without a consistent pattern across stimulus trials.

The data as shown in Figure 2 were used to quantify the amount of sway. Because the characteristic of primary interest was the variability in the sway pattern and the influence of the stimulus conditions on the sway variability, standard deviations of sway amplitude in the lateral and forward-backward directions were used as the primary data points. For each subject, the sway amplitude was measured in centimetres of displacement in the lateral and forward-backward directions, and the standard deviations of those sway amplitudes were calculated.

Figure 3 shows the "squiggle plots" (two left columns) and the elliptical standard deviation plots (two right columns) of the displacement in the lateral direction (abscissa) and the forward-backward direction (ordinate) for the subject whose data are shown in Figure 2. The squiggle plots provide a visual account of amplitude of the sway of the subject collapsed over the 30-second recording period. The means and standard deviations of these excursions were calculated and are displayed in the elliptical plots, which show both the ±1 (inner ellipse) and ±2 (outer ellipse) standard deviations of the amplitude of the sway during the recording. In both parts of this figure, the top row shows movement with eyes open and closed, and the remaining rows show displacement induced by each of the stimulus velocities (20–100°/sec) to the right or to the left, as indicated.

The first comparison of interest was in the stabilizing effect of vision on the sway amplitude. Mean standard deviations of sway from the subject group were analyzed with a two-way repeated measures analysis of variance (ANOVA), comparing sway in the lateral and forward-backward directions for eyes open and closed conditions (Northwest Statpak[1]), and the results are summarized in Table 1. The average forward-backward sway amplitude, as expected, was significantly greater than the lateral sway

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[1] Northwest Analytical (1986) Statpack, Version 4.1. Portland, Oregon: Northwest Analytical, Inc.

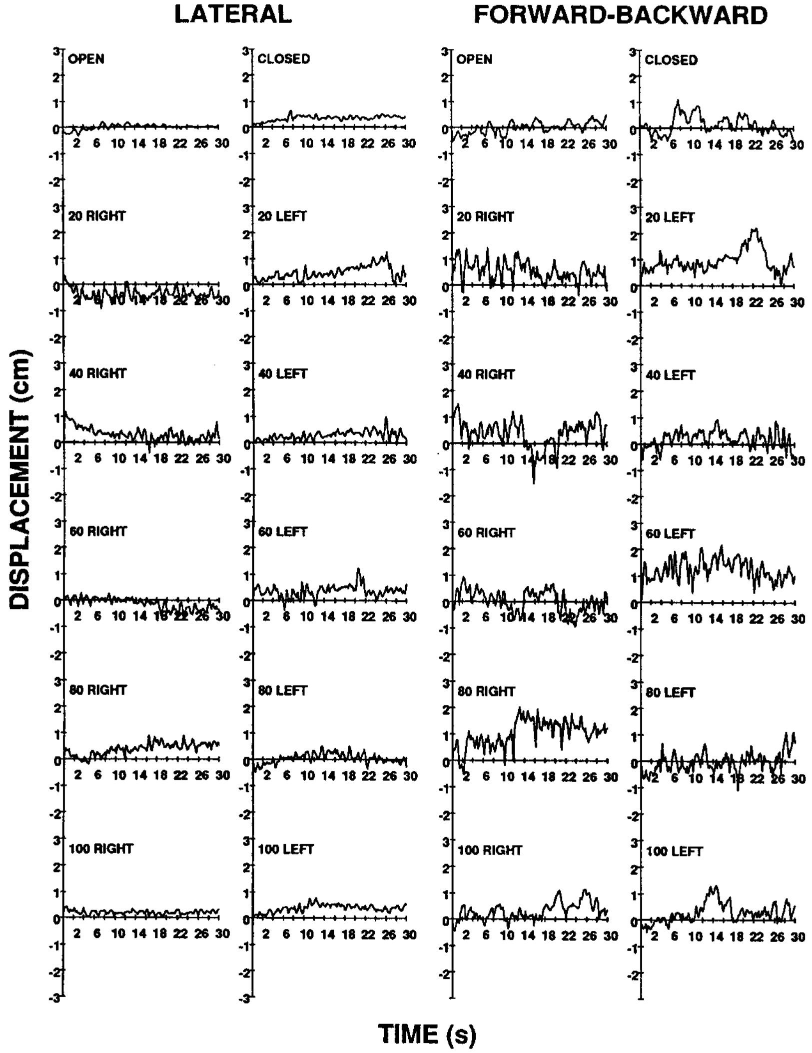

Figure 2 Posturographic data for a representative subject (M.T., 51 years) showing lateral sway (two left columns) and forward-backward sway (two right columns). Positive values correspond to sway to the right or forwards; negative values are to the left or backwards. Stimuli are eyes open and closed (top row) and eyes open with horizontal optokinetic stimuli of 20°/sec, 40°/sec, 60°/sec, 80°/sec, and 100°/sec (bottom five rows).

amplitude. This preponderance produces the approximate elliptical shape to the sway pattern seen in Figure 3. The eyes closed condition produced significantly greater sway than the eyes open condition, demonstrating the powerful stabilizing effect of vision on postural sway. A significant interaction indicates that the eyes closed condition had greater effect on the forward-backward sway than on lateral sway.

To evaluate the effects of optokinetic stimuli, the lateral and forward-backward sway were analyzed independently. Sway in the lateral and forward-backward directions were each analyzed with a two-way repeated measures ANOVA

Table 1 **ANOVA results for 30 Control Subjects**

		F value	*df*	*p value*
Open/ Closed	Open/closed	5.08	1,29	< .05*
	Sway direction	76.24	1,29	< .05*
	Interaction	9.68	1,29	< .05*
Lateral sway	Stimulus direction	2.38	1,29	> .05
	Stimulus velocity†	4.17	4,116	< .05*
	Interaction	0.90	4,116	> .05
Forward-Backward	Stimulus direction	0.58	1,29	> .05
	Stimulus velocity‡	2.72	4,116	< .05*
Sway interaction		0.60	4,116	> .05

* Statistical significance.

†Newman-Keuls: sway at 20°/sec < 100°/sec; ‡Newman-Keuls: failed to localize significant difference.

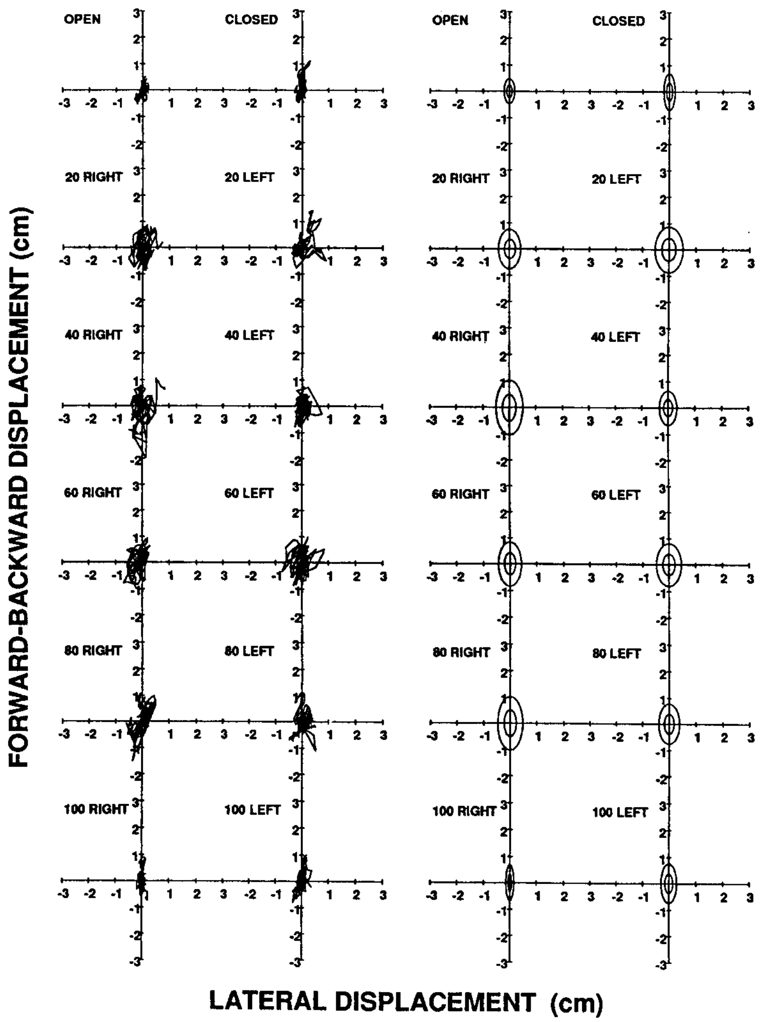

Figure 3 "Squiggle plots" (left figures) and concentric ellipses giving the mean ±1 and ±2 SD, respectively, of the amplitude of sway for the same subject as in Figure 1. The abscissa conveys lateral body position; ordinate gives forward-backward position. The three test conditions are eyes open and eyes closed (top row) and horizontal optokinetic stimulation at the indicated stimulus velocities and directions (bottom five rows). Sway amplitude is larger with eyes closed and during optokinetic stimulation than with eyes open.

comparing the amount of sway induced by stimulus velocity (20°/sec, 40°/sec, 60°/sec, 80°/sec, 100°/sec) and stimulus direction (right, left). These results are also shown in Table 1. There were no differences attributable to stimulus direction for sway in either the lateral or forward-backward directions. Stimulus velocity, however, significantly affected sway both in the lateral and forward-backward directions. Figure 4 shows the mean sway (±1 SD) for the subject group, with lateral sway shown in the left panel and forward-backward sway in the right panel. For comparison, the eyes open and closed conditions are included along with the stimulus velocities across the abscissa. A post hoc Newman-Keuls' test indicated significant differences only between the 20°/sec and 100°/sec stimulus velocities for lateral sway, and failed to localize the difference for the forward-backward sway.

The subject group included a wide age range, and previous studies have indicated that sway increases with age during eyes open, eyes closed, and anterior-posterior sway referencing of the visual surround. To test this relationship in the present subject group, and to examine the effects of conflicting (horizontal optokinetic stimuli)

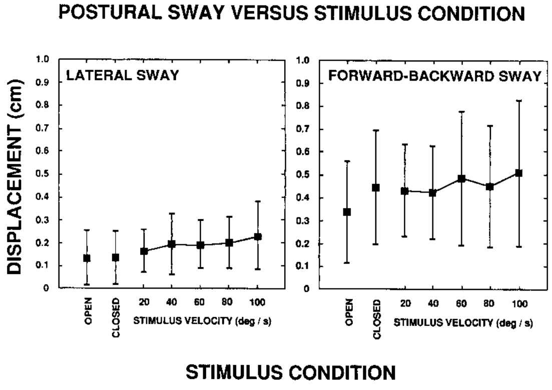

Figure 4 Mean displacement (±1 SD) for the subject group for lateral sway (left panel) and forward-backward sway (right panel) for each of the stimulus conditions listed on the abscissa.

visual cues on posture, subject age was correlated with lateral and forward-backward sway for eyes open, eyes closed, and for a representative stimulus condition (20°/sec to the left). Data for the individual subjects are plotted in Figure 5, with age on the abscissa and sway amplitude on the ordinate. Lateral sway is shown in the left column and forward-backward sway is shown in the right column. Sway was not correlated significantly with age for eyes open (top row) but was correlated with age in the forward-backward direction for eyes closed (middle row). Finally, with the HOKS stimulus present, increasing sway was correlated significantly with increasing age (bottom row).

The group of six subjects in the oldest age range of 60 to 75 years was compared with a group of six subjects in the age range of 30 to 45 years. Their group sway patterns are shown in Figure 6, in which the ellipses are the ±1 and ±2 standard deviations of the sway in the lateral (abscissa) and forward-backward (ordinate) directions, respectively. Each of the stimulus conditions is shown. Clearly, from this figure, the older subjects demonstrate increased variability in their sway patterns when compared to the younger group.

DISCUSSION

The results of the current study indicate that lateral and forward-backward sway amplitudes are significantly higher when subjects view a horizontal optokinetic pattern than when they view stationary patterns or have their eyes closed. The effect of HOKS was to increase the amplitude of sway, although the direction of the sway was variable. Some subjects drifted in the direction of the stimulus, and others drifted away from the stimulus. Most subjects, however, showed changes that were independent of stimulus direction. Thus, the directionality of postural sway induced by horizontal optokinetic patterns is more variable than the directionality induced by linear optokinetic patterns acting in the sagittal plane (Lestienne et al, 1977), or torsional patterns rotating about the line of sight (Dichgans et al, 1976). With these two other stimuli, the postural sway was reliably in the same direction as the image motion, that is, forward sway was produced with forward-moving stimuli and backward sway was produced with backward-moving stimuli.

The present stimulus-response curves showing the mean amount of sway for each stimulus velocity indicate that destabilization of posture by HOKS is only minimally dependent on the stimulus velocity. In contrast, anterior-posterior optokinetic stimuli appear to produce a tighter stimulus-response relationship. In a study of the effects of linear optokinetic motion, Lestienne et al (1977) showed that postural deviation increases with increasing stimulus velocities and saturates at about 75°/sec. A major reason for the relatively flat stimulus-response curve in the present study was the variability in the response amplitude and response direction among subjects, as indicated by the large population standard deviations in the stimulus-response curves.

Although there have been a number of previous studies using various forms of fixed, sway-referenced stimulus (programmed to move with the subject) or moving visual stimuli, none has employed HOKS, which makes cross-study comparisons difficult. Cross-study comparisons are also difficult because of differences in the type of sway measurements (amplitude vs velocity), visual stimuli (sway-referenced vs projected patterns), and posturography techniques (static vs dynamic). The present use of a fixed-platform to test eyes open versus eyes closed condition is a relatively standard clinical tool, generally referred to as the Romberg test. The average forward-backward sway amplitude, as expected (e.g., Leroux et al, 1973), was significantly greater than the lateral sway amplitude. This preponderance produces the approximate elliptical shape to the group sway patterns (see Figs. 3 and 6). Also consistent with previous studies on Romberg testing, the eyes closed condition produced significantly greater sway amplitude than the eyes open condition (e.g., Henriksson et al, 1967; Black, 1985). The eyes

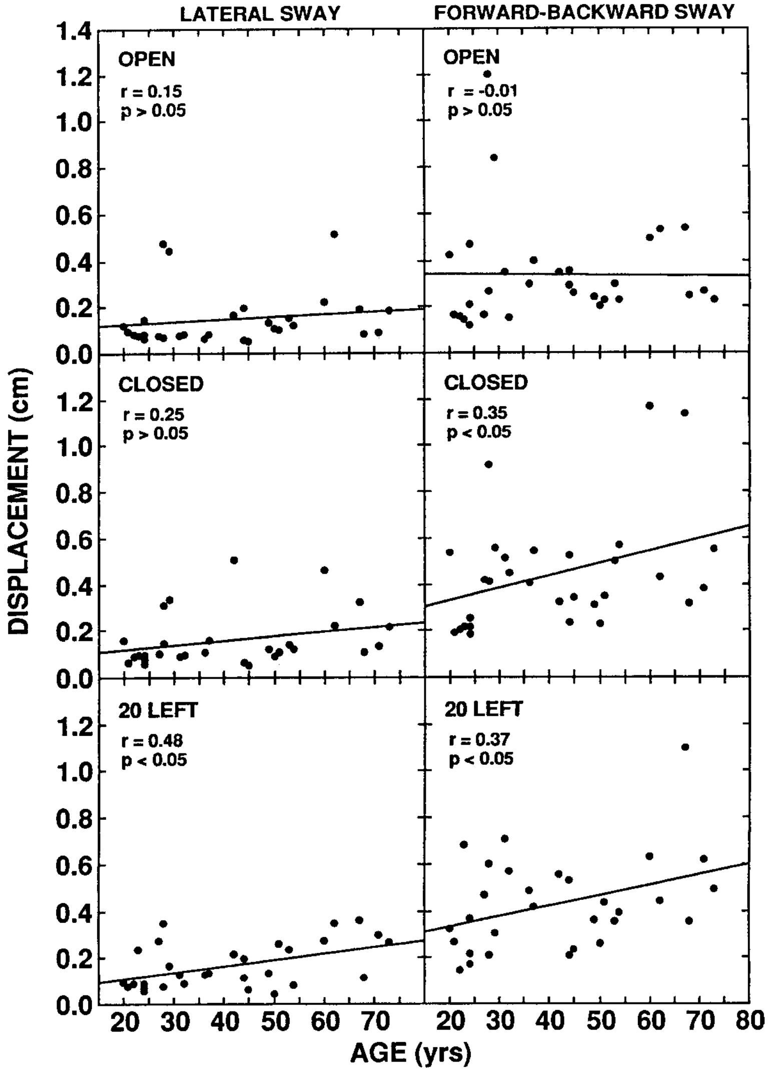

Figure 5 Scatter plots showing correlation of sway amplitude in the lateral (left column) and forward-backward directions (right column) for eyes open (top row), eyes closed (middle row), and stimuli 20°/sec to the left (bottom row) as a function of age.

closed condition had a greater effect on the amplitude of forward-backward sway than on the amplitude of lateral sway.

Many previous studies using fixed-platform posturography have demonstrated age-related increases in postural sway (e.g., Sheldon, 1963; Hasselkus and Shambes, 1975; Murray et al, 1975; Overstall et al, 1977; Dornan et al, 1978; Brocklehurst et al, 1982; Era and Heikkinen, 1985; Hytonen et al, 1993; Baloh et al, 1994). All agree that vision is important for stabilizing posture, as evidenced by comparing the eyes opened condition with the eyes closed condition. Additionally, the general finding is that subjects from mid-to-late teens (16–19 years) up to 60 years of age are highly comparable and show relatively stable posture, whereas individuals over 60 years of age show increasing postural instability characterized by (1) increased body sway amplitude (Sheldon, 1963; Stelmach et al, 1989; Pyykkö et al, 1990) or velocity (Baloh et al, 1994) during standing with and without platform perturbations; (2) impaired timing and coordination of antigravity muscles serving balance (Woollacott et al, 1986); (3) delayed response (increased latency) to onset of platform perturbations during standing (Woollacott et al, 1986); and (4) an increased number of falls on the balance platform during diminished or conflicting visual/somatosensory/vestibular cues (Woollacott et al, 1986; Pyykkö et al, 1990; Wolfson et al, 1992).

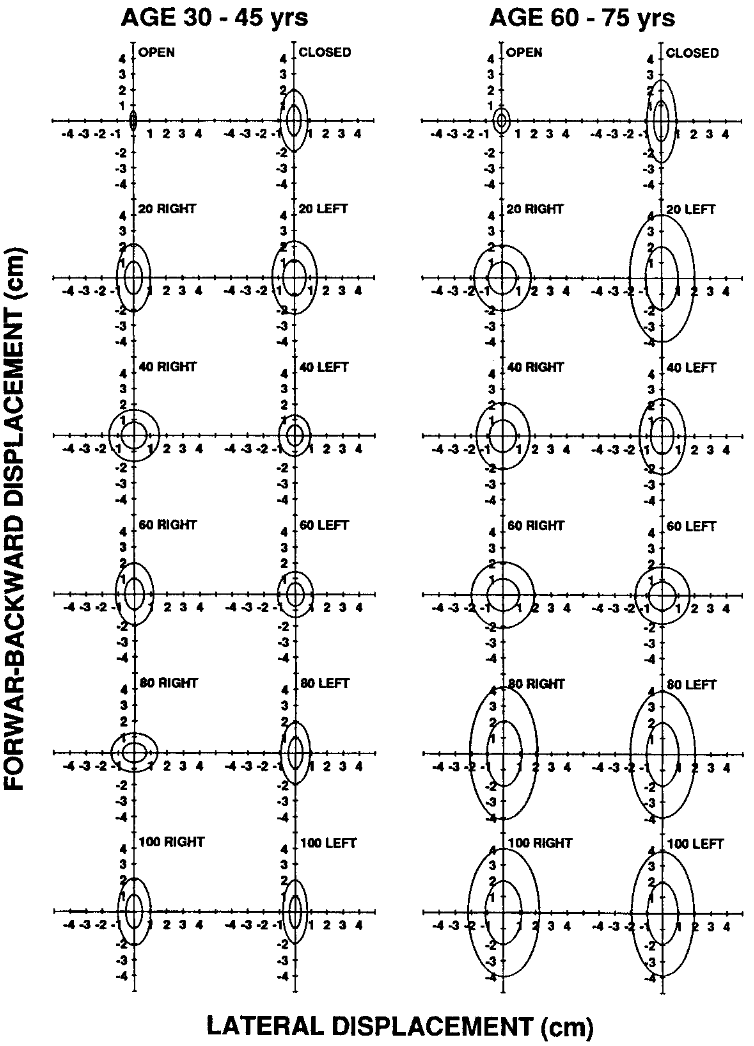

Figure 6 Mean lateral and forward-backward sway amplitudes ±2 SD for six younger (30–45 years) and six older (60–75 years) subjects.

In the present study, the sway amplitude was not correlated significantly with age for eyes open condition, but sway amplitude in the forward-backward direction was correlated with age for eyes closed condition. Additionally, with the optokinetic stimulus present, increasing sway was correlated significantly with increasing age. Thus, in the absence of vision (eyes closed conditions) or with conflicting visual cues (HOKS), the older subjects demonstrated increased variability in their sway patterns when compared to the younger group.

The mechanism for the age-related decline in posture is multifactorial and probably related to decrements with age in muscle strength (Larsson et al, 1979) and sensory function (visual, vestibular, and somatosensory) (Rosenhall and Rubin, 1975; Larsson et al, 1979; Horak et al, 1989). The elderly population also have a higher incidence of neurologic and general medical problems, which led Wolfson et al, (1992) to conclude that "...balance dysfunction in older individuals is produced primarily by age-related disease processes superimposed on the modest decline of balance." The elderly are at high risk of serious injury from falls (Tobis et al, 1981; Tinetti et al, 1986), but an increased sway velocity per se was not predictive of those who reported falls in the "normal" older population (Baloh et al, 1994). Other factors such as the psychological fear of falling (Maki et al, 1991) and complex motor parameters evaluated only by a broad, activity-based assessment of balance and gait are more predictive of risk of falling

(Tinetti, 1989; Topper et al, 1993). Although the functional importance of increased sway in the elderly is unclear, the present results confirm the need for age-appropriate norms for sway patterns.

To the extent that HOKS produces visual cues that conflict with vestibular and somatosensory mechanisms of postural control, HOKS could be likened to the sway referencing of the visual surround with the subject on a fixed platform, which is similar to condition 3 using dynamic-platform posturography (e.g., EquiTest system) (Nashner, 1982). In this context, early posturography studies found no significant differences between the sway of young adults and older subjects in conditions of eyes open, eyes closed, or with sway-referenced visual targets (i.e., EquiTest conditions 1, 2, and 3, respectively) (Woollacott et al, 1986; Peterka and Black, 1990). They did, however, demonstrate significant age-dependent balance decrements when visual and tactile-proprioceptive input were occluded or distorted (conditions 5 with eyes closed and a sway-referenced platform, and condition 6 with sway-referenced stimuli and platform) (Isaacs, 1985; Woollacott et al, 1986; Peterka and Black, 1990; Pyykkö et al, 1990). A more recent study by Wolfson et al (1992) compared the EquiTest results from a larger population (234 elderly subjects; 34 young controls) and found, as before, that older subjects did progressively worse with increasing difficulty of the test conditions, such as those involving sway referencing of the support platform with normal vision (condition 4) or with eyes closed (condition 5) and sway referencing of the visual surround and platform (condition 6). More importantly, as in the present study, the two age groups were equal when subjects stood on a fixed platform with eyes open (condition 1), but the sway of the elderly group was significantly greater than the sway of the young group for sensory conflict situations most comparable to those employed in the present report, that is, standing on a fixed platform with eyes closed (condition 2) and with eyes open with sway-referenced motion of the visual surround (condition 3). From these data, Wolfson et al (1992) concluded that the smaller sample sizes in earlier EquiTest studies may "...obscure real, albeit modest differences in balance..." with age.

The HOKS appears to provide an acceptable challenge to the postural mechanism in much the same way as sway referencing of the visual surround using the movable platform (condition 3). Both HOKS and sway referencing of the visual surround destabilize the subject by reducing the reliance on the visual mechanism for balance, theoretically allowing an examination of the vestibular and somatosensory mechanisms. Thus, the use of HOKS with fixed-platform posturography may provide a relatively cost-effective tool both for diagnosis of balance disorders and for the assessment of treatment or recovery from vestibular pathologies. This hypothesis is currently being tested in patients with known vestibular disorders.

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