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AGE-RELATED CHANGES IN HUMAN POSTURE CONTROL: SENSORY ORGANIZATION TESTS

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Postural control was measured in 214 human subjects ranging in age from 7 to 81 years. Sensory organization tests measured the magnitude of anterior-posterior body sway during six 21 s trials in which visual and somatosensory orientation cues were altered (by rotating the visual surround and support surface in proportion to the subject's sway) or vision eliminated (eyes closed) in various combinations. No age-related increase in postural sway was found for subjects standing on a fixed support surface with eyes open or closed. However, age-related increases in sway were found for conditions involving altered visual or somatosensory cues. Subjects older than about 55 years showed the largest sway increases. Subjects younger than about 15 years were also sensitive to alteration of sensory cues. On average, the older subjects were more affected by altered visual cues whereas younger subjects had more difficulty with altered somatosensory cues.

Key Words: posturography, vestibular, somatosensory, vision, equilibrium, development.

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INTRODUCTION

The automatic control of upright stance is an active sensorimotor process which must keep the body's center of gravity over the base of support (the feet). This process requires that deviations of body position from upright be sensed and processed to initiate motor commands which oppose the initial deviation and return the body to an upright position. The vestibular, somatosensory, and visual systems are the main sources of sensory information on body motion. However situations commonly arise in which information from the various sensory systems is absent or altered even in individuals with physiologically normal sensory function. For example, somatosensory cues from compliant surfaces can be misleading, and visual cues are eliminated when the eyes are closed. In order to maintain postural control under a variety of environmental conditions, motion information from sensory systems must be organized by the central nervous system so that inappropriate or inadequate sensory inputs can be ignored when necessary.

One method for testing postural control, which we will call sensory organization tests, involves postural responses which occur over tens of seconds to minutes when subjects attempt to stand quietly in various sensory conditions. The simplest sensory organization tests are the clinical standard Romberg tests, which characterize spontaneous postural sway when the subject's eyes are open and closed (1,2). The standard Romberg tests can be extended by altering somatosensory and/or visual motion cues. The alteration of somatosensory and/or visual cues by rotating the subject's visual field and/or support surface in equal proportion to the subject's own sway (3) tests the subject's ability to maintain equilibrium when various combinations of sensory cues are inappropriate or inadequate for orientation to earth vertical. Postural control under these altered conditions may be more difficult than when information is missing, as with eyes closed.

The increased incidence of falls in the older population (4) suggests that one or more of the components required for accurate postural control degenerates with age. Studies which have looked for differences in postural control between young and old adults have generally found them (1,5), including increased sway or falls in various sensory organization tests. In addition children show developmental changes in postural control which converge to adult patterns at about age 10 years (6,7). However, the limited scope of these studies with their small sample sizes and restricted test paradigms have not clarified either the time course or the mechanisms involved in the changes in use of sensory information for postural control with increasing age. We tested a putatively normal population with a wide age distribution using both postural motor coordination (8) and sensory organization tests. In addition, vestibulo-ocular (VOR) and optokinetic reflexes (OKR) were independently tested in the same individuals (9,10) for comparison to postural responses.

METHODS

Postural sway under various sensory conditions was measured in 214 human subjects (90 male and 124 female) aged 7 to 81 years. Ages were approximately uniformly distributed over the entire range. Details of subject selection are given in a previous paper (9). No subjects were excluded from the population based on any vestibular, optokinetic, or posture test results.

Body Sway Measurements. The anterior-posterior (AP) sway angle (θ_{ap}, see Figure 1) of each subject was recorded using a rod attached to a potentiometer. The potentiometer was mounted on a post next to the subject. The end of the rod rested in a V-shaped holder centered on the subject's back at hip level. A voltage proportional to the angular displacement of the potentiometer was recorded and later transformed using appropriate trigonometric conversions to θ_{ap}. A second potentiometer mounted at shoulder level recorded AP displacements at the shoulder in the last 65 subjects tested. A measure of hip angle (θ_h, Figure 1) was calculated from AP angles measured at the hip and shoulder. An approximate center-of-gravity AP sway angle (θ_{cg}) was calculated using the following formula:

$$\theta_{cg} = \tan^{-1}\left[\frac{0.860\sin\theta_{ap} + 0.242\sin(\theta_{ap}+\theta_h)}{0.860\cos\theta_{ap} + 0.242\cos(\theta_{ap}+\theta_h)}\right]$$

This formula was derived assuming the subjects had average body mass distribution and average proportional lengths of various body segments (11). To the extent that the various subjects deviated

from average body configurations, the measurement of θ_{cg} would be in error. This error was probably not more than 10% in this population. Sway angles were sampled at 50 Hz.

Test Conditions. Subjects stood with feet separated by about 20 cm on a movable support surface surrounded in front and on two sides by a visual surround which could also move. The visual surround was a box with randomly placed 2 cm black dots on a white surface. The average spacing between the dots was about 20 cm, and the distance from the subject to the box was about 50 cm. Support surface motion was controlled by a hydraulic position servo system which could produce toe up and toe down rotations about an axis collinear with the subject's ankle joints. Visual surround motion was controlled by a separate hydraulic servo system which rotated the box about the ankle joint axis. Subjects wore a harness attached to the ceiling to prevent injury in case of a fall. The harness did not impede body motions even during large amplitude sways.

Each subject performed six tests which provided a functional evaluation of the ability of the subject to effectively use vestibular, somatosensory, and visual information in the control of his upright posture (3). The subject's task was to maintain an upright stance for 21 seconds during each of the six conditions with as little postural sway as possible and without moving the feet. The test was rated a fall if the subject required the assistance of the harness to maintain upright stance or if a step was taken in order to prevent a fall into the harness.

Conditions 1 and 2 required the subject to stand on a stable surface for 21 seconds facing an earth-fixed visual field with eyes open and then with eyes closed. The remaining four conditions placed the subject in more demanding sensory environments. These environments were created by rotating the visual field and/or the support surface in equal proportion to θ_{ap}. For example, as the subject swayed forward, the visual field rotated forward about an axis through the ankle joint. Under this condition the normal relationship between body motion and retinal image motion is altered. This is referred to as sway-referenced vision as opposed to the earth-referenced vision in condition 1. The precise relation between the retina and the box depended on the movement patterns which subjects used during sway. The same technique was applied to the support surface by rotating it about the ankle joint in proportion to θ_{ap}. This sway-referenced support condition greatly reduced the change in ankle joint angle as the subject swayed forward and back and therefore altered the somatosensory cues contributing to postural control. The entire sensory test sequence included all six combinations of eyes closed, sway-referenced, and earth-referenced vision and support surface conditions given in Table 1.

Body Sway Analysis. Sway data were summarized by two measures: average rectified sway (ARS) and peak-to-peak sway. Both measures were calculated over the final 20 seconds of the 21 second trials (the visual field and support surface were always earth-referenced during the first second of each trial). For ARS calculations, sway data was normalized by subtracting the average sway values

recorded in the first second from the entire sway record. Sway data samples less than zero were then rectified (inverted), and then this new sway trace was averaged over the final 20 s. ARS often did not reflect how close a given individual was to a fall since, for example, a subject who leaned forward by a few degrees and stayed in that position throughout the remainder of the trial could score the same as a subject who oscillated back and forth during the trial with the peak of the oscillations close to the threshold of a fall. The peak-to-peak sway measure was more indicative of the closeness of sway to fall thresholds.

Movement Strategies. Subjects typically use one of two body motion strategies to maintain upright stance without moving the feet (12). A hip strategy consists of θ_h and θ_{ap} motions which are out of phase. Subjects can be forced to use a hip strategy by asking them to stand on a narrow beam which limits the amount of torque that can be exerted at the ankle. A pure ankle strategy occurs when all motion is about the ankle joint (AP sway angles measured at the hip and shoulder are equal and θ_h is zero). A less pure ankle strategy occurs when there is some motion about the hip joint, but θ_{ap} and θ_h are in phase with each other. In order to quantify the type of body motion, a strategy measure was calculated according to the following formula:

$$\text{strategy score} = [\overline{(\theta_{ap}-\overline{\theta_{ap}})(\theta_h-\overline{\theta_h})}]$$

where the bars over the various terms indicate the average values over time. In words, the strategy score is the average product of zero-meaned θ_{ap} and θ_h calculated over the duration of the trial.

The strategy score is negative if θ_h and θ_{ap} are out of phase indicating that the trunk and legs move in opposite directions, positive if they are in phase and the body moves like a whip, and zero when the body moves like an inverted pendulum with no bending at the waist. Since this measure is an average over the entire trial, changes in strategy during the trial would not be correctly characterized by this single measure. In practice, this was not a problem since this putatively normal population did not show marked strategy changes within trials.

Visualization of Trends. In order to visualize trends in scatterplots, a robust locally weighted regression analysis (lowess fit) was used to smooth the scatterplots (13). This smoothing is similar to a moving average filter, but is less sensitive to outlying points and allows variable amounts of smoothing. A lowess smoothing parameter of 0.5 and iteration parameter of 2 were used on all data sets.

RESULTS

As visual and somatosensory sensory information were removed and/or altered during the various sensory test conditions, subjects became less stable (Table 2) and falls became more likely. Most subjects did not fall in any condition, but their sway amplitudes increased as they were deprived of orientationally accurate sensory reference information. Some subjects, particularly older subjects, did fall. The pattern of falls was

not random, but rather was restricted to certain conditions and combinations of conditions.

Sway Responses. All subjects were very stable with eyes open on a stable surface, and with eyes closed on a stable surface (conditions 1 and 2, see Figure 2). No subjects fell in conditions 1 or 2. Postural sway increased in condition 3 when the visual surround rotation was referenced to the subject's sway. The median of the condition 3 sway distribution in Figure 2 was only about one degree higher than condition 2 indicating that most subjects had only slightly more difficulty controlling their posture under the sway-referenced vision condition than with eyes closed. However, the condition 3 distribution is highly skewed toward larger sway amplitudes indicating that a significant fraction of the population had difficulty maintaining their upright posture when visual orientation information was present but sway-referenced. In addition, 30 of 214 subjects (14.0%) fell on the condition 3.

Condition 4 provided earth-referenced visual cues but sway-referenced somatosensory cues. This distribution was skewed toward larger sway angles in a similar manner to the condition 3 distribution. However subjects, on average, were more stable in condition 4 than in condition 3 since only three subjects out of 214 (1.4%) fell in condition 4.

Visual cues in condition 5 were absent (eyes closed) and somatosensory cues were altered by the sway-referenced support surface. This condition presumably forced a greater reliance on vestibular cues for postural control. Average sway was larger than on any of the previous conditions and was also skewed toward larger values. Twenty eight of 214 subjects (13.1%) fell on this condition.

Condition 6 was the most difficult of the six conditions. Under this condition, both the visual surround and the support surface were sway-referenced. As with condition 5, this condition forced a greater reliance on vestibular cues for postural control. However the presence of altered visual orientation cues in condition 6 (as opposed to absent vision in condition 5) apparently increased the difficulty of the task. The average sway for subjects who completed condition 6 was larger than on any other conditions, and 70 of 214 subjects (32.7%) fell.

Movement Strategy. The use of an ankle strategy was by far the most common mode of postural sway in these subjects. The 65 subjects whose body motions were measured at both the hip and shoulder were the older portion of the entire population with a mean age of 56.2 years (12.5 s.d., range 27 to 81 years). Their mean strategy scores were close to zero and the variances of the scores were small on all six conditions (Table 3). This was confirmed by plotting peak-to-peak θ_{cg} versus peak-to-peak θ_{ap}. For pure hip strategies θ_{cg} and θ_{ap} should be relatively unrelated whereas a pure ankle strategy would have equal θ_{cg} and θ_{ap}, and correlations close to 1.0. Correlation coefficients between peak-to-peak θ_{cg} and θ_{ap} data ranged from 0.93 to 0.98 for the six conditions. Data points were tightly clustered around the line of equal θ_{cg} and θ_{ap}.

Fall Patterns. Table 4 summarizes the data on subjects who fell during one or more of the six conditions. Falls during sensory test conditions were not random occurrences, but rather were associated with the inability of some subjects to obtain and/or coordinate the sensory information available for the control of posture. Consider subjects who fell on two of the four conditions which presented them with sensory conflict situations. There are six possible combinations of paired falls within the grouping of the four more difficult conditions. If paired falls occurred randomly they would be evenly distributed across the six possible combinations. This was clearly not the case since four of the six combinations of paired falls either were not observed or were rare. That is, no subjects fell on 3-4 and 4-5 paired conditions, and only two subjects fell on the 3-5 and one on the 4-6 combination of conditions. Therefore paired falls were primarily limited to only two of the six possible paired combinations with 12 subjects falling on 5-6 conditions, and 15 falling on 3-6 conditions.

The six subjects who fell on three conditions were also not randomly distributed among the 4 possible combinations. Rather all six subjects fell on the same set of three conditions which was the 3-5-6 combination. This combination combines the features of the two most common paired condition falls, 3-6 and 5-6 as reported previously (3,14,15). Most of these subjects were older (aged 45, 48, 60, 66, 69, and 70 years).

There was a clear learning effect when sensory tests were repeated immediately following a fall. Thirty-three of the 131 first test falls were repeated. Only 6 of the 33 subjects (18%) fell on the repeated test. The number of repeat test falls for the four sensory conditions where falls occurred were 1 of 8 for condition 3, 0 of 2 for condition 4, 2 of 8 for condition 5, and 3 of 15 for condition 6.

Age-Related Changes. Generally, the number of falls increased with increasing age. These results are summarized in Table 5. The incidence of falls was lowest for subjects aged 20 to 40 years. Subjects ages 13 to 19 years had a high incidence of single condition falls (33%) but low multiple condition falls (11%). With the exception of condition 3, peak-to-peak sway was also higher in the younger as compared to 20-40 year olds (Figure 3). This difference between subjects was most evident in sensory conditions 4,5, and 6 suggesting that younger subjects were sensitive to alterations in somatosensory cues. The occurrence of single condition falls increased rapidly for subjects older than about 45 years, although the incidence of multiple condition falls remained quite stable through the 50's before showing an increase in the 60 to 70 year olds. A possible anomalous result was obtained in the over 70 age group for multiple falls. Their multiple fall rate was less than the fall rate for 60 to 70 year old subjects and approximately the same as for subjects 40-60 years. This may be a result of the small sample size of the over 70 age group, an exceptionally healthy condition of this group, or an exceptionally high fall rate for subjects in the 60-70 age group.

Surprisingly, the increased incidence of falls in older subjects in conditions 3 and 5 was not accompanied by a trend toward increasing peak-to-peak θ_{ap} among non-fallers (Figure 3). This is in contrast to condition 6 where both sway and falls increased with age. Since it is not possible to maintain stance with the body's center of gravity outside of its base of support, the theoretical limit of peak-to-peak sway is dependent on foot size and body mass distribution. Since most subjects have a 10° to 12° range of stable AP sway, and peak-to-peak θ_{ap} average 3° and 5.3° for conditions 3 and 5, respectively, it seems that there was some room for the non-falling population to shift toward larger sways in conditions 3 and 5, and that this shift would be accompanied by an increased number of falls. Although the falls increased, the peak-to-peak sway amplitude of non-fallers did not.

DISCUSSION

Age-related changes in postural control performance were not present in subjects older than about 15 years when they were tested under "normal" operating conditions during sensory test conditions 1 and 2. That is, when subjects stood on an earth-fixed support surface with eyes open or closed, their sway was small and the oldest subjects performed as well as the younger ones. Since the first two sensory tests are characterized by the presence of multiple sensory system inputs which converge and cooperate in the generation of appropriate postural control responses, it is apparent that subjects are well adapted to an environment without conflicting sensory cues. However it is also clear from the other sensory test conditions that the "parts" which make up the "whole" of postural control are not equally functional in all individuals. The prevalence of falls and the wide range of postural sway amplitudes in sensory test conditions 3 through 6 demonstrate this functional inequality.

Analysis of Fall Patterns. The pattern of falls among subjects who fell in two or more conditions can be logically associated with specific types of peripheral sensory or sensory integration problems. The 15 subjects who fell on the 3-6 conditions were highly sensitive to visual cues which were altered by sway-referencing the visual field. These subjects behaved paradoxically. The fact that they did not fall in condition 5 indicates that they were presumably able to use vestibular cues to properly maintain stable stance since no visual and only altered somatosensory cues were otherwise available. However when visual cues were present in 3 and 6, they chose to ignore earth-referenced vestibular and somatosensory cues in condition 3 and earth-referenced vestibular cues in condition 6 in favor of the altered visual reference. Although the mechanisms which cause and sustain this preference for a visual reference are not known, it seems likely to be a sensory selection problem rather than a motor coordination problem (3).

The second most common paired falls occurred in conditions 5 and 6 which force subjects to rely primarily on their vestibular systems for postural control since somatosensory and/or visual cues are either absent or altered. This pattern of falls is found frequently in subjects who have peripheral vestibular deficits (3,16). A subject with total bilateral peripheral loss of vestibular function is the extreme form of vestibular deficiency. Patients with bilateral loss as judged from absent caloric and rotation responses invariably fall in conditions 5 and 6 (3,15).

Falls in both conditions 5 and 6 could theoretically also arise from central mechanisms. The central postural control mechanisms perform complex tasks which include both the generation of the correct motor commands to the muscles and the selection of an appropriate orientation reference based on information from several sensory systems which at times may be conflicting. It is possible that peripheral vestibular signals may be normal, but the central mechanisms which make use of this information are faulty. The "fault" may have more than one source. For example, the processing of the sensory information may simply be too slow, in which case the appropriate motor commands never arrive at the muscles or arrive too late to prevent a fall. Alternatively, the central processing which must deal with conflicting sensory information may produce inappropriate responses based on the available sensory signals. These inappropriate responses could drive the system into instability with a resulting fall. A possible example of this may be learning disabled children with normal VOR function who often fall in conditions 5 and 6 (16,17). Finally, motor coordination deficits and muscle weakness could also play a role in 5-6 fallers since these conditions evoke relatively large sway amplitudes in most subjects.

Developmental Postural Changes in Children. Subjects aged 7 to 15 years showed increased peak-to-peak sway amplitudes on all sensory test conditions except condition 3. This is consistent with previous results in children aged 2 to 15 years (7) and 1 1/2 to 10 years (6,18). Both studies show increased AP sway in sensory condition 1 in the youngest children with a convergence toward adult performance at about age 8 to 10 years. One of these studies (6) also used sway-referenced tests identical to conditions 3 through 6 and again found the poorest performance in the youngest children but with incomplete convergence to adult values by age 10 years for all four conditions. Sway-referenced vision (condition 3) results presented here differ from this previous study (6) since the average peak-to-peak sway of the youngest subjects did not differ from adult sway values. However condition 4, 5, and 6 results presented here agree with the previous findings (6) and extend those results to show that adult performance is not fully attained until about age 20 years under these sensory conditions.

In all conditions with altered somatosensory inputs (conditions 4, 5, and 6), subjects younger than about 20 years showed more sway, on average, than middle-aged adults. This suggests that younger subjects rely more heavily on somatosensory cues than do middle-aged and many older adults even when accurate, earth-referenced visual and vestibular cues are available. Many children had sway results compatible with adult sways, while others swayed considerably more than middle-aged adults. This wider range of postural sway for children compared to adults may be associated with differing rates of development of postural control abilities in different children.

Postural Control Changes in the Elderly. Sensory test results showed that most falls occurred in subjects older than about 50 years. In condition 6, the increased number of falls was accompanied by increased sway among non-fallers. However older non-fallers performed about the same as younger subjects in conditions 3 and 5 even though there were increased falls in the elderly group.

The finding that there is no general increase in sway with age in conditions 3 and 5, but there is an increase in falls suggests that the elderly fallers form one or more subgroups within the elderly population. These elderly fallers apparently either lack information required for postural control or have adopted postural control schemes which are distinct from the remainder of the population and which place them at increased risk for falls in particular sensory environments. However when redundant sensory cues are available (conditions 1 and 2) and sway amplitudes are greatly reduced, these fallers cannot be distinguished from the remainder of the population.

A simple explanation for these results could be that the average body alignment of these subjects places their center of gravity near a stability limit so that relatively small increases in sway produce a fall (19). If this explanation were correct, then subjects who fell on condition 3 should also fall on other conditions (4, 5, and 6) which increased their sway above the levels on conditions 1 and 2. In general, this pattern of falls did not occur.

Impairments in either sensory system inputs, central nervous system processing, or motor system output could potentially initiate or facilitate the development of postural control schemes which are generally adaptive, judging from the good performance on conditions 1 and 2, but which are inadequate or nonadaptive in other sensory environments. These impairments might include reduced or altered sensory information, reduced, delayed or absent motor responses, or incorrect patterns of muscle activation resulting in inappropriate and non-compensatory responses. Comparisons of sensory organization test results with postural motor coordination results, and VOR and OKR responses gives some insight into the factors which contribute to the age-related decline in postural control in this putatively normal population.

Comparison with Motor Coordination Tests. Neither the amplitude nor timing of postural motor responses to forward and backward platform translations (8) were correlated with the level of sway during sensory tests. Also, the motor response parameters of subjects who fell during sensory tests were not distinguishable from non-fallers. This would tend to support a hypothesis that sensory system deficits and/or inappropriate central nervous system organization of sensory information are responsible for the increased likelihood of falls independent of motor coordination problems.

However the amplitude of platform translations used in the motor coordination tests did not produce body sways near fall

thresholds, and thus did not require subjects to exert maximal muscular responses. A larger perturbation might have revealed relative muscle weaknesses as well as response timing problems within the subpopulation of fallers. Muscular strength relative to body mass and precise timing of responses might contribute to falls in conditions 5 and 6 where the average level of sway is closer to fall thresholds than in the other four conditions.

Comparison with VOR and OKR Function. There was evidence of VOR and OKR abnormalities in some subjects who fell on two or more conditions. Of the three subjects with the shortest VOR time constants (9,10) one was a 5-6 faller and two were 3-5-6 fallers. The 5-6 faller with a short VOR time constant also had a significant partial unilateral loss of vestibular function on the caloric test. The subject who had the largest OKR time delay (average delay to the onset of eye movement following visual field movement) of any subject tested (268 ms) was also a 5-6 faller. Among subjects over 50 years, two of the three subjects with the lowest OKR gain constants were 3-5-6 fallers, and the other was a 3-6 faller. Finally, the two older subjects with the largest OKR time constants, indicating decreased sensitivity to higher frequency visual field motions, were both 3-6 fallers.

With the exceptions mentioned above, VOR and OKR parameters of most subjects who fell on two or more conditions were not distinguishable from those of subjects who did not fall or fell on only one condition. A comparison of the overall incidence of extreme VOR and OKR parameters (above 97.5 or below 2.5 percentile points) among subjects who fell in two or more conditions with the incidence of extreme parameters among subjects who fell in no more than one condition showed no significant difference between the groups.

There are at least three possible explanations for the weak correlation between VOR and OKR abnormalities and poor postural control. First, our VOR tests measured primarily horizontal canal function whereas head movements during postural sway primarily stimulate vertical canals and otoliths. To the extent that a vestibular abnormality may only affect one or a limited number of the vestibular receptors in each ear, horizontal VOR and posture results could differ. Second, our OKR tests used horizontal plane visual motion stimuli while the visual system contribution to postural control during sensory tests is associated with the detection of pitch plane movement and with depth cues from the disparity of images on the retina of each eye. There might be a higher correlation of abnormal pitch plane OKR and vergence control responses with postural control deficits than with horizontal plane OKR. Third, differences between our VOR and posture test results could relate to central nervous system problems in the organization of sensory system interactions. Abnormalities in the central nervous system pathways involved in the organization of posture might be specific to the postural control system and therefore would not effect VOR responses.

In conclusion, it is apparent that some equilibrium control deficits exist in a putatively normal population. These deficits are more common in children and subjects older than about 50 years, but are normally masked by the presence of redundant sources of sensory orientation cues. In susceptible subjects, the loss of redundant information can unmask their deficit and cause a sudden loss of postural control.

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Table 1 - Sensory organization test conditions.

	TEST CONDITIONS			SENSORY INFORMATION		
Condition	Sensory Conflict	Visual Reference	Support Surface Reference	Earth-referenced (Accurate)	Sway-referenced (Altered)	Absent
1	no	earth	earth	visual, vestibular, somatosensory	-	-
2	no	eyes closed	earth	vestibular, somatosensory	-	visual
3	yes	sway	earth	vestibular, somatosensory	visual	-
4	yes	earth	sway	vestibular, visual	somatosensory	-
5	yes	eyes closed	sway	vestibular	somatosensory	visual
6	yes	sway	sway	vestibular	somatosensory, visual	-

Table 2 - AP sway measures on completed sensory test conditions.

All values are in degrees (mean ± 1 s.d.).

Condition	N	Average Rectified θ_{ap} Sway	Peak-to-Peak θ_{ap} Sway
1	214	0.26 ± 0.21	0.82 ± 0.44
2	214	0.42 ± 0.33	1.25 ± 0.58
3	189	0.68 ± 0.57	2.78 ± 2.00
4	213	0.74 ± 0.49	2.95 ± 1.97
5	192	1.20 ± 0.48	5.54 ± 2.23
6	155	1.32 ± 0.53	5.75 ± 2.12

Table 3 - AP sway measures for subjects with sway measured at shoulder and hip, and who completed the sensory tests. All values are in degrees (mean ± 1 s.d.).

Condition	N	Peak-to-Peak θ_{ap} Sway	Peak-to-Peak θ_{cg} Sway	Peak-to-Peak θ_h Sway	Strategy Score
1	65	0.75 ± 0.32	0.72 ± 0.34	1.41 ± 0.56	-0.01 ± 0.05
2	65	1.21 ± 0.54	1.33 ± 0.59	1.78 ± 0.81	0.04 ± 0.07
3	46	3.01 ± 2.16	3.28 ± 2.18	3.56 ± 2.09	0.24 ± 0.56
4	65	2.41 ± 1.20	2.22 ± 1.15	2.96 ± 2.10	-0.14 ± 0.46
5	56	5.31 ± 2.45	5.50 ± 2.37	5.53 ± 3.44	0.21 ± 1.38
6	35	5.27 ± 1.86	5.58 ± 2.12	6.08 ± 4.91	0.49 ± 0.95

Table 4 - Falls on sensory test conditions.

	Condition	# Subjects	% of Total N = 214
1 Fall			
	6	36	16.8%
	5	8	3.7%
	3	7	3.3%
	4	2	0.9%
		53	24.8%
2 Falls			
	3,6	15	7.0%
	5,6	12	5.6%
	3,5	2	0.9%
	4,6	1	0.5%
		30	14.0%
3 Falls			
	3,5,6	6	2.8%
1, 2, or 3 Falls		89	41.6%

Table 5 - Sensory test falls sorted by subject age.

Age Group	#Subjects	Single Falls N	Single Falls %	Multiple Falls N	Multiple Falls %	Total Falls N	Total Falls %
7 - 12	21	3	14.3%	2	9.5%	5	23.8%
13 - 19	27	9	33.3%	3	11.1%	12	44.4%
20 - 29	28	4	14.3%	2	7.1%	6	21.4%
30 - 39	32	4	12.5%	2	6.3%	6	18.8%
40 - 49	32	9	28.1%	6	18.8%	15	46.9%
50 - 59	26	8	30.8%	5	19.2%	13	50.0%
60 - 69	35	10	28.6%	14	40.0%	24	68.6%
70 and over	13	6	46.2%	2	15.2%	8	61.5%
Total	214	53	24.8%	36	16.8%	89	41.6%

FIGURE LEGENDS

Figure 1. Schematic representation of posture test apparatus and definition of body angles for AP sway in a sagittal plane. The interior of the visual field was white with randomly placed black dots. To the right, body sway angles recorded from one subject during a condition 6 sensory organization test are shown along with traces indicating the sway-referenced motion of the visual field, θ_v, and the support surface platform, θ_p.

Figure 2. Histograms of peak-to-peak θ_{ap} under the six different sensory test conditions. Gray bars to the right of each histogram indicate the number of subjects who fell in that condition. One subject in condition 3, and 5 subjects in condition 5 had sways greater than 12° but did not fall, and are not included in those respective histograms.

Figure 3. Peak-to-peak θ_{ap} as a function of age for the six sensory test conditions. Solid dots at the top of each graph indicate subjects who fell in that condition. Solid lines are lowess fits to the data for subjects who did not fall during the test.

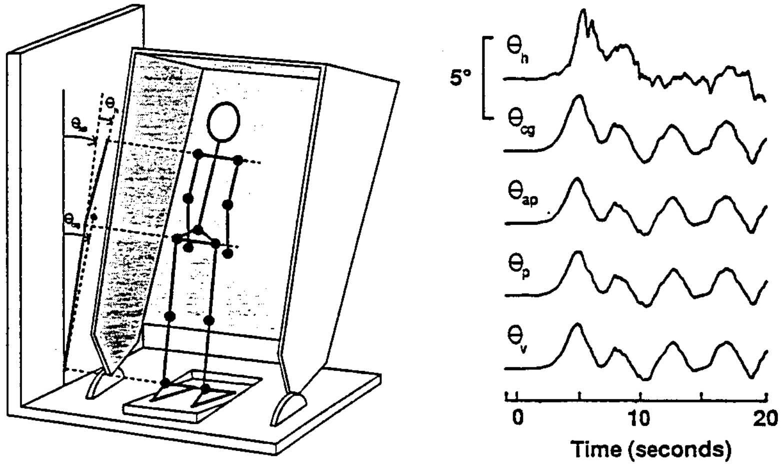

Figure 1

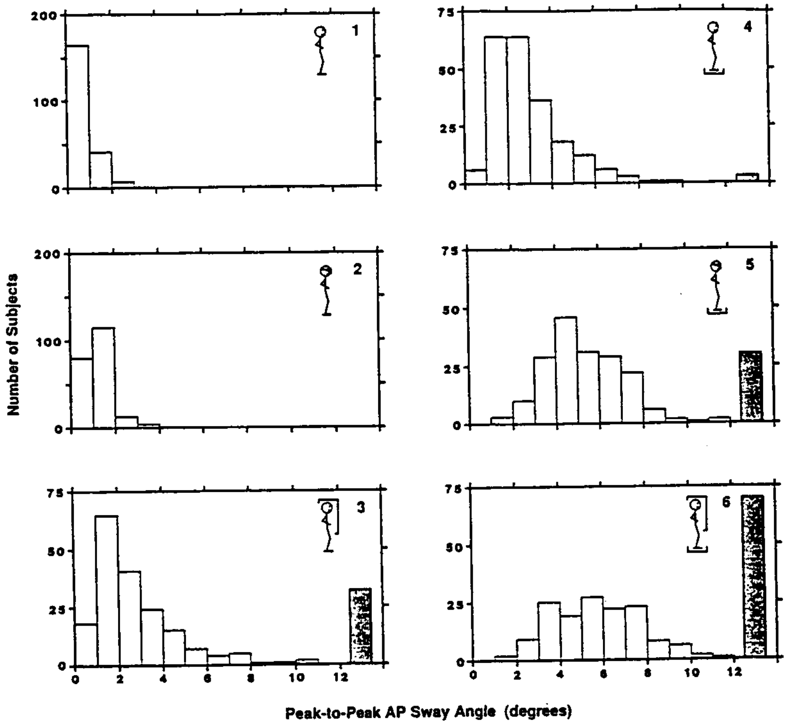

Figure 2

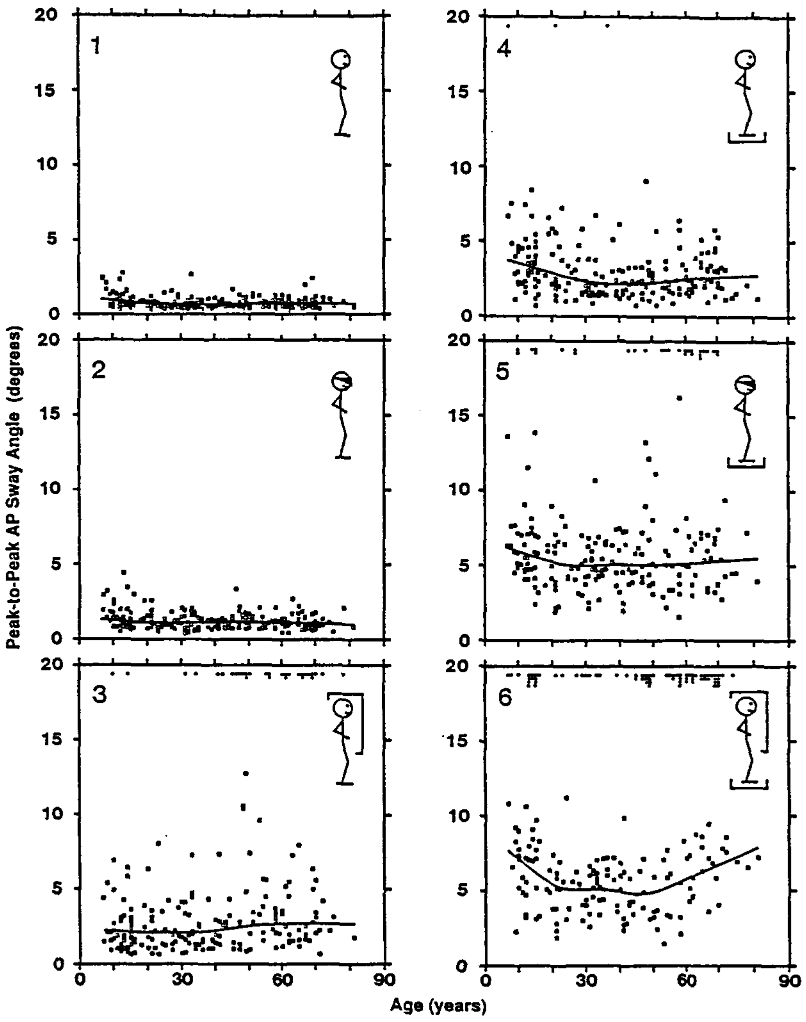1
2
3
4
5
6
Peak-to-Peak AP Sway Angle (degrees)
0
5
10
15
20
Age (years)
0
30
60
90

Figure 3