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ABERRATIONS IN POSTURAL CONTROL, VIBRATION SENSATION AND SOME VESTIBULAR FINDINGS IN HEALTHY 64–92-YEAR-OLD SUBJECTS

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ABSTRACT. To assess changes in postural control among healthy elderly and to correlate with suspected age-related events, 33 women and 16 men were studied. Postural control was evaluated by vibration-induced body sway, measured on a force platform, and vibration sensation was tested with a tuning fork. Occurrence of spontaneous gaze and head-shake-induced nystagmus was observed with infrared charged couple device (CCD) cameras and the subjects' medical history was reviewed.

Vibration perception was the major determinant for the magnitude of body sway. Although these senior citizens considered themselves healthy, they had a variety of ailments in their medical history, diminished vibration sensation and a high prevalence of vestibular asymmetry. Age *per se* was not a determinant factor in any of the findings. The study suggests that interest should also be directed to the status of sensation in the legs and vestibular asymmetry when assessing balance function in the elderly. Furthermore, the term "age concomitant" may be more appropriate than "age dependent" when describing decrements of functions such as postural control in elderly subjects.

Key words: elderly, equilibrium, posture, vestibular, vibration.

INTRODUCTION

Postural imbalance is considered an important predisposing factor to falls in the elderly. Although the cause of falls can be multifactoral (26), postural imbalance is considered an important element and many of the elderly fall due to disturbances that would not lead to a fall in a person with intact balance control (29).

The consequences of falls can lead to minor injuries, soft-tissue damage or fractures, fear of falling, immobility and diminished quality of life for the individual. For the community, the rising costs might be an economical burden. The serious results of falls and the increasing number of elderly have led to increased research into balance control in the elderly population, fallers, patients and the frail but very little research on the healthy elderly. The reason might be that it can be difficult to decide who is, and who is not, healthy, especially among the elderly where there is a general physical wear and tear accompanying age.

Posturographic recordings of the forces actuated by a subject's feet on the supporting surface can objectively measure postural performance (1). To enhance the sensitivity of the posturography, recordings should be made during perturbation, i.e. when challenging postural control (7). Exposing muscles to vibration, thus creating erraneous proprioceptive impulses, has been used to evaluate postural control in the elderly (5), in patients with different disorders (15) and the effect of treatments (10). Other types of perturbations have been used, such as: moving the support surface (16, 30); exposing the subjects to a visual disturbance (30); standing on foam (5); or anaesthetizing the feet (14).

Human postural control is a complex biological function, involving coordinated motor function working under biomechanical constraints and depending on sufficient sensory feedback of visual, vestibular, proprioceptive and mechano-receptive information as well as cognitive and central nervous control (8). With ageing there is a decline in physical capacity, often without any specific diagnoses (25). Diminished proprioception (23) or/and vibration perception (24, 28) has been reported with normal ageing.

The aim of this study was to assess changes in postural control among the healthy elderly and to correlate these changes with suspected age-related events.

MATERIAL AND METHODS

Subjects

This study included 49 subjects (33 women and 16 men) recruited as volunteers from two senior citizens organizations on the grounds that they considered themselves in good health. Their age ranged from 64 to 92 years (mean age 74.9 years). They were all capable of full personal activities of daily living (ADL) and lived independently in the community without any external assistance. None of them used a walking-aid.

They had no current or historical diagnosis of cerebral vascular insult (CVI), showed no overt clinical vestibular or neurological signs and had no prominent complaints of dizziness, light-headedness or vertigo. The subjects were asked to abstain from alcohol and sedatives during the 24-hour period preceding the tests.

The subjects arrived at the Department of Otorhinolaryngology, Lund University Hospital, where the testing was conducted, by public transport, in their own car or on a bicycle. At attendance, they signed an informed consent and answered a questionnaire about their health, medication and level of physical activity. The subjects were all active individuals with a medium activity level of 4 (range 3–5) on a six-grade scale (17). Occurrence of spontaneous gaze nystagmus or nystagmus after head shaking (~2 Hz/15 seconds) was tested with goggles equipped with infrared charged couple device (CCD) cameras (27). In accordance with the findings from medical history and the CCD camera inspection, the subjects were divided into three "Health" groups according to health status: individuals with no medical history or nystagmus were placed in a "Healthy" group; those with a history of medical problems but no nystagmus reaction were placed in a "Medical" group; and subjects found to have head shake or positional nystagmus were placed in a "Nystagmus" group.

Furthermore, the subjects were tested for peripheral neuropathy by testing sharp and light touch sensation on the legs and feet, and vibration sensation was tested with a tuning fork (256 Hz) at the base of the first metatarsal bone, the medial malleolus and the medial surface of the tibia. The subjects were arranged into three groups in accordance with their ability to detect the vibration:

—"Sensation group 1": vibration detected at the metatarsal bone, medial malleolus and tibia
—"Sensation group 2": vibration detected at the medial malleolus and tibia
—"Sensation group 3": vibration detected at the tibia

Postural measurements

Apparatus. To test the postural control the subjects were perturbed by vibration, simultanously applied to the left and right gastrocnemius muscle. The vibration was either of "high" intensity (850 mW, amplitude 1.0 mm) or "low" intensity (120 mW, amplitude 0.4 mm) to elicit stronger or weaker perturbations, respectively. Also, a high-intensity vibration was applied to the paravertebral muscles of the neck. The vibrators (constructed as cylinders of 0.06 m in length and 0.01 m in diameter) were attached to the belly of the calf muscles by elastic straps and the neck muscles by a collar, care being taken to avoid contact with the occipital bone. Forces and torques actuated by the feet were recorded with six degrees of freedom by a force platform developed at the Department of Solid Mechanics, Lund Institute of Technology. Data were sampled at 10 Hz by a computer (HP Vectra DX2/66) equipped with an AD converter (National Instruments AT-MIO-16L-9).

Procedure. The subjects stood erect but relaxed on the force platform with the heels approximately 4 cm apart and feet at a 30° angle, arms crossed over the chest and eyes either closed or focused on a mark on the wall at a distance of 1.25 m. As a precaution the platform was positioned 40 cm from another wall and the operator stood behind the subjects during testing. Prior to the tests the subjects were informed about the force platform and the effect of the vibration.

To ensure homogeneity of the recordings with regard to the subjects'' experience level before each test, the test order was fixed. Six different tests were conducted in the following order:

—High-intensity vibration to calf muscles, with eyes closed and open
—High-intensity vibration to neck muscles, with eyes closed and open
—Low-intensity vibration to calf muscles, with eyes closed and open

Between the testing with eyes closed and eyes open, the subjects stepped off the platform and walked around for 3 minutes. After completion of tests 2 and 4 the subjects had a rest for about 15 minutes.

Each test started with a recording of a quiet stance for 30 seconds followed by vibration at 60 Hz turned on or off according to a pseudorandom binary sequence (PRBS) schedule with pulses between 0.8 and 6.4 seconds for 205 seconds. To reduce interference by environmental noise, the subjects were provided with headphones relaying 2nd and 3rd movements of the Haffner serenade by Mozart. Two subjects did not complete all the tests. One could not cope with high-intensity vibration with eyes closed either to the calf or the neck muscles and demonstrated a tendency to fall. The other felt uncomfortable during high-intensity vibration to the neck and the test had to be terminated before its completion.

Data analysis and statistics. The torque variance ($M = (\mathrm{Nm})^2$) representing the body sway during quiet stance in the anterior-posterior and lateral directions was calculated for each subject, together with the torque variance for the first 100 seconds of vibration (period 1) and the following 100 seconds (period 2), each test thus having six components. Only the first quiet stance period with eyes closed (test 1) and eyes open (test 2) was used for the analysis.

By using regression, the torque variances were found to be dependent on the height and squared weight. Therefore the torque variance was normalized by dividing the values with the subjects' height (h) and squared weight (m), using the formula:

Normalized torque (M_{norm}) $= M/(hm^2)$

The subjects' clinical data were examined and they were divided into groups according to age and the previously described variables "Health" and "Sensation".

Difference in age between the "Health" and "Sensation" groups was calculated by one-way Anova.

Multiple regression (standard least squares) was used to determine the significance of age, gender, "Health" and "Sensation" on the body sway.

Difference of body sway between the age groups, "Health" groups and "Sensation" groups was evaluated by using the Wilcoxon/Kruskal-Wallis test, as the distribution of values within the groups tended to be skewed.

In all the analysis JMP (version 3.0, SAS Institute Inc., USA) was used and $p \leq 0.05$ was considered to be statistically significant.

RESULTS

Subjects grouped by health status

In the "Healthy" group were 16 subjects (1 man and 15 women) aged between 66 and 88 years (mean 75.9

Table I. *Frequency of different ailments in the "Medical" (n = 15) and "Nystagmus" (n = 18) groups*

Medical history/findings	Group "Med" (*n*)	"Nyst" (*n*)
Surgery for lumbal discus prolapse	$2^{c,d}$	
Surgery for cervical discus prolapse	1^{e}	
Lumbago	3	2
Neck complaints	1	3
Possible whiplash	1^{b}	
Knee complaints[f]		$3\ (1^{c})$
Fracture of patella		1^{a}
Fracture of ankle	2^{e}	$2^{d,e}$
Fracture of vertebra	1^{c}	
Colles fracture		$1^{d,e}$
Bypass surgery	2^{a}	
Pacemaker implantation	1^{b}	
Congenital heart disease		1
Heart-valve operation	$1^{a,d}$	
Heart fibrillations	1	1
Hypertension (treated)	6	4
Intermittent claudicatio	2	1
Unspecified neurological disease	1^{e}	
Recovered stroke	1^{a}	1^{e}
Recovered facial paralysis	1^{b}	
Subjective numbness of feet		1
Ear disease, childhood[f]	1	$4\ (1^{e})$
Surgery for unspecified ear disease	1^{e}	1^{e}
Prostate cancer (treated)[f]	$2\ (1^{a,b})$	
Asthma	2	
Tuberculosis (treated)		1
Insulin-medicated diabetes	1	
Medicated struma	2	

[a–e] Where appropriate, the number of years since the events are indicated by: a = 1–5, b = 6–10, c = 11–15, d = 16–20, e > 20 years ago.
[f] One subject (1) had surgery.

years). In the "Medical" group were 15 subjects (6 women and 9 men) with some medical history (Table I). Their age was between 64 and 83 years (mean 72.3 years). In the "Nystagmus" group were 18 subjects (12 women and 6 men) who represented positional or/and head shake nystagmus in the CCD camera inspection. Their age ranged from 68 to 92 years (mean 76.1 years). Thirteen of the subjects in the "Nystagmus" group had additional medical problems (Table I). The division of subjects in "Health" groups according to age can be seen in Table II.

The difference in age between these three groups was not significant ($p = 0.188$). The two subjects that did not complete all the tests were both in the "Nystagmus" group.

Subjects grouped by vibration sensation

Ten subjects, all women from 66 to 80 years old (mean 71.4 years), were in "Sensation group 1". "Sensation group 2" held the most, with 28 subjects (17 women and 11 men) aged between 64 and 89 years (mean 75.4 years). In "Sensation group 3" were 11 subjects (6 women and 5 men) from 66 to 92 years old (mean 76.7 years). The difference in age between the three groups was not significant ($p = 0.148$) but women had significantly better vibration perception than men ($p = 0.04$). The division of subjects into "Sensation" groups according to age can be seen in Table II, and according to "Health" groups in Table III.

One of the subjects who did not complete all the tests was in "Sensation group 2", the other was in "Sensation group 3".

Table II. *Subjects in the three different "Health" groups and "Sensation" groups divided into age groups*

	Age (years) 64–69	70–74	75–79	≥80	Total
Healthy	3	3	5	5	16
Medical	6	3	4	2	15
Nystagmus	4	4	5	5	18
Total	13	10	14	12	49
Sensation 1	4	4	1	1	10
Sensation 2	7	4	10	7	28
Sensation 3	2	2	3	4	11
Total	13	10	14	12	49

Correlation between body sway and age, gender, "Health" and "Sensation"

Multiple regression analysis showed the "Sensation" variable to be the major determinant for magnitude of body sway (Table IV). This was most noticeable during high-intensity vibration to the calf muscles and to a lesser extent during low-intensity vibration to the calves. Age was a significant factor in quiet stance, but only in the lateral body sway during the vibration periods and mainly with eyes open, bearing in mind

Table III. *Subjects in the three different "Sensation" groups divided into the "Health" groups*

	"Healthy"	"Medical"	"Nystagmus"	Total
Sensation 1	5	2	3	10
Sensation 2	9	10	9	28
Sensation 3	2	3	6	11
Total	16	15	18	49

Table IV. *Correlation between normalized torque (torque variance divided by squared weight and height) and "Sensation", "Health" and age, in quiet stance, for the first 100 seconds of vibration (period 1) and the following 100 seconds of vibration (period 2) in the six tests*[a]

	"Sensation"		"Health"		Age	
Test	Ant-post.	Lat.	Ant-post.	Lat.	Ant-post.	Lat.
Quiet stance, eyes closed		*	*		*	*
Quiet stance, eyes open					*	
Vibration, eyes closed						
High intensity—calves						
Period 1	***	**				
Period 2	**					
High intensity—neck						
Period 1						
Period 2						
Low intensity—calves						
Period 1	*	*				
Period 2						*
Vibration, eyes open						
High intensity—calves						
Period 1						**
Period 2	*	*				
High intensity—neck						
Period 1			*			**
Period 2						
Low intensity—calves						
Period 1		*				**
Period 2						

[a] Ant-post. = antero-posterior direction of normalized torque; Lat. = lateral direction of normalized torque; * $P<0.05$; ** $P<0.01$; *** $P<0.001$.

that vibration perturbs the subjects in the antero-posterior direction (Table IV). The "Health" variable was only a significant factor in anterior-posterior sway during quiet stance with eyes closed and vibration to the neck with eyes open (Table IV). Gender had no affect on the sway.

Comparison of torque variance between the three "Sensation groups"

The subjects with best vibration perception, "Sensation group 1", tended to sway the least, followed by subjects in "Sensation group 2". Those with the most impaired sensation, "Sensation group 3" swayed most (Fig. 1). The difference in sway between the three groups was significant in most of the tests (Table V).

Comparison of torque variance between the age groups and "Health" groups

There was very little difference in body sway between the different age groups. Significant difference in body sway was only found between the subjects below 70 and above 80 years of age, where the older group swayed more but mainly in the lateral plane (Table VI). Difference in body sway between the three "Health" groups was also very little. Significant difference was only found between the "Healthy" group and "Nystagmus" group, which was most apparent during vibration to the neck (Table VI).

DISCUSSION

In spite of the fact that all the elderly subjects considered themselves healthy, only 33% (16 of 49) of them had no medical history and/or did not show signs of vestibular dysfunction in the head shake test. The division of the subjects into the three "Health" groups did not follow any age pattern as can be seen in Table II. Nearly half of the subjects under 70 years of age (6 of 13) were in the "Medical" group, and of the 12 subjects over 80 years of age, 5 were in the "Healthy" group and 5 in the "Nystagmus" group.

The observation that nearly 37% (18 of 49) of the subjects investigated had nystagmus after head shaking is an unexpected and interesting finding. The head shake test is a non-localizing but reliable sign of vestibular

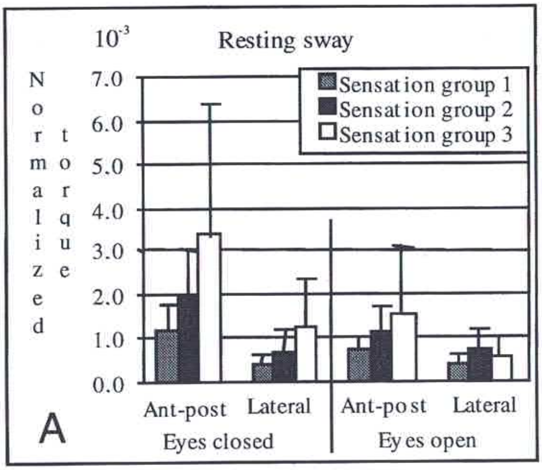
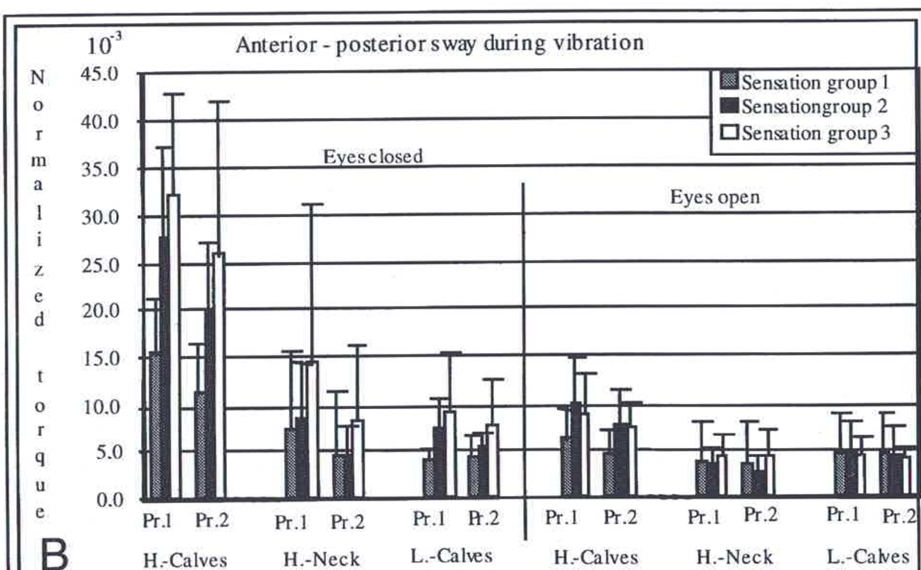


Fig. 1. Normalized torque (torque variance divided by squared weight and height) representing body sway in the anterior-posterior (Ant-post) and lateral planes with eyes closed and open during quiet stance (A) and during vibration in the anterior-posterior plane (B) and the lateral plane (C). Period 1 (Pr. 1) indicates the body sway during the first 100 seconds of vibration and Period 2 (Pr. 2) indicates the following 100 seconds. Mean and SD are given for "Sensation" groups 1, 2 and 3. H = high intensity; L = low intensity.



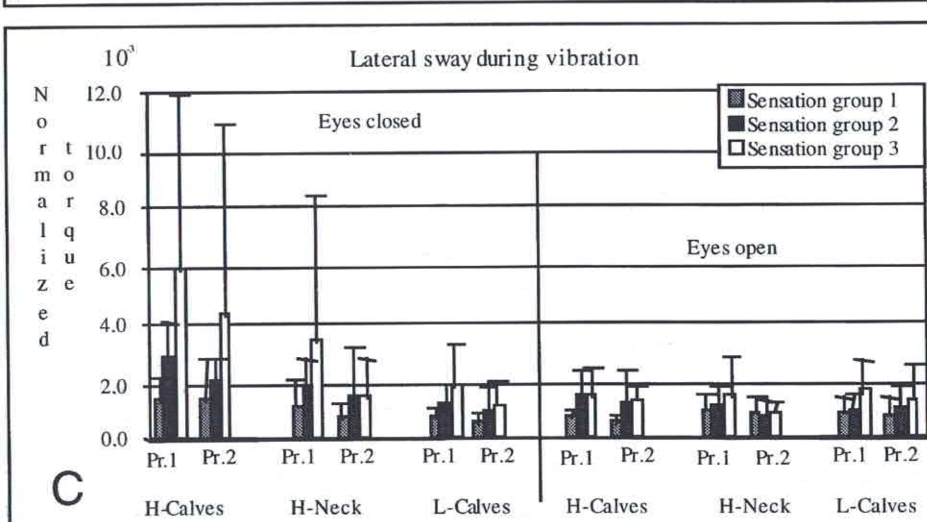


Table V. *Comparison of normalized torque (torque variance divided by squared weight and height) between "Sensation" groups 1 and 2 (Sens. 1/Sens. 2), 2 and 3 (Sens. 2/Sens. 3) and 1 and 3 (Sens. 1/Sens. 3) during quiet stance and vibration periods for the first 100 seconds of vibration (period 1) and the following 100 seconds (period 2)*[a]

Test	Sens. 1/Sens. 2 ($n=10/n=28$)		Sens. 2/Sens. 3 ($n=28/n=11$)		Sens. 1/Sens. 3 ($n=10/n=11$)	
	Ant-post.	Lat.	Ant-post.	Lat.	Ant-post.	Lat.
Quiet stance, eyes closed	*	*			*	*
Quiet stance, eyes open						
Vibration, eyes closed						
High intensity—calves						
Period 1	**	***		*	***	***
Period 2	**	**			***	*
High intensity—neck						
Period 1						
Period 2		*	*		*	*
Low intensity—calves						
Period 1	**	**			*	**
Period 2		*				*
Vibration, eyes open						
High intensity—calves						
Period 1	*	***				**
Period 2	*	***			*	***
High intensity—neck						
Period 1						
Period 2			*			
Low intensity—calves						
Period 1				*		
Period 2						*

[a] Ant-post. = antero-posterior direction of normalized torque; Lat. = lateral direction of normalized torque; * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

disturbance (12). The new technique, observing for nystagmus with goggles with CCD cameras, might have increased the sensitivity of the test but it is the authors' experience that head shake nystagmus is generally not encountered among normal younger subjects. When it does occur, however, it ordinarily indicates a vestibular asymmetry and accompanies other findings of such a defect. Vitte & Sémont (27) did not find a spontaneous or head shake nystagmus in their asymptomatic control group in CCD cameras inspection, and McAuley et al. (18) stated that positional nystagmus observed with the Frensel lenses was probably pathological. However, the origin of the head-shake-induced nystagmus will not be elucidated further. An age-dependent loss of sensory cells in the vestibular end-organ that parallels that found in the cochlea has been described (22). It is feasible to assume that deterioration of the vestibular end-organ may occasionally proceed with some asymmetry, in a similar way that presbyacusis does. This asymmetry should then be compensated for within the central nervous pathways of the vestibular reflexes. However, with age-dependent, or rather "age-concomitant" degrading and loss of nerve cells and vascular supply, the older persons might face a higher risk of defect compensation. In situations disparate from normal everyday life, the compensatory process might not be sufficient because it is known that vestibular adaptation is mainly apparent in the low frequency range (9). Thus, the initial fast head movements in a fall might be in a frequency range outside that of the compensation.

The standing posture changes with age. There is an increased kyphosis and the head is carried further forward (31). The changed alignment in the neck may affect the cervical–vestibular interaction and the postural control mechanism as it can in other vestibular tests (11). The occurrence of nystagmus does, however, indicate an asymmetric perception of head movements as interpreted by the vestibular system.

The threshold of vibration perception, measured with a biothesiometer, has been reported to rise with age (28). Steinberg & Graber (24) also found a rise of vibration threshold with age, but there was a considerable spread of threshold values in healthy individuals over 60 years

Table VI. *Comparison of normalized torque (torque variance divided by squared weight and height) between subjects under 70 and those over 79 years of age, and the ''Healthy'' group and ''Nystagmus'' group, during quiet stance, for the first 100 seconds of vibration (period 1) and the following 100 seconds of vibration (period 2)*[a]

	Age ≤70/≥80 ($n=13/n=12$)		''Healthy''/ ''Nystagmus'' ($n=16/n=18$)	
Test	Ant-post.	Lat.	Ant-post.	Lat.
Quiet stance, eyes closed		*	**	*
Quiet stance, eyes open	*			
Vibration, eyes closed				
High intensity—calves				
Period 1				*
Period 2				
High intensity—neck				
Period 1			*	
Period 2				
Low intensity—calves				
Period 1				
Period 2		**		
Vibration, eyes open				
High intensity—calves				
Period 1				
Period 2				
High intensity—neck				
Period 1			**	
Period 2			*	
Low intensity—calves				
Period 1		*		
Period 2				

[a] Ant-post. = antero-posterior direction of normalized torque; Lat. = lateral direction of normalized torque; * $p<0.05$; ** $p<0.01$.

of age. Our findings are more in agreement with those of Steinberg & Graber (24) as the subjects in the three ''Sensation'' groups were spread in all the age groups. The subjects with the best vibration perception tended to be in the lowest age groups, and the poorest perception in the older age groups, but the difference in age was not significant. On the other hand, there was a significant difference between the sexes in vibration perception, males having poorer perception, which is in agreement with Wiles et al. (28).

The subjects in ''Sensation'' groups 1, 2 and 3 were also spread into the three different ''Health'' groups. The subjects in ''Sensation group 2'' were evenly spread between the three different ''Health'' groups. On the other hand, more than half of the subjects in ''Sensation group 3'' (6 of 11) were in the ''Nystagmus'' group and three in the ''Medical'' group. This pattern was reversed in ''Sensation group 1'', where half of the subjects (5 of 10) were in the ''Healthy'' group, two in the ''Medical'' and three in the ''Nystagmus'' group.

In retrospect, one could state from the present criteria that only 5/49 subjects (age 67–80 years, mean 72.8) had optimal health, i.e. they had good vibration perception, no medical history and no nystagmus reaction (Table III). Thus the healthy senior citizens examined had diminished sensation, vestibular symptoms and a variety of ailments in their medical history. The deficits in health status were spread in the different age groups. Age alone was not a determinant factor in any of the findings but a larger population studied might give different results.

Vibratory stimulus applied to muscles activates the proprioceptive organs, thus giving erraneous information on elongation of the muscle into the central nervous system. The afferent inflow from these muscles tends to bring out widespread postural adjustments (4).

Recordings of vibrational-induced body sway on a force platform has been used to assess postural control in patients with vestibular lesions (15, 21), neurological disorders (19) and disorders associated with the neck (10). This method can therefore be considered valid to assess postural control in elderly subjects.

In the present study the vibration perception was the major determinant for magnitude of body sway. This was less prominent during quiet stance but most noticeable during perturbations with vibration, when the postural control system was stressed by disturbing the proprioceptive information. These findings are in agreement with Bergin et al. (2), but they found correlation between vibration sensation and body sway when standing on a foam with eyes closed. Moreover, the subjects with the most intact sensation as tested were found to have least sway in all the tests and differed significantly from the other two groups in all the tests with the eyes closed and during high-intensity vibration to the calf muscles with eyes open (Table V). When the perturbation caused by vibration to the calf muscles was strong, vision could not compensate for the lack of sensation but did so during weaker stimulation to the calves and vibration to the neck muscles.

The importance of the inputs from the proprioceptive system for postural control and the role of the vestibular and visual inputs has been reported previously (2, 3, 13, 14). The present study supports those findings, as it demonstrates a group correlation between vibration perception at the feet and lower leg and magnitude of sway.

Measuring vibration perception with a tuning fork is not as precise a method as using a biothesiometer, but it is a readily available method that seems to be sensitive enough to give an indication of balance control in the elderly.

Age correlated with resting sway both with eyes open and closed. Comparison of sway between the different age groups revealed, however, only a significant difference between the youngest and oldest groups in the lateral plane with eyes closed and anterior-posterior plane with eyes open. It is noteworthy that correlation of age and sway was only found in the lateral plane during the vibration periods as vibration perturbs the subjects in the anterior-posterior direction. Vibratory stimulus applied to the calf muscles produces a backward movement of the body around the ankle joints but stimulus to the neck muscles produces a forward movement (20). To stand in a standardized upright position for nearly 4 minutes (3 minutes and 55 seconds) is demanding on the muscular and circulatory systems in the legs. To diminish the strain the older subjects possibly shift their weight more from one leg to the other than the younger ones do.

Another explanation might be a change in the postural control pattern with ageing, as elderly fallers have a preference to fall sideways (6).

Comparison of sway between the three ''Health'' groups showed that the subjects in the ''Healthy'' group tended to sway the least, those in the ''Medical'' group swayed more and then those in the ''Nystagmus'' group swayed the most. Significant difference was only found between the ''Healthy'' and ''Nystagmus'' groups during quiet stance with eyes closed and during vibration on the neck. Increased sway during vibration to the neck has been associated previously with central vestibular dysfunction (21). Two of the subjects did not cope with vibration to the neck. Both of them had nystagmus and diminished vibration perception. One was in ''Sensation group 2'' and the other in ''Sensation group 3''.

Although the subjects considered themselves healthy, they had a variety of ailments in their medical history, diminished vibration perception and a high incidence of possible vestibular dysfunction. Vibration sensation was the major determinant for magnitude of sway. Age *per se* was not a determinant factor in any of the findings. The study suggests that interest should also be directed to the status of sensation in the legs and vestibular asymmetry when assessing balance function in the elderly. Furthermore, the term ''age concomitant'' may be more appropriate than ''age dependent'' when describing decrements of functions such as postural control in elderly subjects.

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