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Otolith Function Assessed with the Subjective Postural Horizontal and Standardised Stance and Gait Tasks

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Key Words
Otolith function · Subjective horizontal · Unilateral vestibular neurectomy · Stance and gait tests

Abstract

If otolith function is essential to maintain upright standing while moving along slanted or uneven surfaces, subjects with an otolith deficit should have difficulty judging whether the inclination of the surface on which they are standing is tilted or not. We tested this judgement and compared it with the ability to control trunk sway during standardised stance and gait tests. Thirteen patients with unilateral vestibular nerve neurectomy at least 6 months prior to testing and 39 age-matched controls were asked to move a dynamic posturography platform on which they were standing back to their subjective 'horizontal' position after the platform had been slowly tilted at 0.4°/s to 5° in 8 different directions. Normal subjects left the platform deviated in pitch (forwards-backwards) at about 0.7° on describing the platform as levelled off for all directions of tilt. Patients showed larger deviations of about 1.3° in pitch with significant differences for forward right tilt (1.58 ± 0.73° compared to 0.73 ± 0.11° for normals; mean and SEM) and for forward left. Roll (lateral) deviations were about 0.4° for normals and 0.5° larger for the patients (for example, for backward left, 1.13 ± 0.24° compared to 0.4 ± 0.07° in normals). Except for a tendency towards greater deviations to the lesion side of patients with eyes closed, no differences were noted between tests under eyes open and closed conditions. However, for backward and roll tilts patients needed to steady themselves first by grasping a handrail when tested with eyes closed. Stance tests on foam showed increases in roll and pitch trunk sway with respect to controls. Patients had significantly larger trunk roll sway deviations during 1-legged stance tests and during gait trials. For stance trials, the patients lost their balance control prior to the end of the standard 20-second recording time. We conclude that a unilateral loss of otolith inputs due to nerve resection permanently impairs the ability to judge whether the support surface is horizontal, and leads to excessive trunk sway when standing on a compliant surface as well as excessive trunk roll sway during gait.

J.H.J. Allum has a commercial interest in the company selling the SwayStar™ device used in part of this study.

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Introduction

Otolith function remains the primary area of human vestibular physiology without a simple reliable clinical test. Subjective visual vertical and ocular rotation tests during whole-body eccentric rotation [Clarke et al., 2001] and vestibular evoked myogenic potentials (VEMPs) recorded from the sterno-clavicular muscles [Colebatch et al., 1994] are accepted as 'gold' standards, but these tests have a number of drawbacks. The amount of technical effort and equipment required to perform eccentric rotation tests hinders their widespread use in dizziness clinics. Although VEMPs are easier to perform, these seem to be of predominantly saccular origin [Halmagyi and Curthoys, 1999; Murofushi et al., 1996] and therefore do not test utricular function. Likewise subjective visual vertical tests during whole-body rotations [Clarke et al., 2001] examine the utricular function only. A simple otolith test, similar to the observation of eye saccades during head thrusts in different directions for unilateral horizontal and vertical canal dysfunction [Halmagyi and Curthoys, 1999], would be preferable.

A simple clinical test for otolith disorders needs to be specific for and sensitive to otolith dysfunction. Furthermore, it is important to know if the otolith-deficient patients can use somatosensory or visual inputs effectively for controlling balance thereby switching to inputs better able to register imbalance. It is also crucial to know clinically whether or not this switching helps patients recover completely from an otolith deficit, especially if there is a risk of falling in their workplace.

Several methods have been used to test the otolith function, e.g. measurements of horizontal, vertical and torsional eye movements during off-vertical, eccentric whole-body rotations, and linear body accelerations, as well as psychophysical settings, such as tilt estimation, in response to the linear accelerations produced by swings, sleds, centrifuges, tilt chairs and barbeque spit rotations [Curthoys et al., 1991b; Friedmann, 1970, 1971; Furman et al., 1992; Halmagyi and Curthoys, 1999]. While these tests have provided important information on the interaction between otolith and semicircular canal system, their main disadvantages as a clinical test are cost and practicability. The most commonly used examination, the subjective visual vertical [Hafstrom et al., 2004; Vibert and Häusler, 2000], can be highly variable and therefore of limited value for clinical follow-up examinations.

Normal spatial orientation is essential for the maintenance of gaze, posture and locomotion. Otolith organs sense the direction of gravito-inertial forces providing a basis for subconscious postural reflexes and a contribution to the perception of spatial orientation [Böhmer and Mast, 1999; Bisdorff et al., 1996; Dai et al., 1989; Mast and Jarchow, 1996]. Thus, the otoliths, maculae utriculi and maculae sacculi, sensing roll and pitch tilt, respectively, have been considered to play a decisive role in the control of upright posture and sense of the subjective upright [Bucher et al., 1992]. Nevertheless, somatosensory [Anastasopoulos et al., 1999], proprioceptive [Biguer et al., 1988; Karnath et al., 1994] and visual feedback signals [Betts et al., 2000; Dichgans et al., 1975] also contribute to inputs used by the CNS to yield a common command for balance control. Furthermore, in the absence of one sensory input, it has been suggested that other inputs are used almost immediately [Peterka and Loughlin, 2004].

Posturography, both in the form of reactions to moving support surfaces and measurements of trunk sway during stance and gait tests, has previously been used to test vestibulospinal function as well as to define the functional status of vestibulospinal reflex compensation [Nashner et al., 1982; Carpenter et al., 2001; Allum and Adkin, 2003]. Thus, one way to test otolith-spinal function directly may be to use a moving support surface system with two modifications: first, relying on the subjectively perceived horizontal, rather than automatic postural reactions as the investigated variables; second, using slow rotations with low accelerations to avoid stimulating vestibular canal systems. The subjective reactions on support surface tilt could then be compared with quantified balance control measured during quantified stance and gait tests.

Removal of a tumour from the vestibular nerve and with it a section of the nerve unilaterally eliminates both semicircular and otolith inputs to the CNS. This form of surgical intervention is probably the most commonly available to provide in man insight into otolith function [Bisdorff et al., 1996; Böhmer and Mast, 1999; Bronstein, 1999; Halmagyi and Curthoys, 1999; Kamura and Yagi, 2001; Lempert et al., 1998]. For this reason, we investigated the subjective postural horizontal of patients who had undergone this intervention and compared their results with those of age-matched healthy subjects.

Materials and Methods

All experiments were performed in accordance with the Helsinki Declaration after having received approval of the local ethics committee. All subjects gave their informed consent prior to inclusion in the study. The subjects were not familiar with the theoretical background of the experiments and had not been involved in a dynamic posturography experiment or test at any time.

An inclusion criterion for healthy subjects was the ability to stand 20 s on one leg with their eyes closed. Exclusion criteria were any neurological, psychiatric, orthopaedic and vestibular disorders. Forty-five healthy subjects participated in the study. They had a mean age ± SD of 40 ± 14.5 years (range 21–67 years); 24 were female and 21 male. In order to evaluate the effect of age on the subjective postural horizontal, subjects were divided into three groups of 16, 15 and 14 members, respectively (young: 20–30 years, mean 25 ± 3.55 years, range 22–30; middle-aged: 30–50 years, mean 38.1 ± 5.8 years, range 31–49 years, and older: 51–75 years, mean 58.5 ± 5.2 years, range 51–67 years).

A total of 14 patients were tested (10 female and 4 male). One female patient was excluded based on our inclusion criterion for patients (using the surgical reports) with a complete unilateral resection of the vestibular nerve in the course of removal of a vestibular nerve schwannoma. A retrosigmoidal surgical approach was used in 10 cases and a transtemporal approach for the other cases. Only patients with a tumour removal more than 6 months prior to the experiments (mean 34 ± 20.9 months) were tested under the assumption that any possible compensation of otolith disfunction might be complete by this time. Tumour size was less than 3 cm in all cases, however brain stem damage as a conflicting factor was controlled for tumours greater than 2 cm by examining operation reports for surgically imposed brain stem damage. Exclusion criteria for patients were any other operation possibly affecting the vestibular system (e.g. middle ear surgery), systemic illnesses and orthopaedic or neurological illnesses. At the time of surgery, all patients had normal horizontal vestibulo-ocular reflex (VOR) gains [for normal reference values, see Allum and Ledin, 1999] for whole-body rotations with accelerations of 5 and 20°/s^2 towards the non-tumour ear. VOR gains for rotation towards the affected ear were reduced to 47 and 81% of normal, respectively, and VOR time constants [measured as described in Allum et al., 1988] were reduced to 12.4 ± 3.5 s compared to normal values of 20.4 ± 4.8 s for triangular velocity rotating chair profiles with 20°/s^2 accelerations. Patients were on average 54.4 ± 14.2 years old (range 32–75 years). For comparisons between patients and control subjects, an age- and gender-matched control group of 39 subjects was chosen from among the 45 control subjects.

A dynamic posturography platform which was gimballed to move in the pitch and roll directions simultaneously was used to test the subjective horizontal. Starting from the objective horizontal, subjects were tilted 5° (using an acceleration of 2°/s^2) at an average velocity of 0.4°/s in one of eight different directions twice. The directions were denoted as 45, 105, 135, 165, 195, 225, 255 and 315° where 90° is a pure roll right and 0° is pitch toe-down (fig. 1). A predominance of backwards rotations was used as pilot experiments indicated that patients had more difficulty with such directions. Once the platform had reached 5°, subjects were requested to return the platform back to their subjective horizontal position using a hand-held joystick controller. During testing under the eyes open condition, the subjects were asked to fixate a point 3 m distant and not to look at their feet. There was no time limit for performing the test. Once subjects verbally indicated the platform was at their subjective postural horizontal, the remaining deviation from the objective horizontal was measured separately for roll and pitch deviations as the voltage corresponding to an angle command required to drive the platform to the true horizontal. Next the subjects were tilted back into the objective horizontal again and remained in this position for 5 s before a new tilt was imposed on them. At the objective horizontal, the mean voltage deviations across all directions repeated twice in pitch and roll were 0.002°. Subjects were tested first under the eyes open condition and then with their eyes closed. The subjective postural horizontal was calculated separately for tilting directions, visual conditions and subject groups.

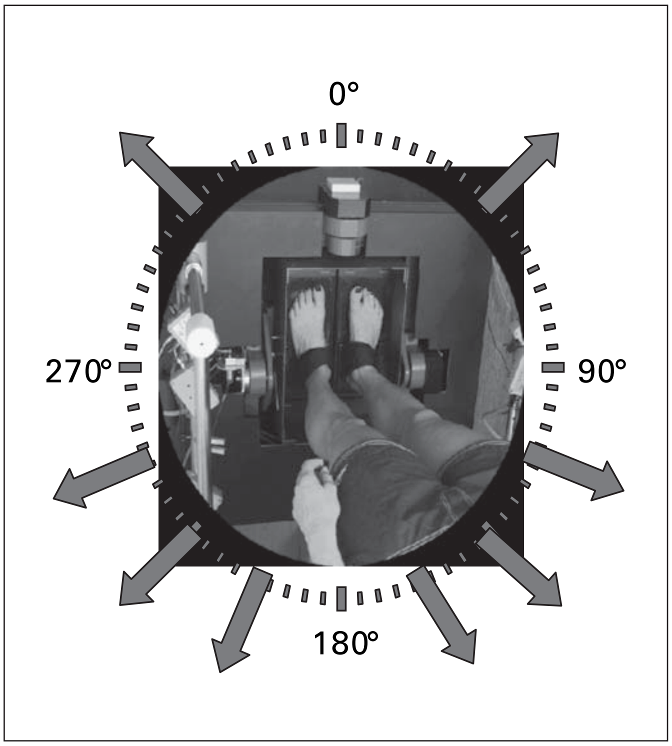

Fig. 1. Schema of the perturbation directions. A bird's eye view of the gimballed platform is shown with arrows indicating the tilt directions of 45°, 105°, 135°, 165°, 195°, 225°, 255° and 315°. 0° is indicated by a toe-down tilt, and 90° by a right tilt.

To study the effects of unilateral vestibular neurectomy on balance control, we evaluated trunk sway during 14 different standardized stance and gait tasks [Allum and Adkin, 2003]. The test battery comprised 2- and 1-legged stance tasks performed for 20 s or until balance control was lost under normal (eyes open), altered visual (eyes closed), and altered proprioceptive (foam support surface) conditions. Gait tasks consisted of walking with head pitching or head rotation, or with eyes closed or in tandem gait. Quantification of trunk angular sway was performed using a system consisting of two angular velocity transducers mounted on a belt at the level of lumbar 1–3 (SwayStar™ Balance International Innovations, Switzerland). The sensors measured trunk sway in the roll and pitch directions. The output of the sensors was integrated to yield the sway angle. From the recordings, the peak-to-peak and 90% range of the sway angle and velocity in both directions were measured (fig. 2).

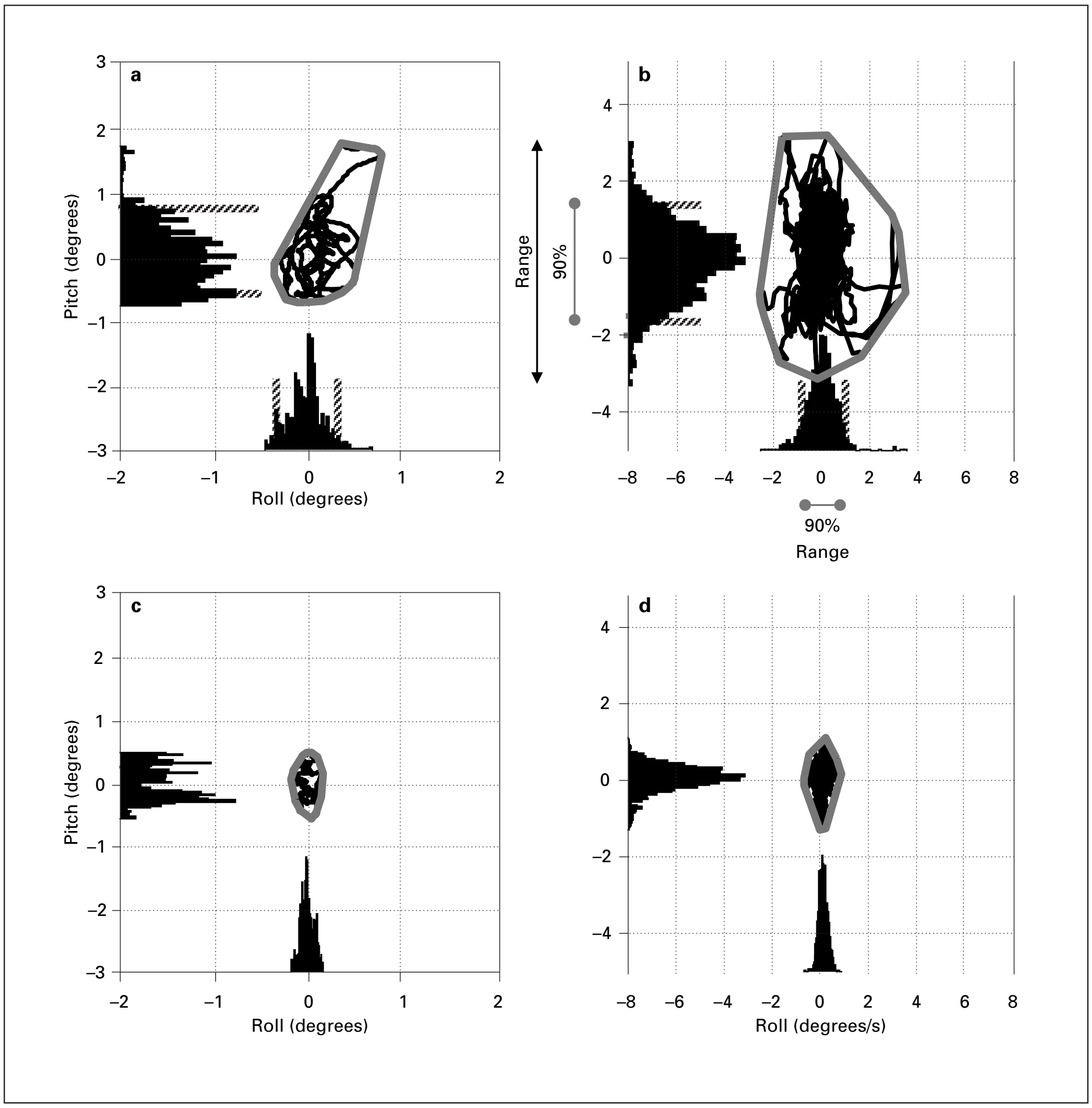

Fig. 2. Plots of trunk angle (**a**, **c**) and trunk angular velocity (**b**, **d**) for a typical patient (**a**, **b**) and control (**c**, **d**) for the task of standing on foam with eyes open. Angle and angular velocity are plotted for the pitch and roll as an x-y plot over the complete recording. An envelope (mathematically the convex hull) is drawn as a grey line around the plots. In each of the 4 panels with x-y plots, a histogram of pitch and roll displacements is shown. To compute the histogram, the extent of deviation in pitch (and roll) is divided into 40 bins. Each angle and angular velocity sample is then placed in the appropriate bin to create the histogram. From these histograms, a peak-to-peak and 90% range can be defined as indicated. Note the larger displacements of the patient.

Statistical Analysis

Statistical testing was performed with SPSS. To enable the recordings from all patients to be treated similarly for statistical analysis, individual data of the perceptive postural horizontal were pooled as if all patients had right-sided unilateral vestibular deafferentation. As data were not normally distributed, a 2-tailed Mann-Whitney U test for paired and unpaired observations was used to evaluate differences between patients and healthy controls and between the age groups of healthy controls. $p < 0.05$ was considered statistically significant for results of standardised stance and gait tasks. As multiple testing was performed for results of subjective postural horizontal (8 directions), a Bonferroni correction was employed thereby elevating the significance to $p < 0.00625$ (0.05/8).

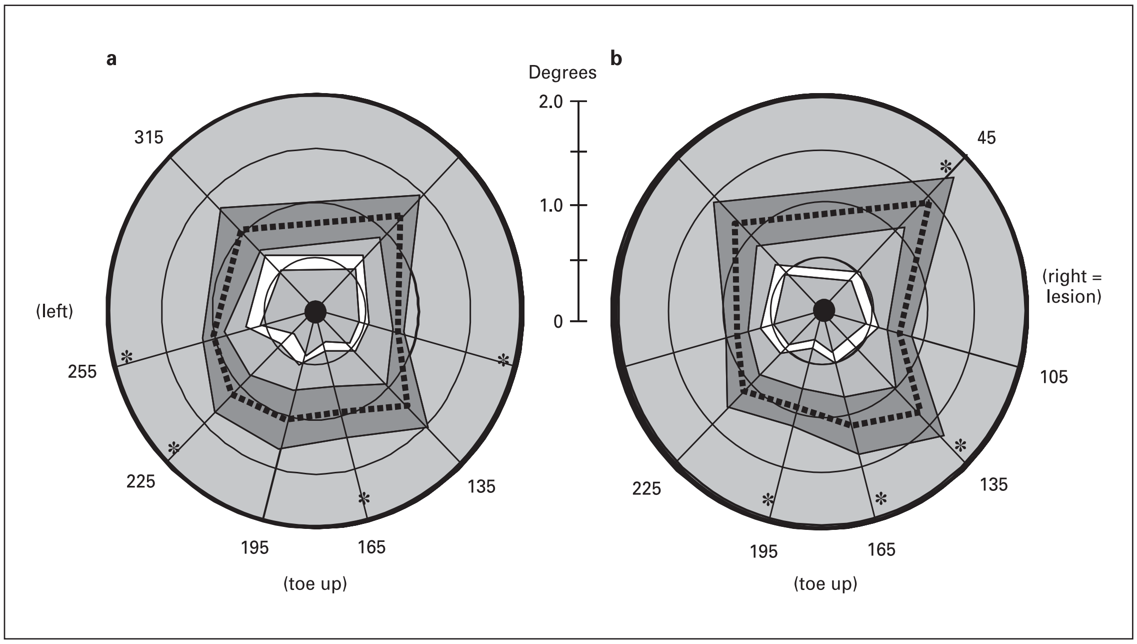

Fig. 3. Polar plots of the mean roll angle deviation of patients and controls for each direction of tilt. **a** Values for the eyes open condition. **b** Values for the eyes closed condition. The white area indicates the mean ± SEM for the controls and the outer dark area for the patients. The mean for the patients is marked as a black dotted line. Each value is plotted as an amplitude along the radial spoke of the polar plot corresponding to the tilt direction. Differences between patient and control sample population means are indicated by an asterisk. Patients with the dissection on the left had the values mirror-imaged so that the deficit side is plotted on the right.

Results

Normal subjects showed 0.5° roll (lateral) deviation, on average, for the subjective postural horizontal, a value that did not vary with tilting direction (fig. 3). The standard error of the mean (SEM) across directions averaged 0.07°. Pitch deviations were 0.75° on average with SEM of 0.13° for all tilting directions (fig. 4). When the 10 controls in the 18–30 age group were retested, the test-retest differences averaged 0.25° in pitch and 0.06° in roll. SEMs averaged 0.25 and 0.18°, respectively. No significant changes were observed when control subjects performed the task with their eyes open or closed. Roll deviations between subjects, divided into three age groups, showed no significant differences for any deviation of tilt. Pitch deviations, especially with eyes closed, were larger for backward tilts for subjects older than 50 years (mean 0.95°, SEM 0.12°) compared to 18- to 30-year-olds (mean 0.52°, SEM 0.07°), indicating an age effect.

Patients with unilateral vestibular nerve resection showed greater deviations of the subjective postural horizontal for all tilt directions (fig. 3, 4). Significant differences in roll direction occurred with eyes open after tilt in backward and roll directions and with eyes closed after tilt to the lesion side and backwards (fig. 3). Pitch deviations were significantly larger following forward tilt under both eyes open and eyes closed conditions (fig. 4).

When tested with eyes closed, about half of the patients, but no healthy control, needed to touch or grasp the handrails to prevent a fall. Touching or grasping the handrail was scored as a fall. This loss of balance control was more noticeable for backwards and roll tilt (fig. 5).

Measurements of trunk sway during stance and gait tasks showed several significant differences between the patients with unilateral vestibular nerve resection and the healthy controls (table 1). Patients often lost balance control when standing on 2 legs on foam (fig. 6) or when standing on 1 leg before the standard stance recording time was complete. Furthermore, the sway deviations were larger. Figure 2 provides examples of sway records in the form of x-y plots of trunk angle and angular velocity for a typical patient and an age-matched control. Fig-

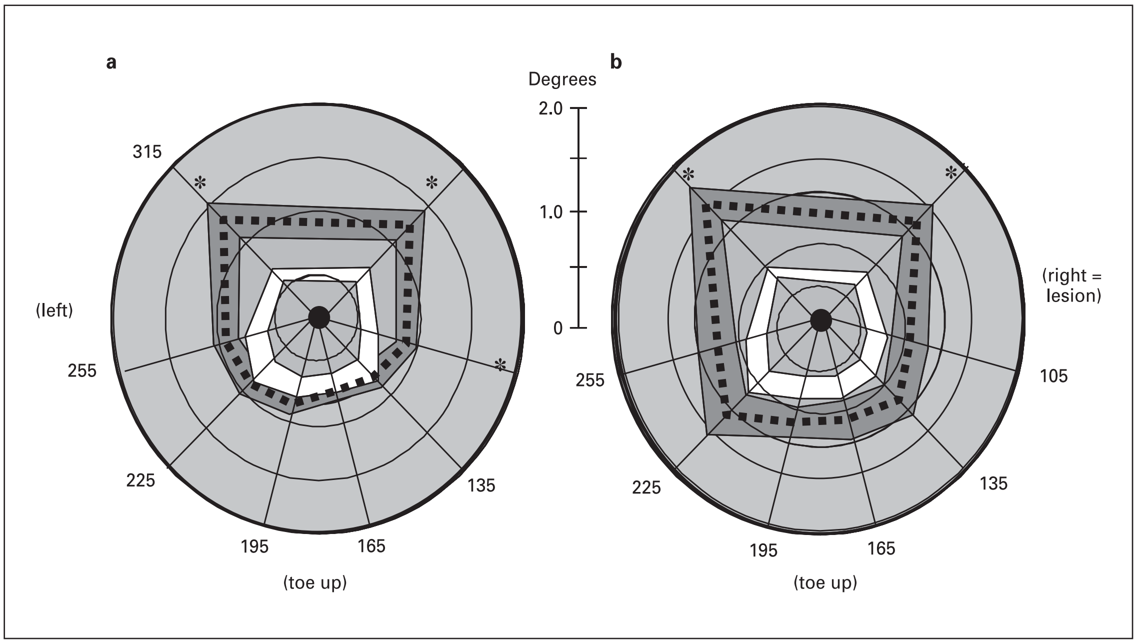

Fig. 4. Polar plots of the mean pitch angle deviations of patients and controls for each direction of tilt. **a** Values for the eyes open condition. **b** Values for the eyes closed condition. The format is identical to that of figure 3.

ure 2 also explains how the peak-to-peak and 90% measurements of trunk sway are calculated. When standing normally (with 2 legs) on foam, trunk sway amplitudes and velocities were considerably greater for the patients with the most significant differences in the roll direction (table 1). For 1-legged stance and gait tasks, the roll angle was consistently larger for the patients. Differences in sway during gait tasks occurred more frequently in the roll than the pitch direction.

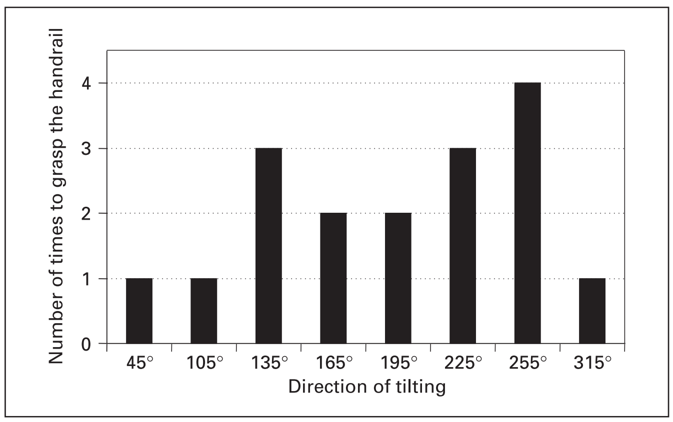

Fig. 5. Histogram of the number of patients who had to grasp the handrail to steady themselves when tilted in different directions with their eyes closed. No controls needed this assistance.

Discussion

We applied a slow body tilt in different directions to standing subjects using a dual-axis servo-controlled support surface that could be produced more cheaply than current rotating chair systems used to test for utricular responses. Our assumption was that we were preferentially stimulating the otolith system, as well as proprioceptive and visual systems (with eyes open) controlling posture. Together these systems provide a sense of the subjective horizontal. By exploring changes in this sense in patients with a resected vestibular nerve on one side we hoped to gain insights into the effect of a unilateral loss of otolith function.

It was previously deduced from animal studies that being tilted is an adequate stimulus for the otolith organs [Fernandez et al., 1972; Ikegami et al., 1994; Uchino, 1997]. As the saccular sensory epithelium is oriented vertically, activation of the saccule occurs with head rotation in the pitch plane [Fernandez and Goldberg, 1976; Fer-

Table 1. Significant differences between patients and controls for standardised stance and gait tasks

Task	Duration	90%[a] and range[b]			
		roll angle	roll velocity	pitch angle	pitch velocity
Standing on 2 legs, eyes open, foam support	0.0001	0.008	0.002	0.016	0.017
		0.009	0.012	0.005	0.03
Standing on 2 legs, eyes closed, foam support	0.0001	0.027	0.0001	0.016	0.0001
		0.023	0.001	0.004	0.002
Standing on 1 leg, eyes open	0.0001	n.s.	0.026	0.041	0.02
		n.s.	0.018	n.s.	0.039
Standing on 1 leg, eyes closed	0.0001	0.044	0.001	n.s.	0.021
		n.s.	n.s.	n.s.	n.s.
Standing on 1 leg, eyes open, foam support	0.0001	0.003	0.003	n.s.	0.011
		0.016	0.13	n.s.	0.024
Walking 8 tandem steps, eyes open	n.s.	0.012	0.008	n.s.	n.s.
		0.024	n.s.	n.s.	0.037
Walking 3 m eyes closed	n.s.	0.0001	n.s.	n.s.	n.s.
		0.001	n.s.	n.s.	n.s.
Walking 3 m pitching head	0.001	0.016	n.s.	n.s.	n.s.
		0.002	n.s.	n.s.	n.s.

[a] 90% is the 90th percentile range of sway defined by a histogram of the patients' sway (fig. 5).
[b] Range is the peak-to-peak sway.

nandez et al., 1972; MacDougall et al., 1999; Uchino, 1997]. Stimulation of the macula utriculi, lying in the horizontal plane, is elicited by head tilt in the roll direction [Ikegami et al., 1994; Uchino, 1997]. The utricular macula shows a moderate preponderance of hair cells that are polarized for excitation by laterally directed roll tilts over medially directed ones [Fernandez and Goldberg, 1976] as the medial area of the utricle is larger than the lateral one both in monkeys [Fernandez et al., 1972] and humans [Rosenhall, 1972]. Otolith neurons showed no sensory threshold during pitch and roll tilt [Fernandez et al., 1972] and 70–75% of neurons of the superior vestibular nerve innervating the utricle are sensitive to ipsilateral rolls and 25–30% to contralateral rolls in the squirrel monkeys [Fernandez et al., 1972]. Therefore, the human utricle has been considered as an asymmetric sensor with preference for ipsilateral tilt [Bergenius et al., 1996; Halmagyi et al., 1993; Tribukait et al., 1996], which is a prerequisite for the feasibility of localizing unilateral hypofunction by means of an otolith test stimulating both otolith sides.

In this study, as well as in our previous pilot study, the perception of the horizontal showed greater differences when the tilt was directed backwards and combined with roll for the roll deviations and forward and roll for the pitch deviations. While the aim of our study was solely to explore the effect of a complete unilateral otolith deficit, it may be worthwhile exploring in future studies whether these directional differences in pitch and roll represent directional sensitivity to saccular and utricular deficits, respectively. Furthermore, future studies should also investigate the effects of a partial otolith deficit on the subjective horizontal, VEMPs and the subjective visual vertical during eccentric whole-body stations, in order to determine the relative clinical usefulness of our studies. Our current findings would be more significant if we had recorded VEMPs and done extensive VOR testing postoperatively to verify functionally unilateral loss of vestibular function imposed surgically.

As patients in the current study quite likely suffered from complete unilateral vestibular loss (based on preoperative testing and the surgical reports), we attempted to eliminate a contribution from contralateral semicircular vertical canal afferents to the subjective horizontal by limiting movement of the platform to less than 2°/s^2 and 0.4°/s. With this motion, we estimate, based on previous experiments [Allum et al., 2003], that mechanically induced roll and pitch accelerations at the head would be less than 0.2°/s^2 and therefore lower than known canal thresholds [Guedry, 1974; Clarke et al., 2001]. Nonethe-

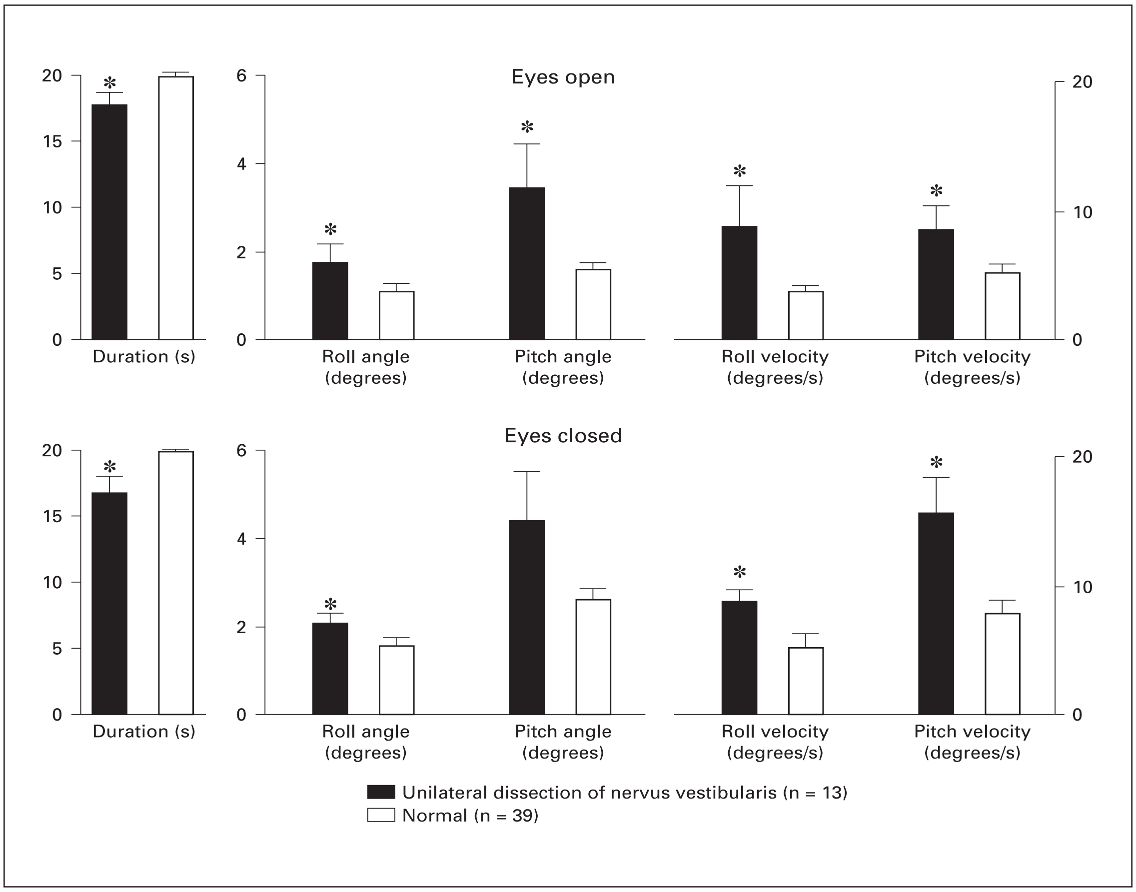

Fig. 6. Mean peak-to-peak sample population values and stance duration means for the tasks of standing on 2 legs on foam with eyes open and eyes closed. The column height represents the mean value and the vertical bar the SEM. Only 13 of the 14 patients performed these stance tests. Significant differences between means of the patients and controls are marked with an asterisk.

less, head movements may have been momentarily faster during the tests. A weakness of the current study is that we did not record these head accelerations. Whether therefore an input from the contralateral vertical semicircular canal afferents contributed to the sense of the horizontal and influenced our results to the extent of producing a separation of pitch and roll differences for tilt forwards and backwards, respectively, is currently unknown.

In order to compare a highly standardized patient group with controls, we tested patients with a unilateral surgical elimination of the vestibular function following nerve resection with removal of a tumour emanating from the vestibular nerve. The vestibular nerve divides into three branches with the superior branch ending at the utricle and at the ampullae of the superior and lateral semicircular canals, the inferior ending at the saccule and the posterior branch at the ampulla of the posterior semicircular canal. Resection of the superior vestibular branch will result in both an otolith (utricle) and a semicircular canal deficit. As we wanted to examine the effect of a unilateral absence of input from both otolith organs, we selected only patients with the more common defect of total unilateral vestibular nerve resection rather than an isolated resection of the inferior vestibular nerve for this study. As we did not note any surgically imposed brain stem damage in our patients, we assume that our results are not influenced by co-existing brain stem damage.

It has previously been reported that approximately 6 months after unilateral vestibular deafferentation offsets with otolith function tests reach a stable, partially compensated, state for example as measured by roll tilt perception with linear acceleration [Curthoys et al., 1991b], by the subjective vertical [Tabak et al., 1997] or 'head heaves' [Nuti et al., 2005]. By choosing patients with such a stable state, that is, those operated at least 6 months (mean 34 ± 20.9 months) prior to testing, we assumed that any central compensation of unilateral otolith dysfunction was complete. Also, as horizontal VOR gains for rotations to the intact ear were normally presurgery, we assumed that otolith spinal gains for the same ear were normal too and therefore would not impede compensation. It should be noted, however, that previous studies using the subjective visual horizontal showed significant offsets 4.5 years after unilateral vestibular deafferentation [Tabak et al., 1997; Tribukait et al., 1998] and therefore compensation is never complete. Thus, at 6 months and more from the time of nerve resection we expected to be able to demonstrate stable group differences, if the subjective postural horizontal detects differences in otolith function.

The application of the method we used is naturally limited to patients who are able to stand upright without an aid for several minutes. All our patients were able to perform the task. Our task has some advantages for patients with poor vision over previously described techniques. The subjective visual vertical and horizontal depend not only on otolith function, but also on a normal visual function.

The high accuracy shown by normal subjects in adjusting the subjective postural horizontal to less than 1° with small SEMs from the true horizontal even with eyes closed argues for a highly stable, body-centred control of body orientation in space using otolith and proprioceptive information. Our results have been confirmed by others recently, albeit only in the frontal plane. Kingma et al. [2004] evaluated the 'subjective proprioceptive horizontal' in 16 healthy subjects and found that controls could also adjust the platform to be almost level with an accuracy like that we found of around 0.5° and with equally small SEM. It is therefore unlikely that subjects were using cues in the platform movement other than its tilt to enhance their perceptual ability.

Elderly normal subjects (51–75 years) showed significant pitch deviations from the results of young healthy controls (18–30 years old) for backward directions. This age effect might partly be responsible for an increased risk of falling backwards and laterally in elderly subjects [Holliday et al., 1990]. As an age effect on otolith function has not been reported before, this observation should be evaluated in patients with unilateral vestibular deafferentation. The lack of an age effect on roll deviations facilitates comparisons with control subjects.

Our results in patients showed more significant deviations in the roll than in the pitch direction with respect to controls. With their eyes closed, patients tended to show slightly more ipsilesional group differences in roll deviation. This is consistent with prior reports of unilateral vestibular deafferentation resulting in a slight permanent ipsilesional offset in the subjective visual horizontal [Halmagyi and Curthoys, 1999], an invariable deviation of torsional eye position [Curthoys et al., 1991a, b] and an ipsilesional tilting while seated adjusting a flight simulator [Aoki et al., 1999]. Furthermore, the subjective visual vertical has shown to shift toward the lesion side immediately after deafferentation for an examination in an upright, static position [Böhmer and Rickenmann, 1995]. It has previously been proposed that some time after unilateral vestibular deafferentation, a shift of the 'centre of graviception' to the intact contralateral inner ear occurred [Böhmer and Mast, 1999]. We observed instead a more general inaccuracy of the perception of horizontality measured after the platform had been tilted from the true horizontal. It is possible that by having the patients first move the platform to their subjective horizontal before moving it a further 5° in different directions we might have noted this shift. The fact that we referred all data to the lesion side would have taken such a lesion-side-based initial misalignment partially into account as a confounding factor. However, it is possible that the perception of the horizontal after tilts in various directions might have been different if we had started trials from the initial subjective rather than the true horizontal.

As our results showed a large number of significant differences in roll deviations corresponding to utricle stimulation, the question arises why saccular dysfunction does not show equally detectable consequences in pitch deviations. Saccular organs, having a higher resting discharge at normal head position, showed a lower sensitivity to being tilted than utricular afferents [Fernandez et al., 1972]. As the end position of tilting in our study was 5° in both pitch and roll direction, differences in saccular afferent output may have been too small to excite consistent differences between saccular-deficient and healthy individuals compared to those for the utriculus.

To detect the amount of influence of vision, we examined subjects first with their eyes open, then with their eyes closed. As patients with unilateral vestibular loss tend to sway more in the frontal plane [Allum and Adkin, 2003] and to veer to the side of their lesion while walking [Bisdorff et al., 1996], particularly in the absence of vision [Allum and Adkin, 2003], we expected increased deviation under the eyes closed condition if vision has a major impact on the perception of the upright. We observed only a trend towards greater ipsilesional group differences during the eyes closed condition for roll deviations. These results indicate that vision has no major influence on the perception of the horizontal under our test conditions. This may have been due to the large fixation distance (3 m) for the eyes open condition. In contrast, in some patients vision does play a crucial role in the compensation of some postural deficits due to vestibular loss: visual-dependent subjects rely more on visual cues, whereas visual-independent subjects rely more on vestibulo-proprioceptive cues [Guerraz et al., 2001]. As the subjective postural horizontal can be examined under eyes open and eyes closed conditions, the technique may help to detect patients that rely more on a proprioceptive input to compensate for a unilateral vestibular deafferentation.

We attempted to correlate the deficits in judgement of the subjective horizontal with deficits in balance control during a battery of stance and gait tasks. Consistent with the results of the subjective postural horizontal, greater trunk sway during both stance and gait tasks occurred more frequently in the roll than the pitch direction in the patients when compared to controls. Roll angle of sway during stance was the most frequent significantly increased parameter, especially if the tasks were performed with impaired visual (eyes closed) or proprioceptive inputs (on foam support). Thus, while our stance and gait tests provided only a measure of disability and not definitive information regarding the site of lesion, the tests provided results consistent with those of the subjective postural horizontal and reflected changes in functional capacity of the patients. It should be noted, however, that during the stance and gait tasks head accelerations may well have a suprathreshold for contralesion of vertical canal systems.

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