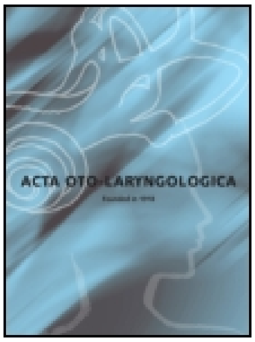

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Balance Control Near the Limit of Stability in Various Sensory Conditions in Healthy Subjects and Patients Suffering from Vertigo or Balance Disorders: Impact of Sensory Input on Balance Control

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Balance Control Near the Limit of Stability in Various Sensory Conditions in Healthy Subjects and Patients Suffering from Vertigo or Balance Disorders: Impact of Sensory Input on Balance Control

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The large inter-individual variability within the normal population, the limited reproducibility due to habituation or fatigue, and the impact of instruction and the subject's motivation, all constitute a major problem in posturography. These aspects hinder reliable evaluation of the changes in balance control in the case of disease and complicate objectivation of the impact of therapy and sensory input on balance control. In this study, we examine whether measurement of balance control near individualized limits of stability and under very challenging sensory conditions might reduce inter- and intra-individual variability compared to the well-known Sensory Organization Test (SOT). To do so, subjects balance on a platform on which instability increases automatically until body orientation or body sway velocity surpasses a safety limit. The maximum tolerated platform instability is then used as a measure for balance control under 10 different sensory conditions. Ninety-seven healthy subjects and 107 patients suffering from chronic dizziness (whiplash syndrome ($n = 25$), Meniere's disease ($n = 28$), acute ($n = 28$) or gradual ($n = 26$) peripheral function loss) were tested. In both healthy subjects and patients this approach resulted in a low intra-individual variability ($< 14.5\%$). In healthy subjects and patients, balance control was maximally affected by closure of the eyes and by vibration of the Achilles' tendons. The other perturbation techniques applied (sway referenced vision or platform, cooling of the foot soles) were less effective. Combining perturbation techniques reduced balance control even more, but the effect was less than the linear summation of the effect induced by the techniques applied separately. The group averages of healthy subjects show that vision contributed *maximum* 37%, proprioceptis *minimum* 26% and labyrinths *maximum* 44% to balance control in healthy subjects. However, a large inter-individual variability was observed. Balance control of each patient group was less than in healthy subjects in all sensory conditions. Similar to healthy subjects, patients also show a large inter-individual variability, which results in a low sensitivity of the test. With the exception of some minor differences between Whiplash and Meniere patients, balance control did not differ between the four patient groups. This points to a low specificity of the test. Balance control was not correlated with the outcome of the standard vestibular examination. This study strengthens our notion that the contribution of the sensory inputs to balance control differs considerably per individual and may simply be due to differences in the vestibular function related to the specific pathology, but also to differences in motor learning strategies in relation to daily life requirements. It is difficult to provide clinically relevant normative data. We conclude that, like the SOT, the current test is merely a functional test of balance with limited diagnostic value. *Key words*: *diagnostic value*, *sensory organisation test*, *video posturography*.

INTRODUCTION

Many patients (1) with complaints of vertigo or balance disorders are characterized by a normal outcome of the standard vestibular examination (spontaneous, gaze, saccadic, optokinetic, smooth pursuit, rotatory chair and caloric tests). Quantitative evaluation of balance control is therefore considered to be of additional value in allowing a more complete interpretation of the patient's complaints (2, 3). In the currently frequently applied sensory organization test (SOT), balance control is quantified in a control condition (Romberg with eyes open) and in five other sensory conditions to allow analysis of the impact of absent or misleading sensory input (4, 5). Unlike other vestibular tests aimed at diagnosing a lesion, posturography is considered as a functional test of balance with limited diagnostic capabilities (4, 6, 7). Goebel and Paige (8) reported that the SOT enhances identification of the balance system abnormalities in patients with and without vertigo, but alone it did not distinguish between patients with and without vertigo, and between central and peripheral disorders. The current SOT is insufficient to provide the clinically desirable levels of lesion specificity (1, 9). Patients with partially compensated lesions often show no abnormality (10), so detection and localization of the lesion is performed with more conventional tools, tools such as history, physical examination, audiometry and caloric testing. Stribly et al. (11), emphasized that it is usually necessary to apply tests with sensory conditions that are significantly difficult to really challenge the nervous system. It seems obvious to assume that deficits of the balance control system can be unmasked only if the patient is presented with a difficult self-adjustable test stimulus to challenge his own postural system capability.

We therefore developed an alternative measuring system to evaluate balance control near the individual limit of stability, where the test subjects are forced to perform optimally to prevent a fall. In this study we examined, in healthy subjects and patients suffering from dizziness, whether measurement of balance control in this way might reduce inter- and intra-individual variability, and increase specificity and sensitivity compared to the SOT.

SUBJECTS

All healthy subjects and patients were studied in accordance with the principles of the Declaration of Helsinki. After informed consent, 97 healthy subjects (50 females, 47 males) participated in the study. Age ranged from 17 to 68 years (females 19 to 68, males 17 to 66) with a mean age of 30.7 years (females 32.3, males 29.0). All healthy subjects showed a normal oto-neurological status in which standard vestibular testing (spontaneous, gaze, saccades, optokinetic, smooth pursuit, torsion swing, calorics) revealed no abnormalities. Also body sway velocity, body sway area, as well as the associated Romberg coefficients of all subjects as revealed by computed stabilometry were within the normal limits. The subjects had no history of neurological or musculo-skeletal problems that would affect their balance and orientation. They had no history of episodes of dizziness or had undergone any ear operation and were not taking any medication at the time of testing. Only subjects who considered themselves as physically moderately active were included (incidental but no regular sports activities).

In addition, 107 patients (41 males and 66 females, 17–76 years old, mean age 46.2 year) with persistent complaints of instability and/or vertigo for more than 9 months participated in the study. Only patients who showed a normal neurological status, normal outcome of the spontaneous, gaze, saccadic, optokinetic, and smooth pursuit test were included. In some patients, abnormalities were found with the torsion swing, caloric test and/or statolith function test. The patients had no history of musculo-skeletal problems that would affect their balance and orientation. The patients had not undergone any ear operation and were not taking any medication at the time of testing. The diagnosis of compensated acute peripheral function loss (APFL) was based on a sudden onset of severe vertigo with a third-degree spontaneous horizontal nystagmus with nausea and vomiting, as well as a caloric hyporeflexia; the symptoms decreased in all patients within 3 months, with normalization of all ENG findings apart from the caloric hyporeflexia, sometimes accompanied by a decreased VOR on the torsion swing test and a decreased statolith ocular reflex. Only patients with persistent vertigo and balance disorders were selected for this study. The diagnosis of gradual peripheral function loss (GPFL) was based on a not clearly perceived, gradual onset of mild vertigo and balance disorders with a normal ENG, apart from a caloric hyporeflexia sometimes accompanied by a decreased VOR on the torsion swing test and a decreased statolith ocular reflex. The diagnosis of definite Meniere's disease was made in agreement with the guidelines of the AAOHNS 1995 classification. Seventeen (out of 28 total) Meniere's disease patients showed a caloric hyporeflexia. All whiplash patients had persistent complaints of instability after rear-end motor vehicle collisions. All of them were considered as chronic cases according to the criteria of the Quebec task force on Whiplash-Associated Disorders (12) and showed normal responses on the caloric and torsion swing test. In the APFL group the caloric test showed a unilateral hyporeflexia in 25 cases and a bilateral hyporeflexia in 3 cases; the VOR induced in the torsion swing test was normal in 23 cases and reduced in 5 cases. In the GPFL group the caloric test showed a unilateral hyporeflexia in 19 cases and a bilateral hyporeflexia in 7 cases; the VOR induced in the torsion swing test was normal in 22 cases and reduced in 4 cases. In the Meniere's patients the caloric test was normal in 11 cases, showed a unilateral hyporeflexia in 14 cases and a bilateral hyporeflexia in 3 cases; the VOR induced in the torsion swing test was normal in 24 cases and reduced in 4 cases.

In 53 patients, ocular counter rolling (OCR) upon 40 degrees lateroflexion was measured as a clinical statolith function test using video oculography. Seventeen patients showed a reduced OCR upon lateroflexion (≤ 4 degrees), of which there were 4 out of 11 with a history of acute peripheral function loss and 4 out of 13 with a history of gradual peripheral function loss, whereas there were 5 patients out of 9 with Meniere's disease and 4 out of 20 with a whiplash injury.

METHODS

The experimental set-up composed of a high resolution (< 0.1 cm) home-built real-time infrared (IR) video body movement tracking system, a dynamic force plate (T-Post, Jaeger-Toennies GmbH, Wuerzburg, Germany) provided with a device for cooling the foot soles (Instrumental Service Maastricht University "ISMU", The Netherlands), a dual Achilles' tendon vibrator (ISMU, The Netherlands), a dynamic slide projection system (ISMU, The Netherlands and Jaeger-Toennies GmbH, Wuerzburg, Germany) and a modified Nystagliner system (Jaeger-Toennies GmbH, Wuerzburg, Germany) for data-acquisition (set at 50 Hz per channel) and stimulus control (platform, slide projection, vibrators).

The 50 Hz IR-video tracker system consisted of a video camera focused on the left side of the subject's body. The camera imaged the position of five active IR markers fixed to the ankle, knee, hip and shoulder joints and near the axis of head nodding. The IR marker positions (x, y in the anterior–posterior plane) were detected in the video frame, grabbed by a personal computer (PC) and subsequently transferred to the data-acquisition PC (Nystagliner). A conventional biomechanical model was used to calculate the position and velocity of the COG in the anterior–posterior plane based on the marker positions detected, the anthropomorphic data (size and weights of body components in relation to body length and weight). The model is described in detail elswhere (13, available on request). The delay between actual body movement and the calculated position of the COG was always less than 13 msec. Body sway velocity was calculated by differentiating the digitized position signal (3 points).

The data-acquisition PC also controlled the dynamic platform that could rotate up to 9 degrees maximum, with a maximum angular velocity of 50 degree/sec and maximum angular acceleration of 1,400 degree/sec^2 (maximum delay 18 msec). The rotation axis of the platform coincided with the axis through the ankle joints.

The dynamic slide projector imaged a random dot pattern on a transview screen (width 3.20 m, height 2.40 m), 50 cm in front of the subject. The slide was projected slightly out of focus for optimal visual impact. Slide position and orientation, along with the focal length of the projection lens, were controlled by four computer-driven synchro motors (maximum delay 2 msec). As a consequence, the image could rotate, translate and zoom in, zoom out to 'counteract' any body or head motion relative to the projection screen, or to mimic any motion of the visual reference frame. Besides the event and time control of the test procedures, the software was able to use 8 signals as an input to produce 8 output signals to control platform rotation (delay 18 msec) or slide position (delay 2 msec) according to a user-defined transfer function.

The vibration was applied through vibrators attached to the right and left Achilles' tendon by an elastic strip. The PC-controlled vibrator's DC motor (Simprop Electronic) housed in a cylinder allowing a certain degree of movement to govern the amplitude of the vibration with a maximum frequency of 250 Hz ($\pm$10 Hz) and a maximum amplitude of 0.2 cm. The cold supporting surface consisted of a metal box filled with ice water (about 1–3°C), specially designed to be placed on the dynamic platform without affecting its movement. The position of the rotation axis was affected by this procedure, but was not taken into consideration with respect to the calculations of performance.

EXPERIMENTS

General aspects

Subjects were asked to stand as stably as possible on the dynamic platform, bare feet, arms folded at the waist, looking straight ahead, facing the slide projection screen without leaning forward or backward during each test period of 20 sec. Temporal vision was blocked by mounting special goggles on the subject. Additionally, all subjects wore a headphone supplied with soft, non-distracting music to prevent spatial orientation on auditory cues. COG position and velocity were continuously measured by means of the video system. The basic platform movement consisted of three mutual harmonically unrelated frequencies (0.16, 0.42, 1.15 Hz) with an initial sum of all three amplitudes of 2 degrees. During the duration of the experiment the amplitude of the platform movement (APM) increased automatically in time with 0.004 degree per 20 ms (0.2 degree/sec) as long as COG velocity was below 5 cm/sec. APM was fixed when the subject could maintain the COG velocity within the range 5–8 cm/sec. APM automatically decreased with 0.004 degree per 20 msec (0.2 degree/sec) when COG velocity exceeded 8 cm/sec. APM also decreased whenever 50% (3.125 degrees) of the maximum angle (6.25 degrees) of forward or backward leaning ("the cone of stability") was reached irrespective of the actual body sway velocity, to prevent the subject from falling. Balance control was expressed in terms of the tolerated platform movement 'TPM' quantified as the average APM tolerated during the 20 sec test duration. The effect of manipulation of the sensory inputs on the TPM was studied in 10 sensory conditions. In all subjects (patients and healthy subjects) the sensory conditions PRM, SRP, VIB, COL, SRS, EC, SRP&S, EC&SRP (see below) were evaluated; in 13 healthy subjects and 20 patients (5 patients of each patient group) these tests were performed twice to investigate reproducibility. Eleven healthy subjects (6 females and 5 males) were also tested in condition SRP&VIB and EC&SRP&VIB. The sensory conditions are described in Table I, which also includes all other abrrevitions used in this article.

Table I. *List of abbreviations and definition of sensory conditions*

APFL	acute peripheral vestibular function loss.
GPFL	gradual peripheral vestibular function loss.
APM	amplitude of the platform movement (degrees).
TPM	average APM tolerated during the 20 sec test duration (degrees).
SOT	sensory organization test
COG	centre of gravity
PRM (1)	*pseudo-random movement*
The subject's base of support was destabilized by the pseudo-random rotation of the platform alone during normal vision (projection of a random dot pattern).	
SRP (2)	*pseudo-random destabilization with a sway referenced platform*
Subjects were tested similarly as described in Condition 1; however, besides the basic pseudo-random movement, the platform angle moved right from the start also according to the body sway angle relative to the vertical with a positive feedback gain of 0.5.	
VIB (3)	*pseudo-random destabilization with vibrators*
Subjects were tested similarly as described in Condition 1 with activated vibrators attached to the right and left Achilles' tendon.	
COL (4)	*pseudo-random destabilization with cooled foot soles*
Subjects were tested similarly as described in Condition 1; however, the supporting surface was equipped with a metal box filled with ice water. Prior to this test, the subjects were seated on a chair, the feet placed on the cooling device (mounted on the rotating platform) for 5 min. After the feet were pre-chilled, the subjects were asked to stand up and the actual measurement took place immediately thereafter.	
SRS (5)	*pseudo-random destabilization with a sway referenced visual image*
Subjects were tested similarly as described in Condition 1; however, the projected image of the slide moved right from the start according to the posterior-anterior sway of the COG (positive feedback gain of 1.0).	
EC (6)	*pseudo-random destabilization with eyes closed*
Subjects were tested similarly as described in Condition 1; however, with eyes closed to prevent any visual orientation.	
SRP&S (7)	*pseudo-random destabilization with a sway referenced platform and visual image*
Subjects were tested similarly as described in Conditions 2 and 5 combined.	
EC&SRP (8)	*pseudo-random destabilization with eyes closed and a sway referenced platform*
Subjects were tested similarly as described in Condition 2; however, with eyes closed to prevent any visual orientation.	
SRP&VIB (9)	*pseudo-random destabilization with a sway referenced platform and vibrators*
Subjects were tested similarly as described in Condition 2; however, also activated vibrators were attached to the right and left Achilles' tendon.	
EC&SRP&VIB (10)	*pseudo-random destabilization with eyes closed, a sway referenced platform and vibrators*
Subjects were tested similarly as described in Condition 9; however, with eyes closed to prevent any visual orientation.	

Data-analysis

The APM during each experiment was recorded as a function of time and TPM was calculated. To evaluate the effect of perturbation, the TPM obtained in each experiment was related to the TPM calculated in condition PRM. The effect of age on the TPM was examined calculating the Pearson correlation coefficients of TPM with age (before and after logarithmic, quadratic or exponential transformations) and by comparison (Mann-Whitney U tests) of the TPMs obtained in four age groups 15–30 ($n = 29$), 31–45 ($n = 29$), 46–60 ($n = 25$), 61–75 ($n = 14$). Additionally, the effect of gender on TPM was examined (Mann-Whitney U tests). Statistical analysis (Mann-Whitney U test, Friedman and Wilcoxon matched pairs signed rank test, discriminant analysis, hierarchical and Kruskal-Wallis cluster analysis) was performed using commercially available software (PC-SPSS version 7.52 for Windows).

RESULTS

Healthy subjects

The mean and standard deviations (SD) of the TPM at condition PRM, SRP, VIB, COL, SRS, EC, SRP&S, EC&SRP ($n = 97$) and at condition SRP&VIB and EC&SRP&VIB ($n = 11$) are shown in the bar graph of Fig. 1. Reproducibility varies from 4.3% to 13.2% depending on the sensory conditions PRM, SRP, VIB, COL, SRS, EC, SRP&S, EC&SRP ($n = 13$, repeated measurements). No statistically significant effect of age or gender is found upon TPM, irrespective of the sensory condition ($n = 97$, $p > 0.05$, $\rho < 0.451$).

TPM decreases significantly ($p < 0.0005$) in all other nine sensory conditions compared with the control condition PRM. All differences observed between these nine sensory conditions are significant ($p < 0.01$), except for the difference between condition SRP and COL ($p = 0.80$) and between condition EC&SRP and EC&SRP&VIB ($p = 0.81$). Balance control reduces maximally via the visual input chan-

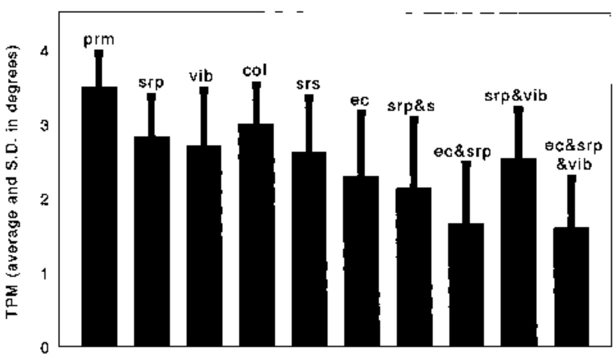

Fig. 1. Balance control in healthy subjects. Mean and SD (Y-axis) of TPM in 10 different sensory conditions (X-axis). For abbreviations, see Table I.

nel in condition EC (35%) and via the proprioceptive channel in condition SRP&VIB (26%). Balance control is maximally reduced in condition EC&SRP&VIB (56%).

Patients

The mean TPM in eight different sensory conditions per diagnostic group is shown in Fig. 2. The data obtained in healthy subjects are displayed as well to allow easy comparison. Just as with the healthy subjects, balance control decreases significantly ($p < 0.0005$) for all patient groups in all other seven sensory conditions compared to the control condition PRM ($p < 0.01$). Reproducibility varies from 3.9% to 14.5% ($n = 20$) depending on the sensory conditions

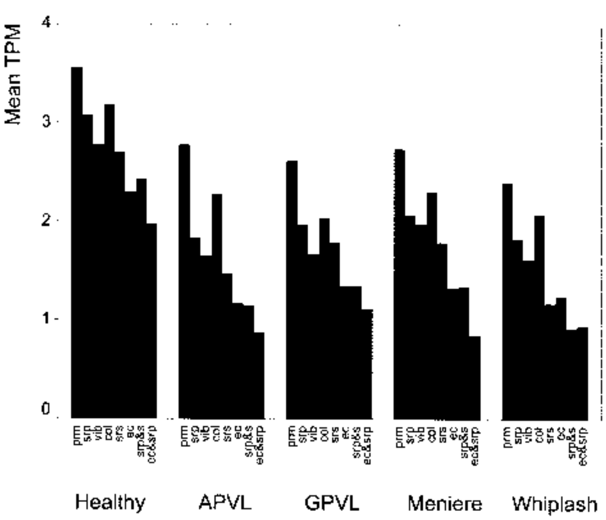

Fig. 2. Mean TPM in eight different sensory conditions per diagnostic group (healthy subjects (abbreviation: healthy), patients suffering from persistent vertigo and balance disorders after an acute (abbreviation: APFL) or gradual (abbreviation: GPFL) arisen peripheral vestibular function loss, Meniere's disease (abbreviation: Meniere) and whiplash patients (abbreviation: Whiplash)). For all other abbreviations, see Table I.

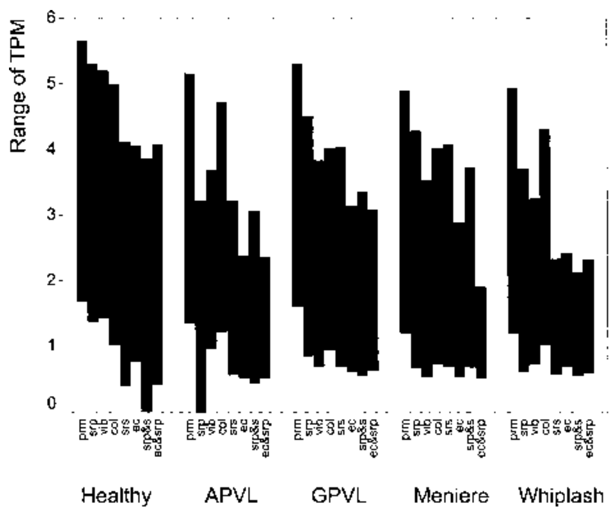

Fig. 3. 95% confidence interval of TPM in eight different sensory conditions per diagnostic group (healthy subjects (abbreviation: healthy), patients suffering from persistent vertigo and balance disorders after an acute (abbreviation: APFL) or gradual (abbreviation: GPFL) rise in peripheral vestibular function loss, Meniere's disease (abbreviation: Meniere) and whiplash patients (abbreviation: Whiplash)). For all other abbreviations, see Table I.

PRM, SRP, VIB, COL, SRS, EC, SRP&S, EC&SRP, but was not significantly different between the patient groups ($p > 0.05$).

With the exception of the Whiplash patients, balance control reduced more in condition EC than in condition SRS ($p < 0.03$); the reduction in the Whiplash patients was no different ($p = 0.83$). Compared to condition PRM, balance control was more reduced in condition VIB than COL or SRP in all but the Meniere's disease patients ($p < 0.007$). In all patients, balance control reduced equally in condition SRP and COL ($p > 0.05$). In EC&SRP balance control reduced more than in condition SRP&S ($p < 0.013$), except for the Whiplash patients ($p > 0.05$).

Balance control of all patient groups is less than that of the healthy subjects for all sensory conditions ($p < 0.002$). With the use of discriminant analysis we explored which sensory conditions contributed most to a possible discrimination between healthy subjects and the patients. Conditions EC, EC&SRP and SRS appeared to contribute maximum, with 90.6% of all cases correctly classified (93.5% of the healthy subjects, 89.3% of the patients).

No significant differences were observed between the four diagnostic patient groups, irrespective of the sensory condition ($p > 0.05$), except for the conditions SRS and SRP&S between Whiplash and Meniere patients ($p < 0.008$), which made a discriminant analysis worthless.

The 95% confidence intervals of TPM in eight different sensory conditions per diagnostic group are shown in Fig. 3, and point to a large inter-individual variability.

Compared to healthy subjects, all patients showed a reduced performance upon the posturography test. As all patients with a history of an acute or gradual peripheral function loss were included, only in the case of a caloric hyporeflexia was the correlation between posturography and calorization 100% for these two groups. Performance was maximally reduced in the case of a bilateral caloric hyporeflexia (not areflexia) but not *significantly* different ($p > 0.05$) from the patients with a unilateral caloric hyporeflexia.

Seventeen out of 28 Meniere's disease patients showed a caloric hyporeflexia; in this group no significant difference in balance control was observed between those with and those without a caloric hyporeflexia, regardless of the sensory condition ($p > 0.05$). No abnormalities with the caloric test were observed in the whiplash patients, who nevertheless also showed a reduced balance control not significantly different from the patients with a peripheral vestibular function loss. Irrespective of the sensory condition, balance control in Meniere's disease patients and patients with a history of a (gradual or acute) peripheral function loss was not different when comparing patients with a normal or abnormal torsion swing test (abnormal $n = 13$, normal $n = 69$). Similarly, balance control was not different ($p > 0.05$) in any patient group when comparing the outcome of the statolith test (abnormal $n = 17$, normal $n = 36$).

DISCUSSION

Balance control near the limit of stability in healthy subjects

Balance control was quantified near the limit of stability, assuming that under these conditions performance might be more reproducible and that balance control might be more sensitive to any perturbation than at quiet stance. Indeed, balance control and the effect of perturbation showed good reproducilibility (test-retest variation better then 13.2 in healthy subjects, 14.5% in patients). Reproducibility of the SOT (trial 1 to trial 3 change) varies with the sensory conditions. In condition 6 (SRP&S), the average trial 1 to trial 3 change is 9 out of an average score of 69 (13%), but both change as averages have wide ranges (± 26.4 and 48 to 100, respectively), suggesting a far greater trial to trial variability. We therefore concluded that the test–retest variation near the limit of stability is less than that of the conventional SOT, which was initially considered as a positive finding for further exploration of this approach.

We observed that balance control was maximally affected by closure of the eyes and by vibration of the Achilles' tendons. On average, the other techniques applied were significantly less effective. Closure of the eyes clearly had significantly more impact on balance control than a sway referenced visual surround. This result is in agreement with the results of the SOT in young healthy subjects (Nashner, pers. comm., 1995). Many subjects indicated that it took a short while to identify the inaccurate visual cues, but that ultimately they were able to use it as a reference. One might therefore hypothesize that even "inaccurate" visual information can be used for orientation relative to the earth vertical.

Vibration of the Achilles' tendons appeared to be the most effective method disturbing the somatosensory-proprioceptive contributions to balance control. The combination of vibration and a sway referencing platform was even more effective. Magnusson et al. (15, 16) combined the vibration technique with chilling of the foot soles in order to obtain an intense disturbing influence on the system. In our study the effect of chilling the foot soles was not very effective. However, we used a milder cooling technique than reported in Magnusson's study: the feet were chilled 5 min prior to the actual measurement, whereas Magnusson chilled the feet 30 min prior to the experiment. Long cooling was not appreciated by our subjects. The vibration technique seems to be an effective, easy and cheap alternative for the sway referencing technique, which requires a motor-driven platform, although the latter equipment is obligatory if a measuring technique is used as presented here.

The impact of disturbing the sensory subsystems near the limit of stability is generally greater than observed with the SOT in relatively quiet stance (Table II, data extracted from the normative graphs of the Equi-test manual (17), maximum estimates based on the assumption that the SOT score is 100 in

Table II. *Decrease of balance control by perturbation near the limit of stability (TPM) and the SOT (upper row: average and, in parentheses, 5th percentiles in 97 healthy subjects aged 17–68 years). For abbreviations see text*

	SRP	SRS	EC	SRP&S	EC&SRP
SOT	18 (30)%	9 (14)%	8 (15) %	33 (52)%	31 (48)%
TPM	14.49%	25.15%	34.79%	33.21%	46.39%

condition 1). In the visual conditions (EC and SRS), the average effect is 3–4 times greater at the limit of stability than it is at quiet stance. Perhaps vision is more important at the limits of stability because it is primarily used as a sway detector or to reduce slow drift of the COG near the limits of stability and contributes much less in quiet stance far from the limits of stability.

The combination of perturbation techniques near the limit of stability is fairly effective, but the effect of perturbation by a combination of techniques is not a simple linear summation of the effect induced by the techniques applied separately. For example, in healthy subjects: EC reduces balance control by 34.79%, SRP by 14.49% and SRS by 25.15%. However, EC&SRP reduces balance control not by $34.79 + 14.49 = 49.28\%$, but by 45.81%, and SRP&S reduces balance control not by $25.15 + 14.49 = 39.64\%$ but by 33.21%. These differences are significant (Wilcoxon, $p = 0.01$). The non-linearity is more pronounced in the case of the combination of three perturbation techniques: EC&SRP&VIB separately: $36.63 + 19.65 + 23.25 = 79.53\%$, but together: 55.94%. This behaviour is observed in the patient groups as well and can be explained by many, but not mutually exclusive, mathematical models that describe balance control in terms of input–output relations (selective thresholds, saturation effects, interaction between sensory inputs, etc.). Despite this, it is still valid to conclude that vibration of the Achilles' tendons and closure of the eyes are the most effective perturbations of proprioceptive and visual input in healthy subjects and patients.

Based on these results one could speculate about the relative contributions of the visual, proprioceptive and vestibular systems to balance control. To do so, two fundamental assumptions have to be made. First, one needs to assume that no other than visual, vestibular or proprioceptive sensory modalities contribute. This assumption is still much disputed. For example, the existence of special gravito-receptors in the human body has been postulated (18). Second, one needs to assume that the different techniques used disturb the visual and/or proprioceptive system completely. This assumption certainly holds for the EC conditions, but most likely does not hold for the proprioceptive system: the balance control system will certainly receive relevant input from joints and ligaments all over the body that is not affected by the perturbation techniques applied here. Nevertheless, the following estimate is made to give an indication of the possible relative magnitudes of the various sensory contributions. At first glance, manipulation of the visual system seems to affect balance control to a greater extent than the proprioceptive system (34.79–36.63% versus 26.1%). Eyes closed combined with a sway referenced platform is effective in "isolating" the vestibular system to some extent in agreement with the literature (19, 20). The combination of eyes closed with a sway referenced platform and vibration leads to a maximum decrease of balance control of about 56%. The labyrinthine input can therefore be estimated to contribute *maximally* 44% to balance control under these conditions, as at least proprioceptive perturbation can be assumed to be far from complete. In summary, these data suggest that, on average, vision contributes *maximum* 37%, propriocepsis *minimum* 26% and the labyrinths *maximum* 44% in healthy subjects, and that depending on the available sensory information and acquired balance control strategies, weighting factors of the sensory inputs may vary within these margins.

The impact of propriocepsis on balance control is twofold. First, propriocepsis, along with visual and vestibular input, serves to perceive the spatial orientation of the body to induce appropriate motor action. Second, propriocepsis serves in the feedback loops of all motor-control systems themselves, and plays an important role on the effector side of the balance control system. As the contribution of the propriocepsis on balance control is studied through detection of motor activity (motion), the question is whether we can ever discriminate between these two aspects with the current methodologies and get a reliable estimate of the first impact.

The results discussed so far refer to the evaluation of the *averaged* values of TMP in the population of 97 healthy subjects. The analysis of the individual data reveal differing results: sensitivity for the various perturbation techniques varies widely between subjects. This might be due to differences in motor learning strategies acquired in relation to daily life requirements.

Balance control does not depend on gender or age. The latter finding is remarkable in the light of the literature that indicates that sway velocity control decreases starting from the 6th decade (14), although this only seems to be a consistent finding in conditions when visual or somatosensory input is altered, or when standing on one leg or leaning forward. However, the inclusion criteria applied in our subjects may play a role in this respect. The 14 aged subjects (> 60 years) admitted to our study were pre-selected like all other subjects based on normal stabiliometry (normal sway velocity), the absence of musculo-skeletal problems that would affect their balance and were physically moderately active: these subjects might therefore represent the group of elderly with a relatively good balance control.

Discrimination between patients and healthy subjects

The influence of peripheral vestibular dysfunction on the vestibulo-spinal reflex has been investigated by many authors (21, 22). Norrè and Forrez reported that a normal posturography test outcome was found in 32.5% of the patients with peripheral vestibular disorders. In another report by Norrè (21), normal results were found in 25.3% in a group of patients with Meniere's disease. Morrison et al. (23) found no significant difference between normals and 17 patients with Meniere's disease using custom-built posturography. Hamid et al. (24), using the SOT, reported that the sensitivity of the abnormal sensory pattern provided by the SOT is near 90%. In contrast, Barin et al. (10) reported that the SOT outcome in patients with unilateral peripheral vestibular loss is within normal limits. They reported that significant differences were found only with different head orientation (head extension or tilt). In 338 patients with peripheral vestibular disorders, it was reported (9) that the sensitivity of the SOT was only 40%.

The clinical usefulness of posturography was recently criticized again (7). In a cross-sectional and prospective study of 22 patients with a bilateral and 7 with an unilateral vestibular function loss (VOR measured with calorics and torsion swing), vestibulospinal function was assessed by the SOT, paced and free gait analysis, and clinical tests of timed gait and standing. SOT scores for the patients did not or at best poorly correlate with any accepted measure of vestibulo-ocular function, clinical measures of balance control, and dynamic gait-performance measures. It was concluded that the SOT did not assess vestibulospinal function. Lacour et al. (25) investigated balance control in a homogeneous population of 50 unilateral Meniere's disease patients 1 day before unilateral vestibular neurotomy, and during the time-course of recovery (1 week, 2 weeks, 1 month, 3 months and 1 year). Data from the patients were compared with those recorded in 26 healthy, age- and sex-matched participants. It was concluded that, in both healthy participants and patients before surgical treatment, subjects have a remarkably different selection of sensory orientation references depending on personal experience, leading to a more or less heavy dependence on vision. After neurectomy, some patients showed a change of sensory strategy and some did not; visual-dependent patients changed into visual less dependent and vice versa. Apparently, sensory dependence seems to depend strongly on the individual, which makes it difficult to define a disease-specific pattern.

It is difficult to understand the background of the discrepancies in the literature. First, it has to be stressed that postural performance is context-dependent: any change in the sensory conditions may activate different control systems and efference copies and lead to confusing results in the same subject. Also, major abnormalities in balance control revealed by stabilometry or dynamic posturography seem only to be present directly after the onset of an acute vestibular function loss or vertigo attack, and many authors indicate that the findings tend to normalize within several weeks after the onset thanks to central compensation and vestibular habituation training. Strikingly, none of our patients suffered from a *recent* acute vestibular function loss, but nevertheless we found a significant decreased balance control, in all sensory conditions, compared to healthy subjects. This suggests that quantification of balance control near the limit of stability is more sensitive than the standard procedures used by stabilometry or the SOT. However, the results of the statistics involved (Mann Whitney U-tests) refer to an evaluation of the population values of TMP and do not indicate whether proper discrimination can be made on an individual basis. We observed that the test–retest variability in patients is not more than that observed in healthy subjects (14.5% versus 13.2%), which indicates that the wide range of TPM scores observed is due to inter-individual variability. These individual data therefore indicate a complication: sensitivity to the various perturbation techniques seems to vary widely between subjects. In line with Lacour et al. (25), this suggests that the contribution of the sensory inputs to balance control differs considerably per individual and may simply be due to differences in the vestibular function related to the specific pathology, but also to differences in motor learning strategies in relation to daily life requirements.

This aspect limits the discrimination between patients and healthy subjects, and also the localization of deficits of the three sensory subsystems in patients based on measurements of balance control. In agreement with this, no clear-cut, significant differences are observed between the four diagnostic groups, only some minor findings. The discriminant analysis indicated that the "most difficult" conditions EC, SRS and EC&SRP are also the most relevant: with the outcome of these three conditions in 90.6% of cases, patients and healthy subjects could be distinguished from each other. This indicates that classification can be achieved even on an individual basis; this "predictive" aspect needs verification in a second study using the selection parameters calculated in this study. Unfortunately, discrimination is not precise, no distinction can be made into a patient category and no specific pattern was observed that could be correlated to a patient category.

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