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SENSORY REWEIGHTING IN CONTROLS AND STROKE PATIENTS

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ABSTRACT

Objective: to test sensitivity to proprioceptive, vestibular and visual stimulations of stroke patients with regard to balance.

Method: The postural control of 20 hemiparetic patients after a single hemispheric stroke that had occurred at least 6 months before the study along with 20 controls was probed with vibration, optokinetic, and vestibular galvanic stimulations. Balance was assessed using a force platform (PF) with two miniature inertial sensors placed on the head (C1) and the trunk (C2) under each sensory condition and measured by 3 composite scores as the mean displacement of the body (PF, C1, C2) during the stimulation. A subject with a composite score greater than the 75th percentile of the composite scores found in the control subjects was arbitrarily considered to be sensitive to that stimulation.

Results: Both control and stroke patients showed large inter-individual variations in response to the three types of sensory stimulation. Among the hemiparetic patients, nearly 65% were sensitive to the optokinetic stimulation, 60% to the galvanic stimulation and 65% to the vibration stimulation. In contrast to the control group, all the hemiparetic subjects were sensitive to at least one type of stimulation.

Conclusion: Stroke patients are highly dependent on visual, proprioceptive and vestibular information in order to control their standing posture and individually differ in their relative sensitivity to each type of sensory stimulation.

Significance: Contrarily to what one might suppose, the increased visual dependence manifested by stroke patients does not necessarily entail any neglect of proprioceptive and vestibular information.

KEYWORDS: POSTURAL CONTROL, STROKE, SENSORY DEPENDENCE, HEMIPLEGIA

HIGHLIGHTS

1-Stroke patients are highly dependent on visual, proprioceptive and vestibular information in order to control their standing posture.

2-They individually differ in their relative sensitivity to each of these sensory stimulations.

3-Contrarily to what one might suppose, the increased visual dependence manifested by stroke patients does not necessarily entail any neglect of proprioceptive and vestibular information.

INTRODUCTION:

Balance maintenance involves complex sensorimotor transformations that must integrate several sensory inputs and coordinate multiple motor outputs to muscles throughout the body (Ting and McKay, 2007, Guerraz and Bronstein, 2009). Firstly, the integration of posture and movement utilizes anticipatory and reactive postural control mechanisms, both of which are modulated by sensory input and influenced by learning and experience (Massion, 1994). Secondly, sensory systems are involved in the representation of the body in space and make up the system of coordinates on which the body's postural control is based (Merfeld et al., 1999). Three types of sensory information are available. Visual information contributes to determination of the orientation of objects in space and to detection of movements, including postural oscillations, whatever the orientations of objects or of the body. Somatosensory information provided by muscular, joint, and cutaneous receptors encode data on relative head, trunk and limb position in space. Finally, vestibular information encodes head position and linear and angular head accelerations, thereby helping to inform the brain both about body orientation and movement. Continuous reweighting of these three types of sensory information is required for efficient, flexible, context-dependent postural control as has been shown by numerous studies since the pioneering publication of Nashner (1976). Computational methods and the application of Bayes theorem have been used to form hypotheses about how information from different sensory modalities are weighted and combined with expectations based on past experience so as to obtain optimal estimates of perceptual variables to control the motor system (Angelaki and Cullen, 2008, Angelaki et al, 2009).

Sensory reweighting is also critical with regard to recovery of balance control in pathological conditions, notably in stroke patients. These patients display complex combinations of sensory, motor, cognitive and emotional impairments. Deficiencies in postural control may impede their ability to independently perform daily living activities and, more particularly, affect their gait, which is an excellent predictor of future autonomy maintenance or achievement, and consequently a tool allowing for accurate estimation of patient-perceived disability following rehabilitation. It is therefore important to evaluate sensory reweighting in stroke patients so as to set up a physiotherapy approach aimed at optimally promoting balance recovery subsequent to stroke (Geurts et al, 2005). Most stroke patients have been found to be excessively reliant on visual information to control their posture in both the frontal and sagittal planes (Corriveau et al, 2004, Bonan et al, 2006, Yelnik et al, 2006). The preponderant role of visual information tends to become evident shortly after a stroke, and some studies have suggested that a rehabilitation program employing visual deprivation so as to promote the use of somatosensory and vestibular inputs may reduce visual dependence (de Haart et al, 2004, Bonan et al, 2004). Proprioceptive information could also be used as efficiently as in a control group to improve postural control in stroke patients deprived of visual information (Di Fabio and Badke, 1991). However, in cases where patients have experienced sensorial conflicts, severe balance problems often persisted for more than a year after the stroke (Bonan et al, 2004). Moreover, in stroke patients, sensory stimulations can be used to normalize to a large extent the postural deficits, and this also holds true for visual stimulations using prism adaptation (Tiliket et al, 2001, Rode et al, 2006 for a review), for vestibular stimulations (Rode et al 1997, Marsden et al 2005) and for somatosensory stimulations (Pérennou et al, 1998, 2001, 2006 for a review).

In this context, the objective of the present study is to test the sensitivity to proprioceptive, vestibular and visual stimulations of stroke patients with regard to balance. The postural control of 20 stroke patients standing at rest was challenged by three types of sensory stimulations: vestibular galvanic stimulations, tendon vibration and optokinetic stimulations within six months following the stroke. Postural sway was quantified using a force platform and two miniature inertial sensors placed on the head and the trunk. The results were compared to those recorded for a group of 20 age-matched control subjects.

METHODS

Participants

The patient group consisted of 20 subjects (13 men and 7 women) whose mean age was 51.4 plus or minus 10.5 years (range 26– 67 years). The patients included had recently experienced their first and only cerebral hemispheric stroke, resulting in at least initial motor and balance impairment. They had to be able to remain standing without human or device assistance for sixty seconds. Patients were excluded when they were over 75 years, if they had perturbed vigilance, a pre-stroke history of neurological disturbances, vertigo, vestibular dysfunction, amblyopia or diplopia. Aphasia, even if severe, was not an exclusion criterion because the procedure was passive and easy to understand. Before testing, each patient was informed of the procedure and had to give his or her consent. We then performed a complete neurological examination in which the following items were examined: motor impairment, using the motricity index (Collin and Wade, 1990), functional independence by the Barthel scale (Mahoney and Barthel, 1965); visual field, assessed at the bedside and confirmed by Goldman campimetry when a visual field defect was suspected. Balance, was estimated by Berg Balance Scale (Berg et al, 1989) and the timed up and go test (Podsiadlo and Richardson, 1991). An ENT examination was conducted for patients with a strong optokinetic reaction. No peripheral disorders were diagnosed. All of the patients were explored by CT scan or MRI of the brain and brain stem, and any tumor, stroke or other pathology of the posterior fossa led to exclusion. The size of the stroke was assessed by a neuroradiologist: using the Talairach classification, the cerebral hemisphere was divided into 10 areas (Talairach and Turnoud, 1988). The lesion was classified as “small lesion” if 1 or 2 areas were affected, “medium lesion” for 3 or 4 areas, and “large lesion” if more than 5 areas were affected. The presence or absence of lesion in the Parieto Insular Vestibular Cortex (PIVC), an area known to be of crucial importance for integration of multisensory information, was ascertained. Twenty consecutive patients were studied (Table 1): 9 had a right hemispheric lesion (RHL) and 11 a left hemispheric lesion (LHL). The stroke, assessed on CT scan or MRI, was hemorrhagic in 7 patients and ischemic in 13. All of the ischemic lesions involved the middle cerebral artery territory.

The control group consisted of 20 control subjects (12 men and 8 women) whose mean age was 43.8 plus or minus 16.5 years (range 23 – 76 years). Because of a technical problem, parts of data from the inertial sensors placed on the head and trunk were lost for one control subject. Mean age did not differ in controls, RHL patients and LHL patients. They were excluded if they presented musculoskeletal, vestibular, visual, or somatosensory impairments. None of the control subjects were taking medication known to interfere with postural control.

The study was reviewed and approved by the Comité de Protection des Personnes, Ile de France IV (number 2007/28). The subjects signed an informed consent form before participating in the study. When presenting the experiment, care was taken to keep them uninformed with regard to the perceptual effects of the vestibular, visual and proprioceptive stimulations and the goals specific to the study. All procedures were performed in accordance with the ethics review board of the CNRS (Centre National de la Recherche Scientifique).

Quantification of postural control

For balance evaluation, subjects stood barefoot on a double force platform (FeeTest of Technoconcept®) consisting of two adjacent force platforms while measurements were made in double-leg stance with their feet placed parallel 12 cm apart, each placed on two force transducers that recorded the vertical ground reaction forces (Fig 1). The placement of the feet was traced on the ground to ensure a constant placement of the subjects during all trials. The subjects were asked to stand at ease, to look straight ahead with their head erect and their arms hanging by their sides. The position of the center of pressure (CoP) was calculated from the ground force reaction force. The data were collected with a sampling frequency of 40 Hz. Movement of the head and the trunk was recorded using two inertial sensors~~.~~ One of them was placed on top of the subject's head (denoted as C1) and the other on the subject's back (denoted as C2) as shown in figure 1. These sensors (Xsens sensors MTx ®) are miniature inertial measurement units with integrated 3D magnetometers (3D compass), with an embedded processor capable of calculating roll (around the Y axis), pitch (around the X axis) and yaw angles (around the Z axis) in real time, as well as outputting calibrated 3D linear acceleration, rate of turn (gyro) and (earth) magnetic field data. Both sensors synchronously recorded movement at 50Hz. The fixation on the trunk and on the head was made using medical tape or on a cap placed on the subjects' heads.

Stability of standing posture

Subjects were asked to stand still, barefoot, arms hanging freely, eyes open, for two trials lasting 35 seconds separated by 1- to 3-minute periods where they were seated. Postural instability was quantified by the variance of the center-of-pressure (CP) movements along the mediolateral axis (Var-CP, mm^2). Among various parameters aimed at evaluating postural instability, variance of the CP movements is known to be one of the least sensitive to data recording conditions, with high test–retest reliability. We chose variance along the mediolateral axis because in stroke patients a more marked instability was found at rest in the frontal plane than in the sagittal plane (Marigold and Eng, 2005, de Haart et al., 2004, Manor et al., 2010). Instability was diagnosed when variance was >7 mm^2 along the ML axis (Guillebastre, 2012).

Sensory stimulations

The experiment lasted about 1 h and was divided into three sessions involving either optokinetic, vestibular or proprioceptive stimulations (Figure 1). The three types of stimulations were applied to challenge postural control both in the pitch (anteroposterior) and roll (mediolateral) plane; several studies have shown that motor control differs in these two planes (Allum et al., 2003, Maki et al, 1994, Carpenter et al, 2001, Matjacic et al, 2001). Twelve types of stimulations were successively tested in the same order for all subjects so as to induce postural sway to the right, to the left, fore and back. Each trial began with a 15-second baseline period, with no stimulation, followed by a 35-second period of stimulation and a final 20-second period of observation with no stimulation.

Proprioceptive stimulation: Electromagnetic Vibrators (VB 115, Technoconcept ®) were adjusted manually perpendicular to the tendon of the muscles to be stimulated. Each cylindrical vibrator head was 7 cm long and 3 cm diameter. Mechanical vibrations (pulse duration: 5 ms, amplitude: 1 mm peak to peak) were delivered at a frequency of 50 Hz on the triceps surae and tibialis anterior et 90 Hz on the gluteus medial. The duration and the frequency of the stimulation was controlled by a software program and lasted 35 s. First, the subjects' tolerance to the vibrations was assessed by exposing them to several stimulations on various muscle tendons. Vibratory stimulation was applied in a lighted room eyes open, first on the tendon of the triceps sural muscle, then on the tendon of the tibialis anterior muscles, and afterwards on the right and left gluteus medius muscles.

V*isual stimulation*: Optokinetic stimulation (OKS) was performed in a dark room without any visual reference cues. First the subjects' tolerance to the optokinetic stimulation was assessed by exposing them to several directions of stimulations in the dark. OKS was induced by numerous luminous spots, produced by a rotating sphere (Optotest, Technconcept®) placed just above the patient's head and going by on an oilcloth placed in front of the subject. For the experimental session, the speed of rotation was 60 degrees per second. The subjects were instructed to stare straight ahead at the stimulus pattern without attempting to follow the moving dots. Four types of visual stimulation were tested: the moving luminous dots were first oriented from top to bottom, then from bottom to top, and finally from right to left and from left to right.

Vestibular stimulation: Binaural bipolar Galvanic vestibular stimulation (GVS) (anode left–cathode right or vice versa) was delivered by 9-cm2 rectangular Ag–AgCl pregelled disposable electrodes placed over each mastoid in a lighted room, eyes open. The electrodes were secured with adhesive tape and an elastic bandage wrapped around the head. The GVSs were computer-controlled and delivered by a battery-isolated constant-current generator. First the subjects' tolerance to GVS was assessed by exposing them to four GVSs of increasing intensity (0.5, 1, 1.5, and 2 mA). The GVSs were trapezoidal: the current intensity linearly increased from 0 up to 2 mA in 3 s, and symmetrically decreased down to 0 mA after a plateau of 29 s. Thus the GVS lasted 35 s (3-s ascending ramp 29-s plateau 3-s descending ramp). The maximal intensity of 2 mA was chosen after a pilot investigation had demonstrated that it was easily tolerated. Four types of vestibular stimulation were tested: cathode placed on the right mastoid process and then on the left mastoid process with the head looking straight ahead ; cathode placed on the side of the cerebral lesion (or on the right side for the control subjects), and head turned to the right and then to the left.

Data analysis

Data from the platform: We analyzed the characteristics of the displacement of the projection of the centre of pressure (CoP) during the proprioceptive, visual and vestibular stimulations.

The displacement (in millimeters) during the stimulation was calculated as the mean displacement of the CoP during the stimulation (from 15 to 50 seconds) minus the mean position of the CoP in the initial resting period (from 2 to 13 seconds). The mean displacement was successively calculated for each direction (anterior, posterior, right and left) and for each type of sensorial stimulation (visual, proprioceptive and vestibular) and expressed in absolute value. We then calculated a composite score (Platform score: PF/ score) for each type of sensory stimulation as the mean of the absolute value of the displacement recorded in the anterior, posterior, right and left directions. The scores for visual, proprioceptive and vestibular stimulations were designated as PF/opto Score, PF/Vib Score, PF/galva Score. We also calculated the mean displacement in the medio-lateral direction as the mean of absolute value of the displacement recorded in right and left directions (PF/ML Score) and the mean displacement in the antero-posterior direction as the mean of absolute value of the displacement recorded in anterior and posterior directions (PF/AP Score) for each type of sensory stimulation.

Data from the inertial sensors: The data recorded from the sensor fixed on the head (C1) and on the trunk (C2) were computed in a similar way. Angular displacement (in degrees) during the stimulation was calculated as the mean angular displacement of the head (for C1) or trunk (for C2) during the stimulation (15 to 50 seconds) minus the mean angular position in the initial resting period (2 to 13 seconds). Mean angular displacement was successively calculated in the anterior, posterior, and right and then left directions for each type of sensorial stimulation (visual, proprioceptive and vestibular) and expressed in absolute value. We then calculated a composite score for each type of sensory stimulation as the mean of absolute value of the displacement recorded in the anterior, posterior, right and left directions. We obtained scores for visual, proprioceptive and vestibular stimulations, called C1/opto Score, C1/Vib Score, C1/galva Score, C2/opto Score, C2/Vib Score, C2/galva Score. We also calculated the mean displacement in the medio-lateral direction as the mean of absolute value of the displacement recorded in the right and left directions (C1/ML Score and C2/ML Score) and the mean displacement in the antero-posterior direction as the mean of absolute value of the displacement recorded in the anterior and posterior directions (C1/AP Score and C2/AP Score) for each type of sensory stimulation.

Statistics: As stated previously, the results of the reactions to the 3 sensory conditions were expressed as the angular displacement of the head (C1), trunk (C2) and the linear displacement of the CoP (PF) for the 20 patients with left-hemisphere or right-hemisphere lesions and were summarized by their median and Interquartile (IQD). First, these results were compared with the data for the normal subjects by using the Mann-Whitney *U* test, which was then used to compare the following groups: patients with right-hemisphere lesions; those with left-hemisphere lesions; those with a lesion involving, or not involving, the Parieto Insular Vestibular Cortex (PIVC); and those considered as unstable, or not unstable. Sizes were compared using the Kruskal-Wallis test. For age and time since stroke, groups were compared with the Student *t* test for unpaired data and with the Mann-Whitney *U* test for qualitative data (sensitivity and motor control). For all tests, the significance level was fixed at 5% by using SAS StatView software[c] or Cytel StatXact software. Principal component analysis (PCA): In addition to the composite scores cumulatively representing recorded (or observed) motion, the individual angular displacements in R (Roll or mediolateral), P (Pitch or anteroposterior) and Y (Yaw) directions, measured by the two Xsens sensors (C1 and C2), were likewise examined by PCA. In the case of multivariable data, PCA is a quantitatively robust method facilitating detection of the variables acting as the main driving forces of the observed event (in our case, motion) by examining their linear covariation. In this study, PCA was used to identify postural response patterns in control and hemiparetic subjects for different types of sensory stimulation. Absolute values of the vectors of temporal variation of the R, P and Y angles around their mean values were considered as the main "variables" and each unit of time as an "observation". Each of the angular displacements in three distinct directions was defined as a weighted sum of three orthogonal compounds (a sum of PCs).

RESULTS

Motor control was fairly good for all patients (mean score 60.8 SD 19). In 10 patients (≥66/100), it was slightly impaired; in the 10 others (<66), it was markedly impaired. Sensitivity was normal in 8 patients and impaired in 12. Patients with right-hemisphere lesions and left-hemisphere lesions were comparable in age, sex, time since stroke, motor control, and sensitivity. Stroke involved the PIVC in 5 patients (3 with left-hemisphere lesions, 2 with right-hemisphere lesions).

Stability of standing posture

Mean Var-CP of the stroke patients was 26.7, 95th percentile 22.8 mm$^{2.}$ Compared with controls, post-stroke subjects were more unstable (mean 26.7, 95th percentile 51.8 mm^{2} vs mean 4.4, 95th percentile 7.05 mm^{2}; $P < 0.003$). Among patients, 9 were classified as unstable; among control subjects, 5 were classified as unstable.

Classification of the subjects in terms of their responses to the three types of sensory stimulation

The composite scores for each subject are illustrated in fig 2. The hemiparetic subjects are labeled from H1 to H20 and the control subjects from N1 to N20. To clarify figure 2, both the hemiparetic and the control groups were ranked according to increasing sensitivity to the visual (optokinetic stimulation), vestibular (galvanic stimulation) and proprioceptive (vibratory) stimulations, using the sum of the angular head displacements (C1) during the three types of sensory stimulation as an index. The subjects were then classified using the C1 sensors because it was more discriminating than the trunk sensor (C2) or the PF when categorizing the subjects. In this figure, subjects H1 and N1 were the least sensitive to the three types of stimulation, while subject H20 and N20 were the most sensitive.

As seen in fig 2, subjects' postural reactions to the visual, vestibular and proprioceptive stimulations were quite heterogeneous. This was the case for both hemiparetic and control subjects and for the three types of data recorded i.e angular displacement of the head (C1 in fig 2), angular displacement of the trunk (C2 in fig 2) and displacement of the Centre of Pressure (CoP) measured by the force platform (PF in fig 2).

We arbitrarily chose the threshold of the 75th percentile to define sensitivity to a sensory stimulation. A patient with a composite score greater than the 75th percentile of the composite scores found in the control subjects was considered to be sensitive to that type of stimulation. In addition, we distinguished as highly sensitive to stimulation the patients with a composite score superior to the 90th percentile.

Amongst the control subjects (N1 to N20), we could likewise distinguish two types of profiles. One group of subjects was highly sensitive to one, two or three types of stimulation (N11, N13, N17, N18, and N19). Another group of subjects was highly insensitive to all of the sensory stimulations (N1 to N5, N7, N8, and N10). In between, an intermediate class of subjects (N6, N9, N12, N15, and N16) could be moderately reactive to one or two types of stimulation.

Among the hemiparetic patients, nearly 65% were sensitive (45% highly sensitive) to the optokinetic stimulation, 60% sensitive (35% highly sensitive) to the galvanic stimulation and 65% sensitive (25% highly sensitive) to the vibration stimulation. In contrast to the control group, all the hemiparetic subjects (H1 to H20) were sensitive to at least one type of stimulation. 75% of them were highly sensitive to one (n=9) or two (n=6) types of stimulation.

Due to temporarily noisy signals on some recorded data, only 19 of 20 hemiparetic subjects and 15 of 19 control subjects could undergo PCA. The heterogeneity of the postural reactions (inter-individual variations) to three different types of stimulation was much more obvious when the PCA scores were taken into account. The threshold of the 75th percentile, arbitrarily chosen for composite score analysis, was found to match a value of 0.5 in cases of PCA scores allowing for categorization of the subjects into “sensitive” and “non-sensitive” groups.

Postural responses to the three types of sensory stimulation

Vibratory stimulations

The vibration score was higher for C1 in hemiparetic patients than in control subjects (p=0.05) (table 2). PCA showed that significant difference between hemiparetic patients and controls for C1 depended on the more sizable contribution of weights in the P direction and not in the R direction. Angular displacements of the head (C1) and the trunk (C2) and displacement of the CoP (PF) induced by the vibratory stimulations were greater in the AP than in the ML directions in control (p=0.0007, p=0.001 and p=0.0004) (Table 3) and in hemiplegic patients (p<0.0001, p=0.001 and p=0.0002)

Optokinetic stimulations

The optokinetic score was significantly higher in hemiparetic subjects than in control subjects for C1 (p=0.001), for C2 (p=0.0001) and for PF (p=0.004) (table 2). The excessive visual dependency of hemiparetic patients in comparison to control subjects observed when using composite scores was likewise clear when using PCA scores. The PCA scores in the R and P directions of hemiparetic subjects calculated on the signals recorded on both C1 and C2 sensors were significantly higher than those of the control subjects for almost all sensitive and non-sensitive subjects.

The angular displacements of the head (C1) and the trunk (C2) induced by the optokinetic stimulations were greater in the AP than in the ML in hemiplegic patients (p=0.006, p=0.001) but not different for PF (p=0.1). There was no difference between AP and ML scores for C1, C2 and PF in control subjects (table 3).

Galvanic stimulations

The galvanic score was higher for C1 and C2 in hemiparetic subjects than in control subjects (p=0.002 and p=0.007) (table 2). PCA showed that the significant difference between galvanic score of hemiparetic and control subjects observed depended not on higher values in R or in P direction but rather on a combination of the movements recorded in these two directions.

Angular displacements of the trunk (C2) and displacement of the CoP (PF) induced by the galvanic stimulations were greater in AP than in ML directions in controls (p=0.002 and p=0.001). However, in hemiplegic patients C1 and C2 and the PF displacements did not differ between ML and AP directions (Table 3)

Effects of motor control, sensitivity, and time since stroke

No significant correlation was observed between motor control, sensitivity, or time since stroke, on the one hand, and the composite scores, on the other, except between motor control and PF/ vibration score (p=0.05).

Influence of the location and size of the stroke

Patients with right- hemisphere lesions tended to have a higher C2/Galva score than patients with left-hemisphere lesions (p=0.052). The patients with a lesion involving the PIVC recorded a lower C1/Vib Score (p=0.01). The size of the lesion influenced displacement of the head under optokinetic stimulation (C1/Opto score, p=0.01).

Relationships between the response to sensory stimulations and postural instability

We found no significant correlation between the stability of standing posture (Var-CP) at rest and the 9 sensory composite scores (C1/, C2/, and PF/composite scores), either for control or for stroke patients when the groups were studied separately, except in control group for the C2/opto composite score (p=0.01), and in stroke patients for the PF/ opto score (p=0.02). Polling the controls and stroke patients data together revealed a relationship between the postural oscillations at rest and during sensory stimulations for C1/vib composite score, p=0.008; C1/opto composite score, p=0.005, C2/opto composite score, p=0.0005; PF/opto composite score, p=0.0008; C1/galva composite score, p=0.02, and C2/galva composite score, p=0.005.

DISCUSSION

The postural control of twenty stroke patients was challenged by three types of sensory stimulation: galvanic, tendon vibration and optokinetic stimulations. The results for these patients were compared to those of a group of twenty age-matched control subjects. Several sensors were placed at different parts of the body to carefully assess the postural behavior of each subject.

During quiet standing, data analysis clearly split the control group into two subgroups, depending on whether or not their postural control at rest was clearly affected by the sensorial stimulations (visual, proprioceptive or vestibular). Some subjects were insensitive to all stimulations. Other subjects were strongly affected by one, two or three stimulations. In between, there were a large number of subjects responding to the given stimulation in an intermediary manner. This type of differentiation had already been noted in previous studies. We found in seated subjects submitted to high-jerk, passive linear accelerations that the subjects' head movement responses were distributed as a continuum between two extreme categories (Vibert et al, 2001). In the study of Sasaki et al (2002), optokinetic stimulations affected the dynamics of the postural control system in only half of the subjects. In the study of Lacour et al (1997), control participants displayed two different behaviors in response to eye closure. The results of Isableu et al (2003) likewise underlined differential weighting of the sensory input involved in both perceptual and postural control, using the rod and frame test (Isableu et al 2003).

Moreover, the instructions given to the subjects and their “intentional behavioural set” may play a role. It has been shown that reflex stiffness at the ankles during standing depends on whether the subjects are told to stand still or to stand at ease (Fitzpatricket al., 1992*).* They swayed either only slightly or quite pronouncedly in reaction to a perturbation they could not detect. In the present study, all of the subjects were told to stand at ease. They might have swayed less if they had been told to stand still but this would not have explained the inter-individual differences. This result is in good agreement with the view that postural control depends on a feedback control scheme predicated on actively generated corrective torque and sensory weighting for both directions of sway control (Ravaioli et al 2004, Peterka and Loughin 2004, Kluzik et al 2006, Cenciarini and Peterka 2006, Carver et al, 2006).

Multidirectional perturbations in the base of support revealed that postural control in both humans (Maki et al, 1994, Carpenter et al, 2001, Matjacic et al, 2001) and quadrupeds (Rushmer et al, 1988) was distinct in the AP and ML planes. As a rule, our controls and stroke patients were more unstable in the AP direction than in the ML plane except in cases of optokinetic stimulation in control subjects and galvanic stimulation in hemiplegic subjects. This is likely due to the fact they were tested with their feet 12 cm apart, which was mandatory for test stroke patients. Under such conditions, horizontal force constraint exerted on the ground was lessened in the frontal plane, a finding similar to that reported in human (Henry et al, 2001) and animal models (Macpherson, 1994). Testing patients with their feet together is likely to lead to different results, with a higher degree of instability in the frontal plane (Allum et al, 2003, M’Bongo et al, 2009). In hemiplegic patients, static postural control appeared to be equally sensitive to galvanic stimulations in the AP plane and in the ML plane. This finding could be due to the fact that galvanic stimulation in the anteroposterior plane was technically difficult to induce in hemiplegic patients since they were required to turn their heads at 90 deg.

As expected, control subjects’ postural reactions to the visual, vestibular and proprioceptive stimulations were quite variable. Inter-individual variability in responses to sensorial stimulation was also observed among the hemiparetic subjects. They individually differed in their relative sensitivity to each of three sensory stimulations (proprioceptive, visual, vestibular stimulation). On the other hand, their sensory profiles differed from those of normal subjects. Firstly, none of the hemiparetic patients were insensitive to all stimulations. Secondly, they were globally more sensitive than the control subjects to sensory stimulations and presented greater displacement for all the proposed sensory stimulations. As expected, an abnormal number of patients showing visual reliance were found. This is in line with previous studies conducted by our group (Corriveau et al 2004, Bonan et al, 2006, Yelnik et al, 2006), but the fact that stroke patients likewise depend on proprioceptive and vestibular information is a new finding. Contrarily to what one might suppose, the increased visual dependence manifested by stroke patients does not necessarily entail neglect of vestibular and proprioceptive information. The heightened sensitivity to galvanic vestibular stimulations fits with the results of the study of Marsden et al (2005): the lateral forces generated by GVS in the stroke group were enhanced on the side of the non-paretic limb and diminished on the side of the paretic limb, which was not the case with controls.

We investigated the relationship between baseline sway and response to stimulations in both control and stroke groups. Our goal was to revisit a controversial point involving the relationship and differences between static and dynamic postural stability. The review of Sell (2012) quotes several studies, all of which show that the correlation between static and dynamic postural stability measures in the same population is poor or absent. In contrast, other publications have suggested that kinetic analyses of standing at rest may provide information that could be used to predict the risk of falls among the elderly (Tokuno et al, 2006, Pajala et al, 2008, Piirtola and Era, 2006). It has also been suggested that using various non-linear and linear measures of static postural control fluctuations can predict the likelihood of subsequent injury (Cavanaugh et al, 2005) and the occurrence of stepping strategies (Hasson 2008). As expected, stroke patients were more unstable in the present study than the control group. We found no significant correlation between stability of standing posture and responses to sensory stimulation, either for control or for stroke patients when the groups were studied separately. However, we found two exceptions to that rule for the C2/opto composite score in controls (p=0.01), and for PF/ opto score in stoke patients (p=0.02) i.e the trunk and the CoP displacements during optokinetic stimulation were greater for the more stable group at rest. Furthermore, polling the control and stroke patient data revealed a relationship between postural oscillations at rest and during sensory stimulations. This type of correlation between static and dynamic postural stability is not surprising in view of past results. Whether or not the correlation might provide a clinically useful index in clinic must await further investigations in a larger sample of stroke patients. It nonetheless remains clear that static postural control at rest is quite unlikely to reveal the individual perceptive style of controls and sensory reweighting of stroke patients, which is required in order to personalize their rehabilitation protocols. In summary, our study has shown that investigation of the static and dynamic posture in stroke patient and controls is highly likely to bring non-redundant complementary information. The question of the respective contribution of the impairment of the control of body orientation with respect to gravity and of the control of body stabilization in the excessive sensitivity of stroke patients to the sensory stimulation remains an open issue in our study. Indeed, in light of the numerous tests already planned in the patients we were unable to test their perception of the subjective vertical. This important issue should be examined in a study specifically tailored to investigate that problem.

Several hypotheses should help to explain the excessive reliance of stroke patients on sensorial afferences in balance control. Since an egocentric frame of reference may no longer be available following stroke, balance control in patients may subsequently be driven by feedback as opposed to centrally driven feed-forward mechanisms. Increased sway amplitude could also represent an adaptation strategy highlighting sensory information (Geurts et al, 2005). Given the fact that the sensory signals serve to create an internal model that is intimately linked with postural control, the participant would sway more in such a way as to generate larger afferent feedback signals that may more potently contribute (e.g. by raising the signal-noise ratio) to central control of balance. In addition, reduced motor output may help to explain the heightened sway of hemiparetic subjects, who are particularly slow and deficient with regard to correcting forces. Finally, the stronger postural responses we observed in the stroke patients compared to controls during sensorial stimulations may also reflect difficulties in ongoing multi-sensory reafferent control of balance in the presence of a continual perturbing signal. Initial GVS postural response is modulated by the availability of visual (Smetanin et al 1990, Britton et al 1993, Fitzpatrick et al 1994) and somatosensory information (Britton et al 1993) at the time of the stimulation, before any feedback loop can be put into place. Following which, as postural response to GVS unfolds, visual information and proprioceptive information provide the reafferent feedback mechanisms displayed by patients with neuropathy, who show exaggerated postural response to GVS (Horak and Hlavacka 2001, Day and Cole 2001, Blouin et al 2007). The same procedure applies during visual and proprioceptive stimulations. Subjects surrounded by a visual display rotating about two axes have typically experienced an illusory sensation of continuous self-rotation (circular vection) coupled with a paradoxical sensation of body tilt, both of them in the direction opposite to the stimulus. Subsequently, as postural responses to the visual stimulation unfold, vestibular and proprioceptive information provides reafferent feedback, as has been shown in astronauts floating freely with a sense of weightlessness (Young and Shelhamer 1990) and bilateral labyrinthine-defective patients (Cheung et al 1989, Bronstein et al 1996) who experienced demonstrably larger circular vection and postural disturbance than was the case with controls. In summary, a number of past studies would appear to indicate that the more pronounced postural responses observed in stroke patients are in all likelihood contingent on two non- mutually exclusive mechanisms. On the one hand, they may be linked to more acute sensitivity to the sensory stimuli during the initial phase of the postural response. On the other hand, they may reflect difficulties in the ongoing multi-sensory reafferent control of balance in the presence of a continual perturbing signal.

The specific loci of the cerebral cortex and brainstem involved in externally triggered postural responses and their respective contributions have been the topic of several studies. In humans, following EEG and brain imaging studies, it has been suggested that vestibular and somatosensory input may be integrated within a distributed cortical network including the inferior parietal lobe, PIVC, posterior insula, thalamus and frontal eye fields, most prominently in the right hemisphere of right-handed individuals (de Waele et al, 2001, Dieterich et al, 2003, Indovina et al, 2005, Marigold and Eng, 2006, Perennou et al, 1999, 2008, Manor et al, 2010). Other studies have demonstrated the involvement of the primary motor cortex (Saitou et al, 1996, Ouchi et al, 1999, Taube et al, 2006) the primary sensory-motor and supplementary motor cortex (Viallet et al, 1992, Dimitrov et al, 1996, Duckrow et al, 1999, Quant et al, 2004), the cingulate cortex and the junction of precuneus and parietal lobe, the occipital cortex (Slobounov et al, 2009). Finally, the posterolateral thalamus appears to play a major role in synthesis of vestibular and somaesthetic graviception. This type of structure constructs and updates internal models of verticality in which somatosensory information is put to work (Barra et al, 2010). Taken as a whole, the different studies have suggested that the primary motor cortex is likely to be involved in the generation of late-phase, feet-in-place and compensatory stepping postural responses, whereas parietal, temporal, insula cortex and thalamus are likely to be essential to sensory integration during postural tasks.

In that context, we have thoroughly examined whether or not patients with particular cortical lesions, as assessed by IRM, were controlling their posture in specific ways. In particular, we tested patients with right and left cortical lesions as well as patients with lesions involving the PIVC and the thalamus. With two exceptions (patients with right hemisphere lesions tended to have a higher

C2/Galva score than patients with left-hemisphere lesions and patients with a lesion involving the PIVC recorded a lower C1/Vib Score), we did not find any relationship between side of lesion, involvement of PIVC, and response to the stimulations. These results should nonetheless be interpreted with caution because of the small number of patients investigated, the high number of scores calculated, the rather extensive lesions existing and the fact that postural control is an emerging property in the processing of several interconnected cortical areas.

Conclusion

We have found stroke patients to be highly dependent on visual, proprioceptive and vestibular information in order to control their standing posture at rest and we have concomitantly discovered that they individually differ in their relative sensitivity to each of these sensory stimulations. Our results call into question the rationale of rehabilitation programs using visual deprivation to promote proprioceptive and vestibular inputs and to reduce visual dependency. Contrarily to what one might suppose, the increased visual dependence manifested by stroke patients does not necessarily entail, let us repeat, any neglect of proprioceptive and vestibular information.

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Figures

Figure 1: Sensory equipment used during the experiments.

Subjects stood on a Force platform (FeeTest of Technoconcept ®), movements of the head and the trunk were recorded using two inertial sensors (Xsens ®) placed on the head (C1) and the trunk (C2) of the subjects. They were successively stimulated by optokinetic, vibratory and galvanic stimulations. Sixteen types of stimulations were tested in order to disturb postural control in the pitch and roll plane.

Figure 2: Interindividual variability of the responses to the sensorial stimulations in control and stroke patients

Composite scores (in degree or mm) of each subject during the optokinetic (red), vibratory (blue) and galvanic (green) stimulations recorded by the inertial sensor placed A)on the head (C1), B), trunk (C2) and C) the platform (PF). The 20 hemiparetic subjects were labeled H1 to H20 and the control subjects from N1 to N20.

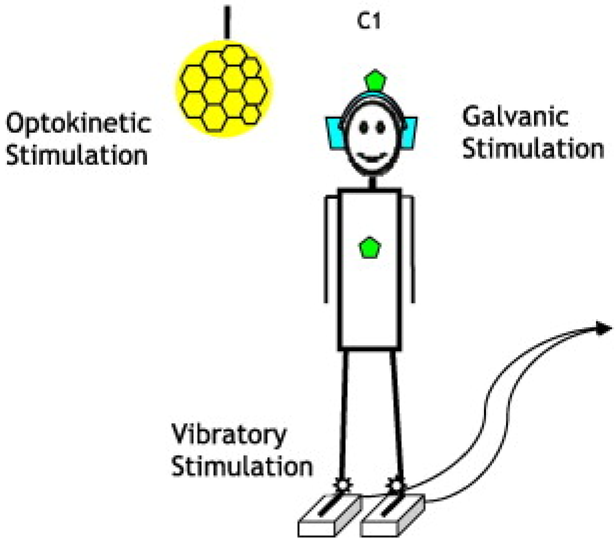

Fig. 1. Sensory equipment used during the experiments. Subjects stood on a Force platform (FeeTest of Technoconcept®), movements of the head and the trunk were recorded using two inertial sensors (Xsens®) placed on the head (C1) and the trunk (C2) of the subjects. They were successively stimulated by optokinetic, vibratory and galvanic stimulations. 16 types of stimulations were tested in order to disturb postural control in the pitch and roll plane.

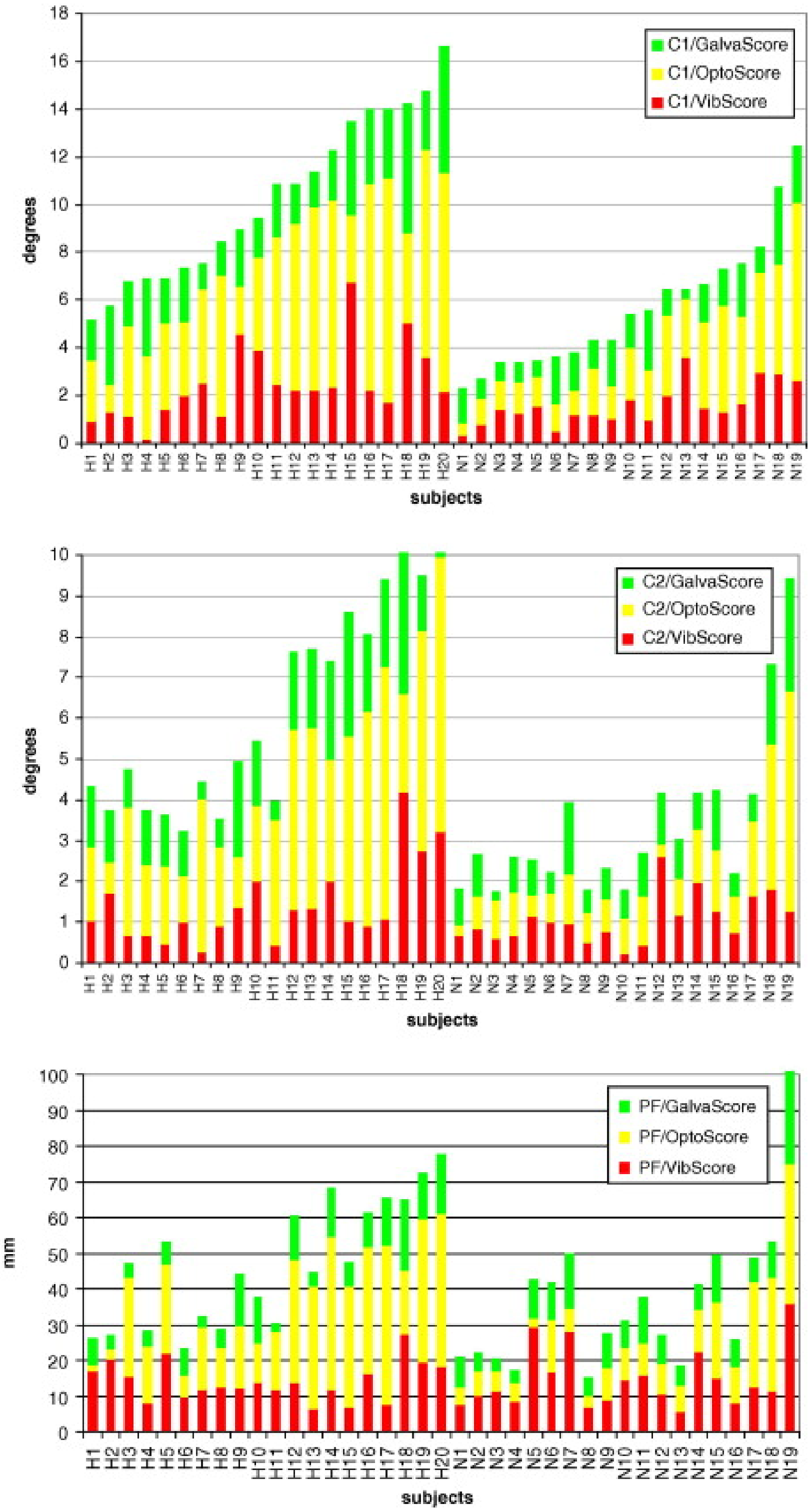

Fig. 2. Interindividual variability of the responses to the sensorial stimulations in control and stroke patients. Composite scores (in degree or mm) of each subject during the optokinetic (red), vibratory (blue) and galvanic (green) stimulations recorded by the inertial sensor placed (A) on the head (C1), (B), trunk (C2) and (C) the platform (PF). The 20 hemiparetic subjects were labeled H1 to H20 and the control subjects from N1 to N20. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1: Demographic data of the hemiplegic patients

	Mean ± SD	Range
Age (y)	51.4±10.5	26-67
Time since stroke (mo)	2.4±1.4	1-5
Motricity index (/100)	60.8±19	23-88
Sensitivity	7.17±1.2	3-8
BBS	53.1±18.3	24-100
TUG (s)	34.2±32.3	12-125
Barthel index (/100)	78.5±14.8	55-100

Table 1: Demographic data of the Hemiparetic patients

	vibration			**optokinetic**			**galvanic**		
	H	C		H	C		H	C	
C1	2.2(1.6)	1.4(0.8)	†	3.9(4.4)	2.1(2.4)	††	2.2(1.5)	1.4(1.0)	††
C2	1.0(1.0)	0.9(0.6)	ns	3.0(2.6)	0.9(0.5)	†††	1.5(1.0)	0.8(0.5)	††
PF	13.3(7.2)	11.5(7.6)	ns	21.6(21.4)	8.8(7.7)	††	7.9(9.0)	7.5(4.9)	ns

Table 2: Differences between the two groups (H hemiplegics and C controls) for the sensorial stimulations

††† p‹0.0001
† †p‹0.01
† p‹0.05
ns non-significant
values are means (IQD)

		Vibration			**Optokinetic**			**Galvanic**		
		AP	*ML*	*AP/ ML*	*AP*	*ML*	*AP/ ML*	*AP*	*ML*	*AP/ ML*
C1	*H*	3.8(3.1)	0.4(0.5)	†††	5.7(7.3)	4.2(2.9)	†	2.0(2.1)	1.9(1.7)	ns
	C	2.2(2.0)	0.4(0.4)	††	1.8(3.4)	1.9(1.8)	ns	1.3(1.4)	0.8(0.9)	ns
C2	*H*	1.6(1.6)	0.7(0.4)	†	3.1(3.6)	2.1(2.9)	†	1.7(2.2)	1.3(1.3)	ns
	C	1.2(1.1)	0.7(0.7)	†	1.2(0.9)	0.6(0.6)	ns	1.2(0.9)	0.4(0.3)	†
PF	*H*	17.8(9.6)	8.5(6.3)	††	18.9(20.3)	27.5(25.9)	ns	5.1(5.0)	7.7(12.1)	ns
	C	15.5(7.5)	6.7(9.3)	††	8.8(9.4)	7.7(7.5)	ns	10.1(7.4)	5.2(3.6)	†

Table 3: Differences between the AP (anteroposterior) and ML (mediolateral) scores for each group

††† p‹0.0001
†† p‹0.001
† p‹0.01
*** p‹0.05**
ns non-significant
values are means (IQD)