Effects of visual feedback of center-of-pressure displacements on undisturbed upright postural control of hemiparetic stroke patients

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Abstract. Purpose: To assess whether insights from postural control without additional visual feedback (VFB) could be gained to explain the possible VFB effects (or non-effects) on upright stance performance.

Methods: The center-of-pressure (CP) displacements of 39 patients with a recent hemispheric stroke (93 days ± 56; mean ± s.d.) were analyzed in two conditions (eyes open and VFB) through various classical parameters and fractional Brownian motion (fBm) modeling. Correlations between their ability to use the VFB technique appropriately and parameters assessing the eyes open condition were also computed.

Results: The fBm modeling showed that the VFB technique improves the control of the CP trajectories over the longer time intervals. In both conditions, the patients with right hemiparesis, compared to those with left hemiparesis, demonstrated improved control of their CP displacement along the AP axis over the shortest time intervals. Overall, 28% of the patients did not use the VFB technique. The correlation analysis indicated that the larger the spontaneous CP movements in the eyes open condition, the greater the effect of the VFB technique.

Conclusions: By emphasizing its particular effects and the profile of the patients who used the technique, these data specify the conditions allowing hemiparetic patients to use the VFB technique appropriately and immediately.

Keywords: Postural control-visual feedback-hemiparesis-center of pressure-rehabilitation

1. Introduction

For most of hemiparetic stroke patients, one of the main early goals of rehabilitation is the recovery of upright quiet stance. Depending on the location of the ictus, different sensory-motor impairments, which prevent the patient from normally controlling his or her balance, can be observed. Among the available techniques, visual feedback (VFB) provided by the output of a force platform must be viewed as a fairly good approach since this information is much more precise than that from the physiological receptors detecting body motions. Its general principle consists in the improved ability of the CNS to rely on this information to optimize motor control. Despite its apparent biomechanical complexity, the resultant center-of-pressure (CP) trajectories was shown to be the most valuable information to provide so as to allow healthy individuals to reduce their postural motions (Rougier, 2007; Rougier, 2009).

For more than two decades, several studies have attempted to use this VFB technique to retrain disabled patients. Given their problems distributing their bodyweight equally on both legs, hemiparetic patients have been involved in many of these studies. Interestingly,
only some of these studies have reported positive results in terms of hemiparetic patients succeeding in reducing their body motions with VFB (Shumway-Cook et al., 1988; Sackley and Lincoln, 1997; Simmons et al., 1998, Dault et al., 2003). On the contrary, other studies were unable to highlight any beneficial effect (di Fabio and Badke, 1990; Walker et al., 2000; Geiger et al., 2001; Cheng et al., 2004). A biomechanical analysis of the VFB task in upright quiet stance could explain the discrepancies in these results. In particular, VFB may allow improved stance symmetry rather than a reduction in sway (Barclay-Goddard et al., 2004). However, one should keep in mind that body-weight distribution is a major component in performing CP displacements, at least along the medio-lateral (ML) axis (Rougier, 2007; Winter et al., 1996), suggesting a potential positive aspect of VFB for at least lateral upright stance control.

Recently, an attempt was made to assess the reasons for which normal subjects more or less succeed in using this VFB technique (Boudrahem and Rougier, 2009). This study highlighted the relations between the postural behavior in a non-VFB (eyes open) condition and the degree of VFB dependency (using a specific index derived from the Romberg quotient). More specifically, the more the subjects were VFB-dependent, the less they leaned forward, the smaller the variance and the better the CP displacements were controlled over the longest time intervals when the subjects stood still with their eyes open. By emphasizing the postural profile allowing subjects to be efficient with this technique, this approach must be viewed as an interesting contribution to assessing the capacity of VFB protocols to be used as rehabilitation tools.

The current study had a double purpose: i) to extend this approach to hemiparetics and thus provide new insights into the conditions required for using VFB in rehabilitation; ii) to analyze the possible relationships between the capacity to use VFB appropriately and clinical features, including the side of the lesion. Considering that postural control impairment in hemiparetics is mainly related to the weight-bearing asymmetry, it is hypothesized that VFB dependency mainly involves postural parameters measured along the ML axis.

2. Methods

2.1. Individuals and protocols

Thirty nine hemiparetic stroke patients (24 males and 15 females; ranging in age between 41 and 82 years; height, 1.69 m ± 0.09; weight, 73.7 kg ± 15.7; mean ± standard-deviation) with a first, recent hemispheric stroke (93 days ± 56) were included in the study. Among them, 22 and 17 patients suffer from left and right hemiparesis, respectively. As required by the Helsinki Declaration (World Medical Association, 2000), they all gave written informed consent in accordance with the guidelines of the local ethics committee. They were able to stand for 60 s at least without technical or human aid. Patients with psychiatric disorders, dementia, orthopedic diseases, or any deficiency that could affect balance were discarded. In particular, patients undergoing severe communication or cognitive impairment that could hamper the understanding of the VFB task were not included.

The severity of the patients’ motor and sensory impairment was assessed by means of a standardized neurological examination. Extrapersonal spatial awareness was assessed using the bells tests (Gauthier et al., 1989). The tactile sense of the paretic side was assessed based on the patients’ ability to discriminate prick and touch at the pulp of the big toe. The spasticity of 5 muscles of the lower limbs were also measured using the Ashworth scale (Bohannon and Smith, 1987). Postural capacity during daily life and functional independence were assessed using the PASS and MIF scores, respectively. Lastly, the function of 8 muscles was tested using the Held and Pierrot-Deseilligny score (Held et al., 1975). It is worth noting that a statistical significant difference was only found for the visuo-spatial neglect (bells test) between patients with left and right hemiparesis. These clinical characteristics, presented in Table 1, correspond to those usually observed in series of patients with a degree of recovery compatible with upright standing maintenance without help for several minutes after a stroke of various size and location.

The patients stood barefoot on a triangular force platform (model PF01; Equi+, Aix-les-Bains, France) in a natural position (feet externally rotated at 30°, heels 3 cm apart). When necessary, the patients were assisted in rising up and adjusting their feet positioning on the force platform. The signals coming from the load cells under the plate were amplified and converted from analog to digital form before being recorded on a personal computer (sampled at 64 Hz without any filtering).

Two experimental conditions were randomly proposed to the patients. In the first condition (VFB), the patients were instructed to reduce the spot on the 17-in. screen positioned in front of them at a 1.3 m distance as much as possible. The display of the spot, which represents the CP displacements, was achieved in real
<table>
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<th>Table 1</th>
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<tr>
<td>Mean (with s.d. into brackets) anthropometric data and clinical scores for the whole group of patients, those with a left hemiparesis (LHP) and right hemiparesis (RHP), those with positive (dep) and negative DC (n-dep). Student t test comparing LHP and RHP groups on one hand and dep and n-dep groups on the other hand are displayed below.</td>
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<th></th>
<th>Number of left handed</th>
<th>Proportion of Ischemic CVA</th>
<th>Proportion of hemispheric CVA</th>
<th>Age (Years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Delay from CVA (days)</th>
<th>Hypoesthesia PASS (/36)</th>
<th>Visuo-spatial neglect (/36)</th>
<th>Spasticity (/25)</th>
<th>Autonomy FIM (/126)</th>
<th>Muscular function</th>
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<tr>
<td>Whole sample</td>
<td>2/39 (5%)</td>
<td>28/39 (72%)</td>
<td>37/39 (95%)</td>
<td>(11.42)</td>
<td>(9.65)</td>
<td>(15.7)</td>
<td>(55.63)</td>
<td>(0.48)</td>
<td>(2.99)</td>
<td>(3.98)</td>
<td>(15.32)</td>
<td>(6.41)</td>
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<td>(n = 39) (24M/15W)</td>
<td>(28 dep/11 n-dep)</td>
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<td>Patients with RHP</td>
<td>2/17 (13%)</td>
<td>15/17 (88%)</td>
<td>17/17 (100%)</td>
<td>(11.53)</td>
<td>(9.35)</td>
<td>(16.61)</td>
<td>(41.67)</td>
<td>(0.46)</td>
<td>(3.08)</td>
<td>(2.22)</td>
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<td>(13.96)</td>
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<td>(n = 17) (8M/9W)</td>
<td>(13 dep/4 n-dep)</td>
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<tr>
<td>Patients with LHP</td>
<td>0/22 (0%)</td>
<td>13/22 (59%)</td>
<td>20/22 (91%)</td>
<td>(11.22)</td>
<td>(9.33)</td>
<td>(14.78)</td>
<td>(64.29)</td>
<td>(0.49)</td>
<td>(2.84)</td>
<td>(3.1)</td>
<td>(3.49)</td>
<td>(16.3)</td>
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<td>(n = 22) (16M/6W)</td>
<td>(15 dep/7 n-dep)</td>
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<td>dep Patients</td>
<td>2/28 (7%)</td>
<td>21/28 (75%)</td>
<td>26/28 (93%)</td>
<td>(12.16)</td>
<td>(9.35)</td>
<td>(16.6)</td>
<td>(56.78)</td>
<td>(0.43)</td>
<td>(3.12)</td>
<td>(2.4)</td>
<td>(3.03)</td>
<td>(16.09)</td>
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<tr>
<td>(n = 28) (17M/11W)</td>
<td>(15 LHP/13 RHP)</td>
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<tr>
<td>n-dep Patients</td>
<td>0/11 (0%)</td>
<td>7/11 (64%)</td>
<td>11/11 (100%)</td>
<td>(9.21)</td>
<td>(9.61)</td>
<td>(12.94)</td>
<td>(52.52)</td>
<td>(0.57)</td>
<td>(2.35)</td>
<td>(3.82)</td>
<td>(4.01)</td>
<td>(13.16)</td>
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*p < 0.05.
time with a scale of 4, indicating that the display on the screen was four times larger than the real CP displacements. The software was set in such a way that the spot was always positioned at the center of the screen at the onset of each trial. To facilitate its tracking, only the last 64 positions (i.e. 1s) were displayed. The horizontal displacements of the CP were displayed on the vertical screen from left to right for the ML component and from top to bottom for the antero-posterior (AP) component. A practice trial, at least, was always performed prior to the measurements to ensure that the patients had mastered the relationship between their body motions and the spot displacements.

In the second condition (EO), the patients were instructed to minimize their body motions as much as possible. A dot (diameter, 5 mm) was placed at the center of the turned-off screen to avoid excessive eye movements.

No particular instruction or suggestion was given regarding the techniques to use to keep their balance. Each condition included five trials lasting 32 s. Rest periods of 15 s and 5 min were allowed between the successive trials of a condition and between experimental conditions, respectively. The standing patients were accompanied during the protocol by the investigator who stands besides them and was ready to intervene if necessary.

2.2. Signal processing

Two approaches were adopted to study the CP displacements: i) a classical method based on mean positions and variances along the ML and AP axes, the surface of an ellipse (Tagaki et al., 1985), the mean velocity, and ii) a mathematical model called fractional Brownian motion (Mandelbrot and van Ness, 1968; Collins and de Luca, 1993), which specifies the degree to which a trajectory is controlled. Its general principle is that the aspect of a trajectory, expressed as a function of time, may be quantified by a fractional, i.e. a non-finite, integer space dimension. The latter thus provides a quantitative measurement of wiggle in the trajectory in a single direction. This fractional dimension D, in a single direction, is actually linked to the Hurst scaling exponent H since $D = 1 - H$ for the present case. This scaling regime graphically corresponds to the half slope of the line portions constituting a variogram depicted bi-logarithmically. The latter in fact expresses the mean square displacements $< \Delta x^2 >$ as a function of increasing time intervals (1/64 s < $\Delta t$ < 10 s) and is given by the formula:

$$< \Delta x^2 > = \Delta t^{2H}$$

It should be noted that the squared distances are simply used to prevent a null mean displacement. A median value for H (i.e. 0.5) indicates a linear relationship between the two variables and thus no correlation between past and future increments, suggesting that the trajectory is in that case totally uncontrolled. On the other hand, if H differs from 0.5, a positive (0.5 < H) or negative (H < 0.5) correlation can be inferred, which is indicative of a given part of determinism in the control. Depending on how H is positioned with respect to the median value 0.5, it can be inferred that the trajectory is more or less controlled: the closer the regimes are to 0.5, the less there is control. In addition, depending on whether H is greater or less than the 0.5 threshold, persistent (the point is drifting away) or anti-persistent behaviors (the point retraces its steps) can be revealed, respectively.

Since two straight line portions generally characterize variograms relative to maintaining undisturbed up-
right stance (a fairly flat line preceding or succeeding a steeper one), a final step is to determine the transition point (slope inflection) along each axis. For this purpose, the distance between the CP variogram and a completely stochastic process (a straight line with a slope of 1) is computed for each increasing Δt. The principle retained, contrasting with the less objective method initially used by Collins and de Luca (1993), is that the Δt for which this distance is maximal is considered the Δt of the transition point (Rougier, 1999a).

Two scaling exponents (indexed as short and long latencies: H_s and H_l) as well as the co-ordinates of the transition point were thus extracted along each ML and AP axis. Figure 1 illustrates this procedure.

2.3. Testing and definition of the two subgroups

A dependency coefficient (DC), involving the average surface covered by the CP displacements, was used to quantify for each patient the influence of VFB on its postural control. Its formula is similar to the one given by Lacour et al. (1997) for differentiating the weighting of visual input in postural control:

\[
DC = \frac{(EO \text{ score} - VFB \text{ score})}{(EO \text{ score} + VFB \text{ score})}
\]

A positive ratio indicates that the magnitudes of the CP displacements are smaller in the VFB than in the EO condition, showing that the subjects succeed in relying on VFB information to control their posture. Conversely, a negative ratio reflects larger CP displacements for the VFB condition.

As seen in Fig. 2, depending on their DC score, two subgroups were defined: one (with DC < 0) composed of the 11 subjects who had larger CP surfaces in the VFB condition, compared to the eyes-open (EO) condition (n-dep), and the other (with DC > 0) including 28 subjects presenting the opposite sensitivity to the experimental conditions (dep). It should be noted that the DC ratios presented a statistically significant difference (using Student t tests) when comparing the two subgroups. The differential weighting of VFB in postural control was characterized by the above-mentioned parameters for each subgroup and then compared through a three-factors ANOVA (experimental condition: EO/VFB; group: dependency/non-dependency; side of the hemiparesis: left/right). When statistically significant results were obtained, Newman-Keuls post-hoc tests were used. Finally, the degree of correlation between the DC values and the parameters measured from the EO condition (plus age, height, body weight and clinical scores) were computed.

![Fig. 2. Bar charts showing the distribution of the subjects according to DC values. Note that a normal distribution characterizes the overall sample and the number of subjects with a DC ratio above 0 (dependent: dep) exceeds those with a negative ratio (non dependent: n-dep).](image)

3. Results

The ANOVA performed with the various parameters retained for characterizing the postural control strategies allowed us to better specify the effects attributable to the experimental conditions, the degree of VFB dependency, the side of the hemiparesis and their possible interactions. For the sake of convenience, only the statistically significant effects are reported throughout this results section.

3.1. Mean positions

No statistically significant effect was observed along the AP axis despite a tendency to see this position backwardly shifted during the VFB condition. On the other hand, along the ML axis, the ANOVA indicated a significant effect for the side of the hemiparesis factor (F(1,70) = 16.09; p < 0.001) and an interaction between the side of the hemiparesis and group factors (F(1,70) = 4.39; p < 0.004). As shown in Fig. 3, left and right hemiparetic patients were characterized by a shift towards the non-paretic foot for both EO and VFB conditions. However, in absolute values, the shift and thus the asymmetry was larger for the patients with left hemiparesis. The simple effects indicated a significant difference for this mean position between the dep
patients and the n-dep patients with a left hemiparesis ($p < 0.01$), hence signifying a lower level of asymmetry in the dep group. Another difference was in the n-dep group between the patients who suffer from left and right hemiparesis ($p < 0.01$).

3.2. Surface of the ellipse with a 90% confidence interval

A statistical significant effect was reported for the group factor ($F(1,70) = 5.54; p < 0.02$). As shown
Fig. 4. Bar charts showing the results from the fBM modeling for the overall sample, for the patients suffering from left or right hemiparesis and for the two subgroups (dep and n-dep) for both REF and VFB conditions.
from the bar charts of Fig. 3, the dep group displayed larger surfaces than the n-dep group.

3.3. Variances of successive positions

The ANOVA pointed out the origin of the surface effect previously mentioned: A significant effect was indeed observed for the group factor but only along the ML axis ($F(1,70) = 5.41; p < 0.02$). The bar charts of Fig. 3 highlight that the larger variances of CP displacements were seen for the dep group.

3.4. Transition point co-ordinates

The ANOVA revealed, along the ML axis, a significant effect for the group factor for the mean square distances $< \Delta x^2 >$, $F(1,70) = 4.92; p < 0.03$. Similarly to the variances along that ML axis, the dep group was the one who engage the corrective process after a longer mean square distance has been covered (Fig. 4). In contrast, and as for the variance along that axis, no statistically significant trend was found along the AP axis.

3.5. Scaling regimes

Along both ML and AP axes, a statistically significant effect was found by the ANOVA for long-latency scaling regimes (H11) for the experimental condition factor [ML: $F(1,70) = 4.22; p < 0.05$ in both cases]. The bar charts in Fig. 4 indicate that an improved control (with more determinism in the control of the trajectories) was seen during the VFB condition. In contrast, a significant effect was found for the short-latency (H1d) but only along the AP axis and for the group factor $F(1,70) = 7.33; p < 0.01$. An interaction between the group and side of hemiparesis factors was also worth noting for these H1d regimes $F(1,70) = 8.63; p < 0.01$. The simple effect analysis revealed significant differences in the n-dep subgroup between left and right hemiparetic patients ($p < 0.001$).

3.6. Correlation coefficients

The computation of the correlation coefficients between the DC ratios and the parameters attempted to describe the postural strategies in the EO condition, the clinical and anthropometrical scores highlighted additional insights. Interestingly, the statistically significant linear correlations involved the classical parameters and those issued from the fBm modeling: surface $(r = 0.47; p < 0.01)$, variance along ML $(r = 0.47; p < 0.01)$ and AP axes $(r = 0.356; p < 0.05)$, and mean square distances $< \Delta x^2 >$ along ML $(r = 0.43; p < 0.01)$ and AP axes $(r = 0.309; p < 0.05)$. In addition, a significant correlation was found for the height $(r = -0.349; p < 0.05)$. These results indicate that the more the subjects were dependent on the VFB technique, the larger the surface or their variances of their CP movements and the longer the mean square distances $< \Delta x^2 >$. It is worth noting that the side of the hemiparesis did not interact with the results, the mean scores for the DC ratios being rather similar when comparing left (0.074 ± 0.185) and right hemiparetic groups (0.122 ± 0.190). This point can be seen in Fig. 5 which features the surface of the CP displacements as a function of DC scores with a differentiation between left and right hemiparetics.

4. Discussion

The main effect of the VFB technique, in hemiparetic patients, consists in improved control of the CP trajectories over the longer time intervals and is therefore evidenced by using the fBm framework. In addition, a noticeable proportion of patients (about 28%) do not use the technique. Lastly, the correlations show that the greater the spontaneous body motions, the greater the effect of the VFB technique.
4.1. With additional visual feedback, hemiparetic patients improve their capacity to control their CP displacements during the corrective process

An interesting point of fBm modeling is its capacity to highlight the cyclic nature of postural control during undisturbed upright stance. Even though the nature of the mechanisms is still a matter of discussion, it can be suggested that a corrective action (operating through a closed-loop mechanism) is always preceded by an exploratory action operating through an open-loop mechanism (Collins and de Luca, 1993; Riley et al., 1997). This view was partly reinforced by showing that the main effect of the VFB was focused on the mechanisms operating over the longest time intervals (Rougier, 1999b). Since this feature is also found in hemiparetic patients, one can therefore conclude that our results are in complete accordance with studies involving healthy subjects. If improving the corrective process contributes to decreasing the postural movements, other factors, such as the degree of control of the exploratory process \( H_{\text{ed}} \) or the spatio-temporal coordinates of the transition points \( \Delta x^2 \), are also involved in the CP displacements and can thus weaken the VFB effect when considering global parameters (Rougier, 2003).

4.2. All hemiparetic patients do not succeed in improving their postural capacity with additional visual feedback

As indicated by our dependency coefficients, a significant proportion of patients do not reduce their CP displacements with VFB. This proportion (11/39, 28\%) is in accordance with what has been recently reported for 65 individuals with similar age (31\%) (Boudrahem and Rougier, 2009). With a similar analysis, it was shown that the dependent subjects in that case were those who experienced less forward leaning, smaller CP displacements and a fair ability to correct their CP displacements along the AP axis (Boudrahem and Rougier, 2009). This profile corresponds quite well the profile reported in the current study for hemiparetic patients. However, the comparison between the dep and n-dep hemiparetic subgroups emphasizes differences mainly along the ML axis (variance and spatial coordinate of the transition point \( \Delta x^2 \)). This particularity could be explained by the biomechanical mechanisms allowing upright stance and the differences in the level of impairment for controlling upright stance. Along the ML axis, upright stance is indeed controlled mainly by loading-unloading principles mobilizing the abductor and adductor muscles (Winter et al., 1996). The lesser impairment of these muscles caused by CVA, as compared to the more distal muscles (Misawa et al., 2008), could explain the capacity of the dep group to improve their control with VFB mostly along the ML axis. This difference in the muscle control impairment could also explain the results by Dault et al. (2003), who reported decreased CP movements with VFB only along the ML axis.

Interestingly, statistically significant differences were found when comparing hemiparetic stroke patients according to the side of the CVA. Nevertheless, the clinical scores reported in this study, such as visuo-spatial neglect, were unable to differentiate the dep and n-dep subgroups. The main explanation might come from the lack of a difference in the variances of CP displacements along the ML axis between the patients with left and right hemiparesis. This postural parameter was indeed shown to be a key factor for predicting VFB dependency in our stroke patients.

4.3. Left or right hemiparesis does not infer comparable use of additional visual feedback

The current analysis has provided two interesting results. The first, the weight bearing asymmetry, as assessed by the mean CP positions (Genthon et al., 2008a), is more pronounced for patients with left hemiparesis, confirming data previously reported (Sackley, 1991; Rode et al., 1997). As seen from the post-hoc analysis, our results emphasize that, among the patients with left hemiparesis, those who succeed in using VFB (dep subgroup) are less asymmetric for distributing their body-weight than the n-dep group. A high level of weight-bearing asymmetry could therefore interfere with the capacity to appropriately use VFB.

Second, postural impairment was similar for both subgroups. Patients with left or right hemiparesis are characterized by similar CP surfaces in both REF and VFB conditions. This result contrasts with a previous study reporting larger deficiencies in right brain-damaged patients (Perennou et al., 1999). Based on this traditional approach, it could be concluded that the capacity to use the VFB technique appropriately would be independent of the side of the CVA. However, interestingly, the patients with right hemiparesis use more determinism to control their CP displacement along the AP axis over the shortest time intervals (as deduced from the increased scaling regimes \( H_{\text{ed}} \)). This applies for the two REF and VFB conditions and is mainly
observed for the n-dep group. Since VFB involving CP displacements in real time was shown to induce more determinism in these exploratory mechanisms, this could explain the incapacity of these patients to use this technique. The fBm modeling allows us to disentangle the postural behavior specificity induced by the side of the lesion.

To conclude, these data have emphasized that VFB does not allow all hemiparetic patients to improve their balance deficiency. As for healthy subjects, the benefit principally concerns those who, in no additional feedback conditions, have problems maintaining their balance. Predictably, the main effect of VFB is focused on the capacity to recover balance once a disrupting CP displacement has been initiated. Patients who encounter problems regaining in securing this ability are therefore those who can expect greater benefit. The lack of correlation with the clinical scores underlines the specificity of this sensory-motor ability even though recent investigations have reported relations between postural control capabilities, especially along the ML axis and spatial neglect (Genthon et al., 2008b). Future investigations aimed at testing short and long-term training with this technique will be conducted in the near future.

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References


