

Effect of Coordination Biofeedback on (Re)Learning Preferred Postural Patterns in Post-stroke Patients

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After stroke, ankle-hip coordination during stance is characterized by changes in the postural system dynamics, specifically the disappearance of the *in-phase* pattern and the reduced stability of the *anti-phase* pattern. This study was conducted to assess the success of a coordination visual biofeedback for the (re)learning of the two preferred patterns, and to explore the effect of this treatment on postural and functional abilities. Twenty four patients were randomly assigned to one of two experimental groups or to a control group. During one month, patients from experimental groups followed a training protocol on the two preferred postural patterns using the biofeedback device. These two groups improved their *in-phase* coordination after the (re)learning compared with control group, and showed a related improvement of the functional independence measure. Results suggest that (re)learning the *in-phase* pattern is possible and seems to improve independence in poststroke patients.

Keywords: postural dynamics, coordination biofeedback, balance, hemiplegia, learning

For the recovery of balance and postural deficits in poststroke patients, various biofeedback (bioFB) devices have been recently developed to complete classical therapies (Dobkin, 2004; Kalra & Ratan, 2007). Visual and/or auditory bioFB techniques with inputs from the center of pressure (CoP) are now often used to enhance symmetry, steadiness and dynamic stability (Nichols, 1997). When postural bioFB training is used, an improvement of weight-bearing symmetry is observed (Shumway-Cook, Anson, & Haller, 1988; Winstein, Gardner, McNeal, Barto, & Nicholson, 1989) as well as an increase in stability limits (Sackley & Baguley, 1993). However, no long-term positive effects of bioFB-based rehabilitation on balance clinical scores have been observed when compared with a nontrained group (Walker, Brouwer, & Culham, 2000). Thus, it is not clear whether CoP-bioFB protocols improve balance

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and functional capacities in poststroke population (see Barclay-Goddard, Stevenson, Poluha, Moffat, & Taback, 2004; Van Peppen, Kortsmit, Lindeman, & Kwakkel, 2006, for a review).

One possible explanation underlying the mixed success of CoP-bioFB protocols in hemiplegic population is that CoP dynamics not only contains information about (the severity of) postural deficits (Dickstein, Nissan, Pillar, & Scheer, 1984; Bohannon & Larkin, 1985; Sackley, 1990), but also reflects compensatory adaptations to these deficits. For example, the observed weight-bearing asymmetry in the direction of the nonparetic leg seems enable the maintenance of stance (Kirker, Jenner, Simpson, & Wing, 2000). In the other hand, recent studies have shown the implication of the nonaffected leg in the increase of CoP oscillation amplitude observed in hemiplegic patients (Genthon, Rougier, Gissot, Froger, Pélissier, & Pérennou, 2008; Ustinova, Goussev, Balasubramaniam, & Levin, 2004). Various interpretations concerning the sway increase, sometimes contradictory, have been proposed which can explain the absence of bioFB effects on functional parameters (Barclay-Goddard et al., 2004).

A different yet nonexclusive explanation is that CoP trajectory is a global parameter resulting from the interaction of several sensori-motor and cognitive components (Fraizer & Mitra, 2008). It reflects partially movements of the center of mass (CoM) and the various moving segments of the body. Thus, use this global variable might not be easily usable by patients. Moreover, the improvement of the upright stance maintenance using a visual feedback of the CoP was tested in healthy population (Rougier, 2003; Rougier, 2004; van den Heuvel, Balasubramaniam, Daffertshofer, Longtin, & Beek, 2009). Results showed that the use of CoP-bioFB is not without consequences on the postural control. Thus, a diminution of postural sway is observed when CoP displacements are display but in a same time, an improvement of ankle stiffness is recorded who could be uncertain on stroke rehabilitation (Rougier, 2003). The introduction of a visual bioFB delay seems reduce the ankle stiffness (Rougier, 2004; van den Heuvel et al., 2009) but to our knowledge, the use of a delay was never tested for the moment in hemiplegic patients.

Important contributors to CoP dynamics are the various postural coordination modes naturally adopted by humans in their interaction with the environment (Horak & Nashner, 1986). In general, the control of standing posture is characterized by rotation of the body around multiple joints, including hips, knee, and ankles. If postural control is to be adaptive (as it almost always is), then the degrees of freedom of the postural system must be coordinated so as to promote functional control actions and avoid dysfunctional ones.

A well-investigated *supra-postural* task used to test the emergence of functional patterns in various circumstances is the body-tracking task (Bardy, Marin, Stoffregen, & Bootsma, 1999). In this task, standing participants are instructed to maintain a constant distance between their head and a visual target that oscillates along the line of sight. They are not given any instructions on how to move their body, and the relative phase ϕ_{rel} between ankle and hip rotation in the antero-posterior direction serves as the main dependent variable. A variant of this task (Faugloire, Bardy, Merhi, & Stoffregen, 2005) requires standing participants facing a screen to reproduce with their body an imposed postural coordination mode projected in front of them in an ankle-hip position plane, using an *visual coordination* bioFB (see Figure 1). The spontaneous vs. required nature of the adopted postures differentiate the two tasks. In both of them, however, two ankle-hip coordination modes were repeatedly observed

in healthy participants: (i) An *in-phase* mode, with the ankle–hip relative phase (ϕ_{rel}) close to 0° for movements of small amplitude and/or executed at low frequency, with the two joints oscillating simultaneously in the same direction, and (ii) an *anti-phase* mode, with ϕ_{rel} of about 180° , for movements of high amplitude and/or executed at high frequency, with the joints moving in opposite directions. The adoption of these two patterns, their abrupt modification following environmental or biomechanical constraints (Bardy et al., 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002) or their destabilization following the learning of new postural patterns (Faugloire, Bardy, & Stoffregen, 2009) constitute today an interesting database against which pathologies of the postural system can be contrasted.

Important in the present context is the observation that these two modes have different intrinsic stability. Due to the double inverted-pendulum nature of the postural system and the mechanical coupling between its various joints, the *in-phase* mode is dynamically more stable and more efficient than the *anti-phase* mode for activities in daily life (ADL) involving small amplitude or velocity of body displacements, even though it produces larger muscular torque at the ankle level (Bonnet, Fraisse, Ramdani, Lagarde, Ramdani, & Bardy, 2008). In contrast, the *anti-phase* mode appears to be used when the limits of stability are reached, for instance when the CoP excursion required to perform a daily routine exceeds the limits of the base of support (BoS).

The capacity of poststroke patients to produce these two postural patterns was preliminary investigated using the *visual coordination* bioFB (Varoqui, Bardy, Lagarde, Froger, & Pélissier, 2010), and contrasted to the performance of a healthy group. Patients were unable to produce the *in-phase* pattern, and were less stable when they produced the *anti-phase* pattern. The incapacity of stroke patients to produce the visually imposed *in-phase* mode can be mechanically explained by the difficulty of producing large CoP displacements (Dettmann, Linder, & Sepic, 1987; Goldie, Evans, & Matyas, 1996), large muscular torque at the ankle joint (Marigold, Eng, & Inglis, 2004; Cruz & Dhaher, 2008), within an unstable and asymmetric BoS (Dickstein et al., 1984; Shumway-Cook et al., 1988).

From the current knowledge about the anomalies of sensori-motor system dynamics, it may be possible to propose adaptive rehabilitation protocols, which may have implications for physical therapies (Scholz, 1990; Wageenar & van Emmerick, 1996). The purpose of this study was to investigate the effect of a new training protocol on the postural coordination dynamics (i.e., 0° and 180° patterns), using the customized coordination bioFB recently tested in the learning of new postural patterns in healthy participants (Faugloire et al., 2005). The following two questions were addressed: (i) Does a specific coordination bioFB training allow the (re)learning or stabilization of the two preferred coordination modes in hemiplegic patients? (ii) Can the training of postural patterns influence the recovery of functional and postural capacities operating in ADL when mixed with classical therapies?

Method

Participants

Twenty-four hemiplegic patients engaged in a neurological rehabilitation program took part in the experiment. They were randomly assigned to three groups: Two

experimental groups of eight patients performed a complete training protocol (groups A and B) and were contrasted to one control group of eight patients who performed a stand-up task (group C).

For the three groups, the inclusion criteria included (i) time since stroke inferior to 6 months, (ii) first unilateral hemispheric acute stroke, and (iii) capacity to stand-up without help or support during 60 s. Patients with other mobility-limiting neurological deficits, previous sensory or orthopedic disease affecting stance, dementia or severe aphasia were not included in the study. Patient characteristics are presented in detail in Table 1.

All participants provided an informed consent statement before testing. The protocol was approved by the local ethics committee, conforming to the declaration of Helsinki.

Clinical Evaluation

Several clinical assessments were obtained by a blind assessor at the beginning (day 1) and at the end (day 28) of the experimental protocol, to quantify the benefits of our protocol. *Motor weakness* of five lower limb muscle groups was assessed on a 5-points scale adapted to central neurological disorders (Held, Pierrot-Deseilligny, Bussel, Perrigot, & Malier, 1975). *Spasticity* of four lower limb muscle groups was assessed using the modified Ashworth scale (Ashworth, 1964; Bohannon & Smith, 1987). *Balance* was measured with two different scales, the Postural Assessment Scale for Stroke (PASS, Benaim, Perennou, Villy, Rousseaux, & Pelissier, 1999) and the Berg Balance Scale (BBS, Berg, Wood-Dauphinee, & Williams, 1995). *Gait capacities* were evaluated with the Functional Ambulatory Category (FAC, Holden, Gill, Magliozzi, Nathan, & Piehl-Baker, 1984). *Autonomy* was tested with the Functional Independence Measure (FIM, Hamilton, Granger, Sherwin, Zielezny, & Tashman, 1987), with motor and cognitive components presented separately. Eight brain locations (frontal, Rolando's, parietal and temporal cortices, corona radiata, internal capsule, striatum, and thalamus) were examined using the atlas of Talairach & Tournoux (1988) and noted as 0 if no lesion was present or 1 if there was a lesion (Pérénou, Leblond, Amblard, Micallef, Rouget, & Pélissier, 2000). All lesions observed were located at the supratentorial level. The lesion size was computed from the number of cerebral areas affected. The results of the clinical assessments before and after the training period are presented in Table 1.

Task and Apparatus

The task used at pretest and posttest for all groups—and during the training period for the experimental groups—was the following. Patients stood barefoot 3.50 m from a projection screen (1.50 m × 1.10 m) in a comfortable position. They were instructed to keep their knees extended, and their toes and heels in constant contact with the floor. They were asked to reproduce with their body the postural pattern projected on the screen—0° or 180°—with the help of a customized postural coordination bioFB system.

The prescribed pattern was visually represented by a Lissajous figure (i.e., ankle-hip angular position plane) in blue. The real-time visual bioFB, displayed at each time point a red dot with ankle and hip angles as X and Y orthogonal

Table 1 Mean (SD) Clinical Characteristics of Hemiplegic Participants at the Beginning and the End of the Protocol.

	Group A (n = 8)		Group B (n = 8)		Group C (n = 7)	
Age (years)	57.49 (10.54)		52.88 (9.99)		60.12 (9.85)	
Gender	3 F—5 M		8 M		1 F—6 M	
Delay between stroke and inclusion (days)	58.50 (29.08)		69.25 (30.81)		72.14 (26.67)	
Type of stroke	1 hemorrhagic—7 ischemic		3 hemorrhagic—5 ischemic		7 ischemic	
Affected side	6 right—2 left		3 right—5 left		4 right—3 left	
Lesion size (max. 8)	3.63 (1.60)		3.75 (2.49)		4.57 (1.51)	
	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
PASS (max. 36)	26.50 (5.58)	33.00 (2.78)	28.25 (4.62)	33.38 (1.77)	27.57 (4.65)	31.14 (4.45)
BBS (max. 56)	34.50 (12.22)	48.00 (8.60)	37.25 (9.74)	51.00 (3.16)	32.86 (14.19)	42.86 (10.68)
Motor weakness, lower limb (max. 25)	12.38 (5.06)	16.06 (5.19)	12.19 (3.37)	15.31 (5.01)	11.93 (4.67)	16.43 (3.90)
Spasticity, lower limb (max. 20)	1.44 (1.76)	1.25 (1.49)	2.13 (2.70)	2.50 (2.51)	2.71 (3.09)	1.71 (2.63)
FAC	2.50 (1.51)	4.00 (1.07)	3.00 (1.60)	4.25 (0.71)	3.00 (1.63)	3.14 (1.77)
FIM						
Motor	54.43 (12.29)	77.43 (11.12)*	57.75 (12.86)	76.75 (8.78)*	51.29 (16.57)	59.29 (13.66)
Cognitive	27.00 (6.86)	32.71 (2.56)	29.25 (7.44)	32.75 (3.15)	23.71 (11.01)	26.00 (9.52)

PASS: Postural Assessment Scale for Stroke Patients

BBS: Berg Balance Scale

FAC: Functional Ambulatory Category

FIM: Functional Independence Measure

*Significantly different from pretest

coordinates respectively, representing the current ankle-hip coordination. The current coordination was superimposed to the prescribed pattern on the same screen (Figure 1). The task for the participants was to perform ankle and hip flexion-extension movements in the sagittal plane to displace the dot on the screen as close as possible to the required figure. Patients were free to choose the frequency of their movements. The maximal angular amplitude displayed on the Lissajous figure was fixed to 8° for each joint, allowing the production of both patterns of coordination.

Hip and ankle angular movements in the sagittal plane were recorded with four electro-goniometers (Biometrics Ltd.) connected to a data acquisition system (DataLink, Biometrics Ltd.). Angular accuracy was 1° and sampling frequency was 50 Hz. Two electro-goniometers were attached to the lateral side of the hips (extending from the greater trochanter to the iliac crest) and the others two were attached to the anterior side of the ankles (extending from the scaphoïde to the inferior third of the tibia). Data recorded online from the goniometers were used to generate the real-time bioFB.

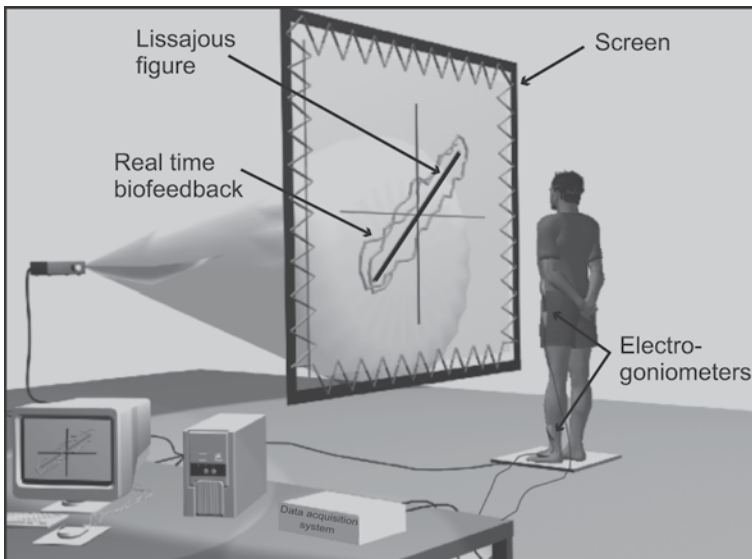


Figure 1 — Experimental set-up illustrating the visual coordination biofeedback task: Participants were asked to match their current ankle-hip coordination (gray line) onto the imposed coordination (the dark pattern). The 0° relative phase (in-phase pattern) is represented by a positive oblique line (illustrated) and the 180° relative phase (antiphase pattern) corresponds to a negative oblique line.

Design and Procedure

The protocol lasted four weeks and included three sessions per week (see Figure 2). Sessions 1, 6, 7, and 12 were the test sessions. In these sessions, participants from the three groups performed ten 60-s trials with the imposed pattern (i.e., 0° or 180°). Data were collected for both legs but the bioFB information originated

only from the affected leg (aFB). The other sessions were learning sessions. Thus, for each pattern, protocol took place on two weeks and included a pretest (day 1), four practice sessions (days 3, 5, 8 and 10) and a posttest (day 12). Participants from the two experimental groups performed four sessions of learning with each imposed pattern. In each session, they were asked to produce twelve 60-s trials with the bioFB originating from the nonaffected side (naFB, Group A) or from the affected side (aFB, Group B). Patients were allowed to rest as long as they wished between trials. The control group (Group C) practiced a stand-up task during 15 min instead of using the bioFB device. The 15-min period corresponded to the practice time experienced by participants from groups A and B in the bioFB task, but with no specific postural training. During the first session with the bioFB set-up, a familiarization period of 15 min in which they learned how to move the target dots in the ankle-hip space. Pattern order was counterbalanced in each group. During this period, patients continued their daily physical therapy at the rate of two 30-min sessions per day.

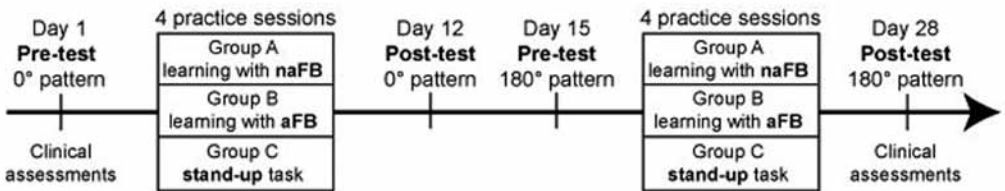


Figure 2 — Experimental design presented for patients beginning the protocol by the 0° pattern (naFB and aFB correspond respectively to the nonaffected and affected biofeedback conditions).

Data Reduction

To determine the postural pattern produced by participants, we estimated the ankle-hip continuous relative phase, ϕ_{rel} , from the joint time series. For this purpose, we used a time-frequency analysis method: the cross-wavelet transform (XWT). This method was chosen because it allows the analysis of nonstationary data with modulation of frequency or amplitude and gives access to complex human coordination (Issartel, Marin, Gaillot, Bardainne, & Cadopi, 2006). First, the continuous wavelet transform (CWT) of each time series was computed with an order-8 Morlet mother function. Then, we computed for each leg the XWT between the CWT of hip and ankle time series. On the XWT spectrum, regions in the time-frequency space exhibiting high common power were localized with a statistical significance test (for details on the method, see Torrence & Compo, 1998). At each time point, the highest power value was searched in the significant regions and the ϕ_{rel} value, between 0° and 360°, corresponding was extracted. When there was no significant common frequency, no ϕ_{rel} value was extracted. If more than one half of a trial could not be extracted, this trial was not kept for further analysis. The wavelet analysis was performed with the Matlab (The MathWorks, Inc.) wavelet coherence package developed by A. Grinsted (Grinsted, Moore, & Jevrejeva, 2004). Figure 3 shows

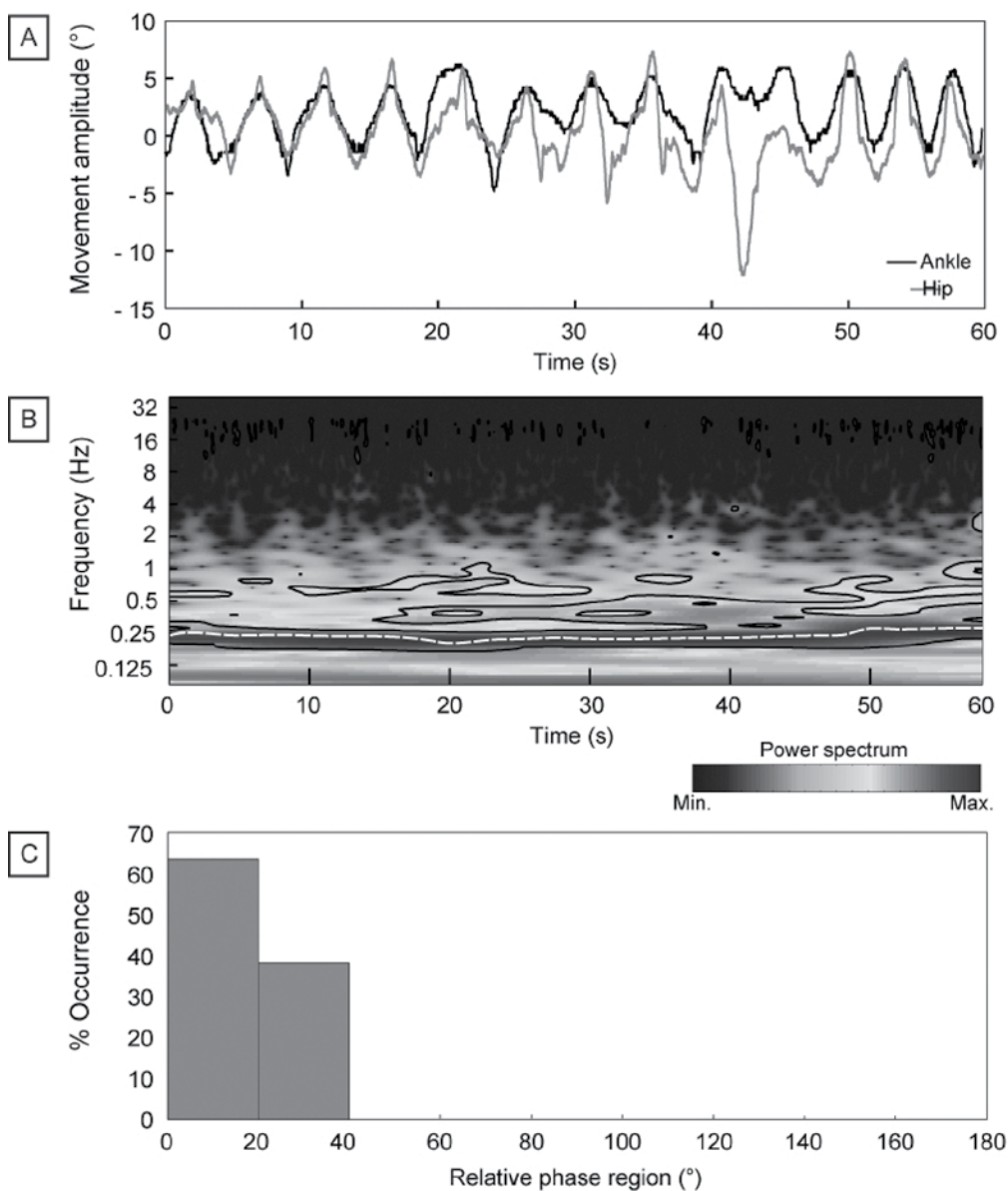


Figure 3 — (A) Time series of hip (black line) and ankle (gray line) angular positions for a representative patient in the 0° pattern (left) at posttest. (B) Cross-wavelet spectrum computed from the two time series. The black lines correspond to the significant regions of the spectrum and the white dash line corresponds to the maximal power value for each time. (C) The distribution of relative phase values extracted to the maximal power values.

data for one representative patient in the 0° pattern, the associated XWT spectrum, and the distribution of ϕ_{rel} values extracted from the spectrum.

From all ϕ_{rel} values, we computed three variables: the ϕ_{rel} distribution of relative phase (*RPD*), the angular deviation ($SD\phi_{rel}$) and the absolute error (*AE*) produced. *RPD* was computed across nine 20° regions of relative phase, ranging from 0° to 180° (although the ϕ_{rel} values were extracted between 0° and 360° , the ϕ_{rel} distributions were analyzed and visually represented between 0° and 180° for an easier readability). For each subject, the number of occurrence of ϕ_{rel} in each region was normalized and calculated for all trials in each test session per leg (i.e., non-affected leg and affected leg). This was done by calculating the mean ϕ_{rel} distribution for each group. $SD\phi_{rel}$ was calculated for both legs with circular statistics (Batschelet, 1981). $SD\phi_{rel}$ indicates the within-trial coordination variability. We also computed *AE*, the absolute value of the difference between the produced relative phase and the intended one, as an index of task performance.

Data Analysis

To ensure the homogeneity of the three groups at the beginning of the protocol, differences in initial (clinical and experimental) values before the learning period between groups were tested. A Pearson's chi-square test was used to test for the affected body side. One-way ANOVAs Group (3) were performed at pretest on age, delay between stroke and inclusion, initial clinical scores, *AE* and $SD\phi_{rel}$ for each pattern.

Moreover, to compare the differential changes in clinical variables between the inclusion and the end of the protocol, we conducted a Group (3) \times Test (2) ANOVA with repeated measures on the last factor on each score. *RPD* were compared in pairs with a Pearson's chi-square test between pretest and posttest for each leg. On $SD\phi_{rel}$ and *AE*, we conducted a Group (3) \times Test (2) \times Leg (2) ANOVA with repeated measures on the last two factors, separately for each pattern (i.e., 0° and 180°).

A hierarchical cluster analysis was also used to differentiate typical learning behaviors when it was necessary. The Ward's linkage method and the Squared Euclidean distance measures were used for this purpose. Four variables coming from the affected leg were entered into the cluster analysis: (i) *AE* and (ii) $SD\phi_{rel}$ at the posttest to quantify the result of the (re)learning and the progress was evaluated with (iii) the error decrease (i.e., *AE* pre/post difference), and (iv) the decrease in variability (i.e., $SD\phi_{rel}$ pre/post difference). All variables were standardized before analysis. Following the cluster identification of homogeneous subgroups, ANOVAs were used on the four variables selected to reveal significant between-cluster group differences.

All statistical tests were run using Statistica version 6.1 (StatSoft, Inc.) with set at 0.05. We used Neuman-Keuls tests when post hoc comparisons were necessary.

Results

One patient from group C was excluded from the analysis, exhibiting no significant region in the XWT spectrum, and thus preventing the possibility to extract ϕ_{rel} values.

Similar Functional Capacities at the Pretest

The three groups did not differ in terms of age ($F(2,20) = 0.99, p > .05$), affected side ($X^2 = 2.29, df = 2, p > .05$) and delay between stroke and inclusion ($F(2,20) = 0.47, p > .05$). Concerning the clinical assessments, none of the variables, i.e., spasticity, motor weakness, FAC, PASS, BBS, motor FIM and cognitive FIM revealed a difference between groups at the beginning of the protocol (all $F_s(2,20) < 0.82, p > .05$). Similarly, the coordination pattern produced at pretest (i.e., *in-phase* or *anti-phase*), did not differ between groups for *AE* or $SD\phi_{rel}$ (all $F_s(2,20) < 1.25, p > .05$).

Persistence of *Anti-phase*

For the *anti-phase* pattern, no significant differences were observed for Group or Test for the two variables, *AE* and $SD\phi_{rel}$ (all $F_s(1,20) < 2.24, p > .05$). The Group \times Test interactions did not reach significance. Patients from the three groups exhibited an *anti-phase* pattern at the two tests (Table 2) and no variability modifications were observed between the two test sessions.

Changes in *In-phase*

Relative Phase Distributions. Comparisons between pre- and posttests for each group exhibited differential changes in the three groups. For group A, a pretest difference was observed for the two legs (affected leg: $X^2 = 41.08, df = 7, p < .001$; nonaffected leg: $X^2 = 27.75, df = 7, p < .001$). In contrast for group B, only the affected leg showed different distributions between the two tests (affected leg: $X^2 = 20.33, df = 7, p < .005$; nonaffected leg: $X^2 = 5.43, df = 7, p > .05$). The control group showed no change between the two tests (affected leg: $X^2 = 3.56, df = 7, p > .05$; nonaffected leg: $X^2 = .93, df = 7, p > .05$).

Thus, only the experimental groups improved their performances in the 0° pattern training (Figure 4): At pretest, distributions were centered around 180° , revealing the impossibility of patients to produce the required coordination. At posttest, the 180° dominance was replaced by a more scattered distribution of ϕ_{rel} values with a higher proportion of values close to 0° , for both legs in group A but only for the affected leg in group B. For the healthy side, group B produced a bimodal distribution with peaks centered around 0° and 180° from pretest. Group C did not learn the required 0° pattern and exhibited an *anti-phase* coordination close to 180° at both tests.

Task Performance. The performance analysis confirmed in part the observations above. The analysis of variance performed on *AE* showed a significant main effect for Test ($F(1,20) = 15.81, p < .001$). *AE* was smaller at posttest compared with pretest. Moreover, a Test \times Group interaction ($F(2,20) = 5.61, p < .05$) revealed an error reduction at posttest for group A ($p < .001$), but not for groups B and C. Thus, only patients from group A exhibited progress in performing the imposed *in-phase* postural pattern during the protocol compared with the other groups (Table 2).

Pattern Stability. The ANOVA did not reveal any change in pattern stability during practice, for Group ($F(1,20) = 1.71, p > .05$) or Test ($F(1,20) = .42, p > .05$).

Table 2 Mean (SD) AE and $SD\phi_{rel}$ at Pretest and Posttest for the Three Groups (0°: in-phase pattern and 180°: antiphase pattern).

	Group A		Group B		Group C	
	Pretest	Posttest	Pretest	Posttest	Pretest	Posttest
AE	120.60 (42.68)	71.64 (51.28)*	91.91 (65.14)	83.09 (71.61)	131.35 (41.52)	122.06 (44.71)
180° pattern	26.26 (38.60)	18.12 (38.03)	13.70 (8.80)	14.06 (27.37)	24.14 (26.88)	39.92 (49.81)
$SD\phi_{rel}$	23.13 (9.57)	23.94 (14.99)	20.31 (10.74)	15.88 (9.94)	24.45 (12.87)	26.59 (16.52)
180° pattern	18.76 (15.65)	13.35 (18.40)	18.50 (11.12)	16.17 (16.83)	26.62 (24.60)	23.22 (27.47)

*Significantly different from pretest

Subgroup Comparison. To discriminate more finely the different behaviors observed between pre- and posttests in the 0° pattern learning, a hierarchical cluster analysis was conducted (see the method section for details). The four variables selected (i.e., AE and $SD\phi_{rel}$ at the posttest, AE and $SD\phi_{rel}$ prepost difference) were included in the hierarchical analysis because they were not correlated between them and were identified by the MANOVA as being able to distinguish four homogeneous subgroups. All participants were assigned to one of subgroups: subgroup 1 contained five patients and the three other subgroups each contained six participants.

The following significant differences between subgroups were observed. The main effect on Subgroup ($F(3,19) = 43.03, p < .001$) showed that AE produced at posttest was less important for subgroups 1 and 2 compared with subgroups 3 and 4 (all $ps < .001$). Moreover, AE was smaller for subgroup 4 than subgroup 3 ($p < .001$). For $SD\phi_{rel}$ at posttest ($F(3,19) = 17.98, p < .001$), subgroup 4 was less stable than the three other subgroups (all $ps < .001$). Concerning progress over time ($F(3,19) = 15.77, p < .001$), the most important diminution of AE was observed for subgroup 1 compared with the three other subgroups (all $ps < .001$). Finally, for $SD\phi_{rel}$ decrease over time ($F(3,19) = 8.20, p < .001$), a reduction in variability was found for group 2 compared with subgroup 1 ($p < .05$), subgroup 3 ($p < .001$) and subgroup 4 ($p < .05$).

Following the hierarchical cluster analysis, the four subgroups were renamed according to their characteristics (see Figure 5A for a representation of these different behaviors). Subgroup 1 demonstrated learning and was thus called the *learning group*. Subgroup 2 was renamed as the *in-phase group* because 0° was already present at pretest. Subgroup 3 was called the *anti-phase group*, patients performed an *anti-phase* pattern throughout the protocol. Finally, subgroup 4 was called the *random group* because patients in this group exhibited a large series of ϕ_{rel} values throughout the experiment with an important variability.

The repartition of original A, B and C patients in each of these new subgroups is presented on Figure 5B. As evidenced, the *learning group* contained a majority (4 of 5 patients) of patients originating from group A, an observation that confirms the results above on relative phase distribution and AE . Patients from group B were shared between the *in-phase group* and the *anti-phase group*, explaining the bimodal distribution observed previously. With one exception, participants from the original group C were distributed between the *anti-phase group* and the *random group*, reinforcing the finding that patients from the control group were unable to produce an *in-phase* pattern without practice.

Clinical Assessments

Comparisons between pre- and posttests were performed to quantify the clinical benefits in standard sensori-motor routines of our training protocol (Table 1). The analysis yielded a main effect of Test for PASS ($F(1,20) = 31.55, p < .01$), BBS ($F(1,20) = 82.19, p < .01$), motor weakness ($F(1,20) = 44.54, p < .01$), motor FIM ($F(1,20) = 61.55, p < .01$), cognitive FIM ($F(1,20) = 18.02, p < .01$) and FAC ($F(1,20) = 16.16, p < .01$). Thus, an improvement of scores in all clinical assessments was observed between pre- and posttests, except for spasticity ($F(1,20) = 0.38, p > .05$). A significant Group \times Test interaction was observed for the motor FIM ($F(2,20) = 4.99, p < .05$), revealing an improvement between tests for groups A

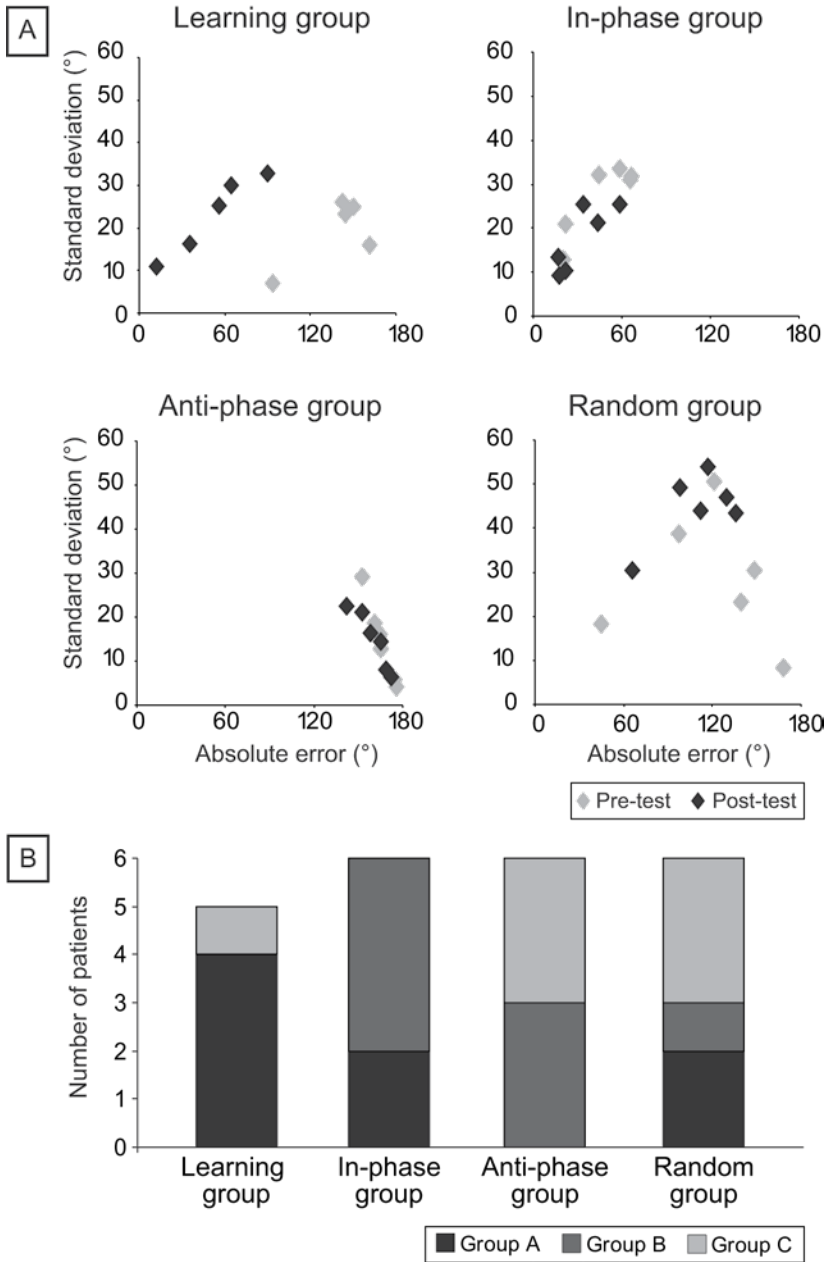


Figure 5 — The hierarchical cluster analysis: (A) Standard deviation of relative phase is represented as a function of absolute error for each subgroup at pretest (gray) and posttest (black). (B) Repartition of original A, B and C patients in each new subgroup.

and B but not to group C (post hoc Newman-Keuls, all $ps < .001$). A mean increase of 18.33 and 19 points was observed respectively for group A and group B whereas Group C had risen to 8 points only. No difference between experimental groups and control group was observed for the two postural scales (i.e., BBS and PASS).

Discussion

The major aim of this study was to assess the (re)learning dynamics of the two spontaneous postural patterns following stroke, using a postural coordination bioFB during a controlled training. The overall conclusion is that (i) when the *in-phase* pattern is lost in stroke patients, its (re)learning is possible with our customized bioFB device, and (ii) the *anti-phase* pattern persists over time. The accompanying improvement of functional autonomy, evidenced by an increase in motor FIM score, for both experimental groups, suggests that specific *in-phase* training is beneficial for hemiplegic patients.

Anti-phase Persistence

All patients performed the *anti-phase* pattern at pretest. Several studies have revealed that postural *anti-phase* can be more attractive and more stable than postural *in-phase* (Bardy et al., 1999; Bonnet et al., 2008; Faugloire et al., 2009), when constraints are imposed to healthy adults (e.g., when for instance the surface of support is reduced; Bardy et al., 1999). Thus, the mechanically more stable pattern persists after stroke. This result echoes recent findings obtained in intermanual coordination, showing the persistence of the strongest—*in-phase* in the case of bimanual coordination—relative phase pattern (Rice & Newell, 2004), or the conservation of general pattern stability (Garry, van Steenis, & Summers, 2005).

The (re)learning of In-phase Pattern

In our two experimental groups, results on ϕ_{rel} distributions indicated the progressive (re)learning of the previously lost *in-phase* mode (Varoqui et al., 2010) contrary to the control group. For group A, this result was confirmed by the diminution of *AE* between the two tests and the inclusion of a major part of this group in the *learning group* show that a (re)learning of the *in-phase* pattern is possible despite the pathology and its consequences. The absence of effect on *AE* for group B can be explain by the preexisting bimodal distribution of ϕ_{rel} values around 0° and 180° at pretest, and to the belonging of B participants in the *in-phase group* and the *anti-phase group*, as revealed by the cluster analysis. The comparison with the results for the control group C (i.e., no difference observed for ϕ_{rel} distributions and *AE* between the two tests, distribution of patients between the *anti-phase group* and the *random group*) suggests that the progressive rediscovery of the *in-phase* pattern is not possible without specific practice at this stage of recovery.

It thus appears that the training of the previously lost *in-phase* pattern is possible using adequate bioFB information about postural dynamics. Whether feedback originating from the nonaffected leg is more efficient than from the affected leg remains an open question. In previous study, we have showed that the coordination produced by the nonaffected leg was more stable compared with the affected leg.

Thus, we supposed that display a naFB could lead the affected leg and improve the coordination produced. On one hand, it seems from the present results that group A with healthy bioFB presented the greater progress in the *in-phase* condition. However, the difference between group A and group B at pretest (i.e., the bimodal distribution of ϕ_{rel} at pretest for group B but not for group A) indicates that the advantage of healthy bioFB training has to be interpreted cautiously.

Improvement of Functional Capacities

Results on clinical assessments revealed for the three groups an increase in all scores, except the spasticity. The improvement observed in one month corresponds to the normal time course of functional recovery in poststroke patients (Jørgensen, Nakayama, Raaschou, Vive-Larsen, Støier, & Olsen, 1995).

The increase in the motor FIM score for the two experimental groups compared with the control group is of interest for our rehabilitation protocol. Daily postural activities such as looking, turning the head, reaching for an object, etc., require to continuously shift the center of gravity (CoG) while maintaining it above the feet. Performing the *in-phase* pattern is known to involve more displacements of the CoG in the antero-posterior axis compared with the *anti-phase* pattern (Bonnet et al., 2008). Thus, training adequately the *in-phase* mode may enhance balance, mobility and goal-directed postures, thus offering new action opportunities and contributing to the general improvement of the motor FIM.

On the other hand, concerning the two postural scales (i.e., BBS and PASS), our results did not exhibit a better benefit for the experimental groups. This lack of effect may be found deceptive at the first sight, but it may well originate from the psychometric properties of the two scales. The PASS is known to be more responsive to changes in the early stage of recovery (i.e., 30 days after stroke; Mao, Hsueh, Tang, Sheu, & Hsieh, 2002), hence much earlier than the time-after-stroke tested in our study (66.39 ± 28.31 days). The BBS score is known to be biased by a floor effect of the scale, and must be completed by different assessments (Blum & Korner-Bitensky, 2008). In addition, the PASS evaluates the capacity to maintain or change a given posture but includes very few items related to postural coordination capacities in ADL (only one item evaluates a change in the standing posture). They contrast with the FIM score, which tests “mobility” and “transfers” in various goal-directed tasks involving postural components (e.g., dressing, toileting, etc.). Thus, the modification of postural dynamics does not seem to affect only postural and balance capacities but also goal-directed movements and ADL.

To resume, the postural coordination training protocol of the *in-phase* pattern combined with a conventional rehabilitation provided additional benefits in terms of functional independence in our stroke population. The evaluation of the postural preferred patterns may be a valid indicator of the functional performance in postural goal-directed tasks of poststroke patients, and may complete the classic clinical postural scales.

Conclusion

Information about postural dynamics can be exploited in the evaluation and rehabilitation phases of hemiplegic postural capacities to complete actual clinical

assessments of posture and balance. In a future work, the different (re)learning behaviors revealed by the hierarchical cluster analyze will be investigate more fully in relation with the patients' characteristics (e.g., localization and size of neural damage, motor and sensory deficits) for a better understanding of the (rehabilitation of) postural deficits accompanying hemiplegia.

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