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Changes in preferred postural patterns following stroke during intentional ankle/hip coordination

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ABSTRACT

We compared the spatio-temporal postural organization between stroke patients and healthy controls in a bipedal standing task where participants had to intentionally produce two specific ankle/hip coordination patterns: *in-phase* and *anti-phase*. The pattern to reproduce was visually represented by an ankle–hip Lissajous figure, and a real-time biofeedback displayed the current coordination sur-imposed to the expected coordination. Contrary to the healthy participants who were successful at reproducing the two patterns, stroke patients were unable to produce the *in-phase* pattern. In addition, when the *anti-phase* pattern was required, a reduction of stability was observed for the stroke group. The impairment of postural capacities following stroke was thus accompanied by a disappearance of one of the two preferred patterns found in healthy participants, a result that have consequences for understanding the etiology of postural pattern formation and the elaboration of rehabilitation programs.

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1. Introduction

Hemiplegia consecutive to a stroke is a cerebrovascular disease yielding postural impairments and related deficits such as motor control asymmetry, spasticity, sensory disorders or alterations in spatial cognition [1]. Research on hemiplegia has largely focussed on balance deficits occurring after stroke. The kinematics of the center of pressure (CoP) is often analyzed as the key parameter. In quiet stance, posture is characterized by an important asymmetry, the healthy leg supporting the major part of body weight [2,3]. A large increase in postural oscillations is observed, particularly along the medio-lateral axis [4]. Moreover, in voluntary weight shifting movements, the area of stability is much smaller [5], in particular in the antero-posterior axis [6]. These instabilities observed at CoP level increase with the intensity of intralimb and interlimb neuromuscular deficits. Post-stroke patients exhibit reduced muscular activation, delayed for the injured leg [7]. Moreover, in standing perturbation protocols, latency of muscular activation increases for the paretic leg and timing between distal and proximal synergists is disturbed compared to the healthy leg [8].

To our knowledge, the related spatio-temporal organization of the postural system has never been explored in hemiplegic patients. This is the goal of the present research. A good assessment

of pathological postural dynamics – the repertoire of stroke-induced postural coordination patterns – is indeed essential to understand the etiology of pattern formation and recommend adequate rehabilitation [9]. Here posture is examined at a functional level defined by the stability of ankle–hip coordination [10]. In healthy population, the organization of the postural system has been studied in great detail (e.g., [10,11]), through for instance the ankle–hip relative phase (ϕ_{rel}) [10]. In tracking task involving the postural system in the antero-posterior axis, two preferred coordination modes were identified, an *in-phase* pattern, with the two joints oscillating simultaneously in the same direction (ϕ_{rel} close to 0°), and an *anti-phase* pattern, with the joints moving in opposite directions (ϕ_{rel} close to 180°) [10]. In recent studies, postural dynamics was explored using a visual “coordination” biofeedback (bioFB) (e.g., [12]). Healthy participants were instructed to reproduce several imposed postural coordination modes. They were not able to perform in a stable way patterns other than the two aforementioned modes.

Important for the present purpose is the biomechanical properties of these two modes. Due to the double inverted-pendulum nature of the postural system and the mechanical coupling between its various joints, the *in-phase* mode has been found to be more efficient than the *anti-phase* mode for body displacements of small amplitude or velocity, even though it produces larger muscular torque at the ankle level [13]. In contrast, the *anti-phase* mode appears to be used when the limits of stability are reached, i.e., when the CoP excursion reaches the limits of the base of support (BoS).

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In the present experiment, post-stroke patients and controls were instructed to reproduce, with the help of a bioFB, the two postural patterns, *in-phase* and *anti-phase*, found in healthy subjects. Due to the cerebral lesion and the accompanying sensori-motor deficits shortly reviewed previously, we expected a general loss of stability together with a reduction in the ability to produce the *in-phase* pattern.

2. Materials and methods

Thirty-six subjects assigned in three groups took part in this experiment. To be included in the injured group (IG), the time since stroke had to be shorter than six months, it had to be their first unilateral hemispheric acute stroke, and patients had to be able to remain standing without help during 60 s. The exclusion criteria were another mobility-limiting neurological condition, previous sensory or orthopaedic disease that could affect standing balance, dementia or cognitive disorders making impossible the understanding of instructions. Clinical assessments were carried out to characterize the deficit of our injured group (Table 1). The motor weakness of five lower limb muscle groups was assessed on a 5-points scale adapted to central neurological disorders [14]. Spasticity of 4 lower limb muscle groups was assessed using the Ashworth scale [15]. Balance was evaluated with the Postural Assessment Scale for Stroke [16], gait with the Functional Ambulation Category [17] and autonomy with the Functional Independence Measure [18]. Hypoesthesia of the paretic side was assessed through pressure sensitivity at the pulp of the big toe using the Semmes–Weinstein test [19]. Visuo-spatial neglect was also evaluated with the Bells [20] and with the line bisection tests [21]. IG included twelve patients, five females and seven males, aged 42–67 years ($M = 56.4$ years, $SD = 8.9$) engaged in neurological rehabilitation. Twelve healthy young participants, two females and ten males, aged 22–31 years ($M = 26.1$ years, $SD = 3.0$) were included in the young group (YG). The age-matched group (AG) was composed of twelve healthy participants, nine female and three males, aged 39–70 years ($M = 57.7$ years, $SD = 8.6$). Cerebral lesions were all hemispheric and for ischemic strokes they all were in the territory of the middle cerebral artery. For YG and AG participants, no neurological or musculoskeletal deficiencies were self-reported. All participants provided informed consent prior to testing, and the protocol was approved by the local Ethics Committee, conforming to the Declaration of Helsinki.

During the experiment, participants were placed 3.50 m in front of a screen (1.50 m × 1.10 m). They stood barefoot in a comfortable position. Four electrogoniometers (SG series, Biometrics Ltd.) were fixed to the ankles and the hips. Two were attached to the lateral side of the hips (extending from the greater trochanter to the iliac crest) and two on the anterior side of the ankles (extending from the scaphoïde to the inferior third of the tibia). Data from the electrogoniometers were recorded using a DataLink data acquisition system (Biometrics Ltd.) with 1° accuracy and sampled at 16 Hz.

The task was to reproduce two ankle–hip postural patterns – 0° and 180° – visually represented on the screen. The prescribed pattern was presented (in blue) by a Lissajous figure (i.e., a line oriented in the ankle–hip angles plane). The 0° mode corresponded to an oblique line with a positive slope, and the 180° mode to an oblique line with a negative slope. To help the participants, a real-time visual bioFB, originating from the goniometers’ output and representing the current ankle–hip coordination state (in red), was superimposed to the prescribed pattern (see Fig. 1). The instruction for the participants was to produce ankle and hip flexion–extension movements to displace the red dot on the screen, following as close as possible the blue line. Participants were free to choose the frequency of their movements. They were asked to keep their knees extended, and their toes and heels in constant contact with the floor during all the experiment. The Lissajous figure imposed a 1:1 amplitude ratio between the ankles and hips, with a maximal amplitude of 8° for each joint.

Table 1
Mean ± standard deviation [minimum–maximum] of clinical characteristics for the hemiplegic participants.

Hemiparetic side (right/left)	5/7
Type of stroke (ischemic/hemorrhagic)	10/2
Delay between stroke and inclusion (days)	108 ± 63.3
Voluntary control of movements, lower limb (maximum 25)	15 ± 4.5 [9–24]
Spasticity, lower limb (maximum 16)	2.2 ± 2.0 [0–7]
Hypoesthesia, paretic side (maximum 6.75)	3.9 ± 0.6 [3.22–4.74]
Bells test (maximum 35)	2.5 ± 4.5 [0–15]
Line bisection (maximum 100 mm)	7.1 ± 10.9 [0–40]
Postural Assessment Scale for Stroke (maximum 36)	32.9 ± 2.2 [28–35]
Functional Ambulation Classification modified (maximum 5)	3.7 ± 1.1 [2–5]
Functional Independence Measure (maximum 126)	108.7 ± 11.5 [83–124]

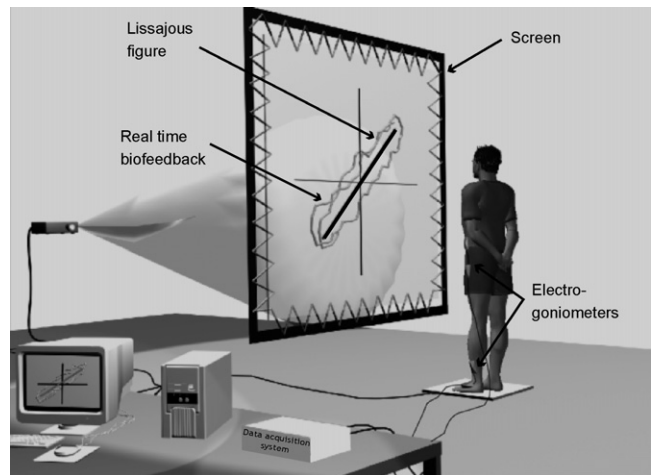


Fig. 1. Experimental design for the visual biofeedback task. Participants were asked to match their ankle–hip coordination (grey line) with the dark pattern (in the example, 0° pattern).

The experiment proceeded over one 50-min session per pattern, on two consecutive days. Subjects started with a familiarization period which included 5 min of practice with the experimental setup in which they learned how to move the target dots in the ankle–hip space. During each session, they were asked to perform ten 90-s trials.

Two bioFB conditions were also tested: in the *hFB* condition, the bioFB came from the healthy side (for IG) or the left side (for YG and AG) and in the *iFB* condition, the bioFB came from the injured side (for IG) or the right side (for YG and AG). Participants performed 5 trials in each bioFB condition. Trial order was counter-balanced for patterns and bioFB conditions over participants.

To estimate the coordination between ankles and hips, we computed the point-estimate of relative phase (ϕ_{rel}) using the peak of flexion of each joint for each movement cycle. For all participants, the last forty ϕ_{rel} values in each condition were kept and used for all analyses. Mean, angular deviation ($SD\phi_{rel}$) and 95% confidence interval for ϕ_{rel} were calculated from ϕ_{rel} values with circular statistics [22]. $SD\phi_{rel}$ indicates the coordination variability. We also computed the absolute error AE as an index of task performance. The absolute difference between each ϕ_{rel} value, transformed in the interval $[-180^\circ$ to $180^\circ]$, and the requested pattern (i.e., 0° or 180°) was computed for this purpose. Finally, in order to estimate the movement frequency (MF), we computed in each trial the Fast Fourier Transform of the ankle time series, and took in the power spectrum the frequency corresponding to the largest peak.

We used Rayleigh uniformity tests on ϕ_{rel} values to determine whether postural patterns stayed significantly closed around a unique value. We conducted Group (3) × Leg (2) × Pattern (2) × bioFB (2) ANOVAs with repeated measures on the last three factors for AE and $SD\phi_{rel}$. For MF, a Group (3) × Pattern (2) × bioFB (2) ANOVA with repeated measures on the last two factors was conducted. When post hoc tests were necessary, we used Neuman–Keuls tests. Because our distributions were slightly skewed, we log-transformed all AE, $SD\phi_{rel}$ and MF values before performing statistical tests.

3. Results

One participant from AG was excluded from the analysis because of a technical problem during data acquisition. Moreover, data from one stroke patient could not be treated with the point-estimate method. This participant was also excluded from the statistical analysis.

3.1. Relative phase produced

Results on relative phase distributions showed different behaviors between groups in the 0° pattern condition (Fig. 2). For IG, mean ϕ_{rel} was 170.53° ($SD\phi_{rel} = 45.43^\circ$) for the injured leg, and 175.32° ($SD\phi_{rel} = 27.52^\circ$) for the healthy leg. For YG, mean ϕ_{rel} was 357.07° ($SD\phi_{rel} = 24.13^\circ$) for the right leg, and 359.07° ($SD\phi_{rel} = 24.13^\circ$) for the left leg. For AG, mean ϕ_{rel} was 314.72° ($SD\phi_{rel} = 65.41^\circ$) for the right leg, and 330.58° ($SD\phi_{rel} = 68.66^\circ$) for the left leg. Rayleigh tests showed that all groups presented a directional distribution (All $ps < .01$) for each leg. Thus, IG

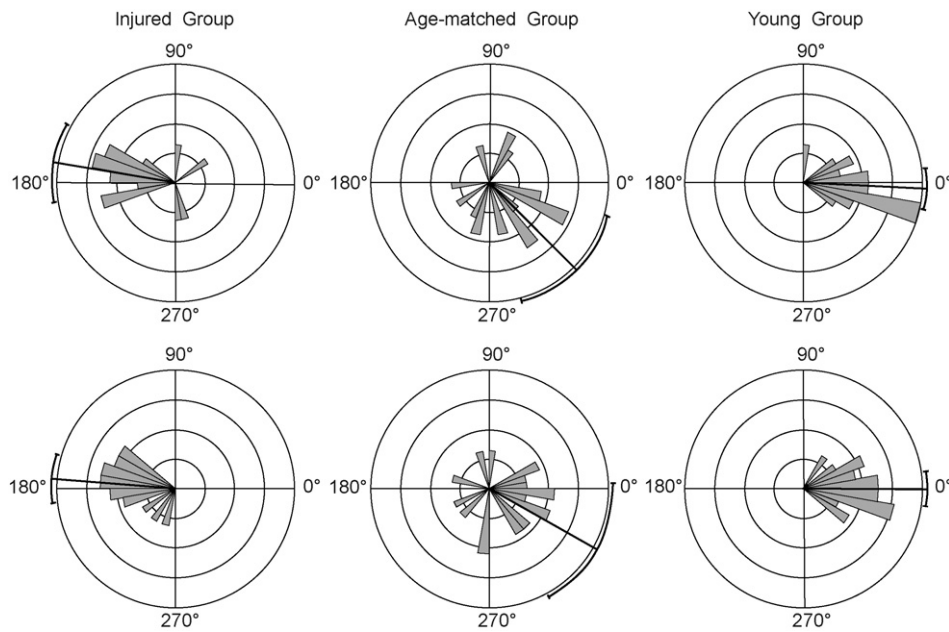


Fig. 2. Circular diagram showing the occurrence of relative phase values in the 0° pattern for the injured/right leg (up) and the healthy/left leg (down), for the three groups. Occurrence rates were computed in 10° intervals. Each concentric circle corresponds to 10 occurrences. The segment and the arc represent the mean relative phase and its 95% confidence interval, respectively.

participants exhibited a coordination close to *anti-phase*, whereas healthy participants exhibited the requested *in-phase* coordination.

In the 180° pattern condition, IG produced a mean ϕ_{rel} of 164.47° ($SD\phi_{rel} = 29.51^\circ$) for the injured leg and 172.82° ($SD\phi_{rel} = 14.86^\circ$) for the healthy leg. For YG, mean ϕ_{rel} was 178.17° ($SD\phi_{rel} = 4.59^\circ$) and 178.86° ($SD\phi_{rel} = 3.03^\circ$) respectively for the right and the left legs. AG produced a mean ϕ_{rel} of 182.36° ($SD\phi_{rel} = 7.21^\circ$) for the right leg and 186.96° ($SD\phi_{rel} = 24.47^\circ$) for the left leg. Rayleigh tests showed that all groups exhibited a directional distribution (all $ps < .01$). To summarize, the two healthy groups produced a coordination consistently centered around the required pattern, whereas the injured group produced a pattern close to 180° in all cases (Fig. 3).

3.2. Task performance

For AE, the ANOVA performed on log-transformed data exhibited a main effect of Group on AE ($F(2,31) = 61.44$, $p < .001$). AE was larger for IG than for the healthy groups (all $ps < .001$). Moreover YG presented a better performance than AG ($p < .001$). A main effect of Pattern was observed ($F(1,31) = 201.49$, $p < .001$), revealing that performance was better in the 180° condition than in the 0° condition. The analysis of variance exhibited a $bioFB \times Leg$ interaction ($F(1,31) = 6.47$, $p < .05$), and the Newmann-Keuls tests revealed that for the healthy/right leg, performance was better when the $bioFB$ originated from this same leg ($p < .05$). No other interaction was significant.

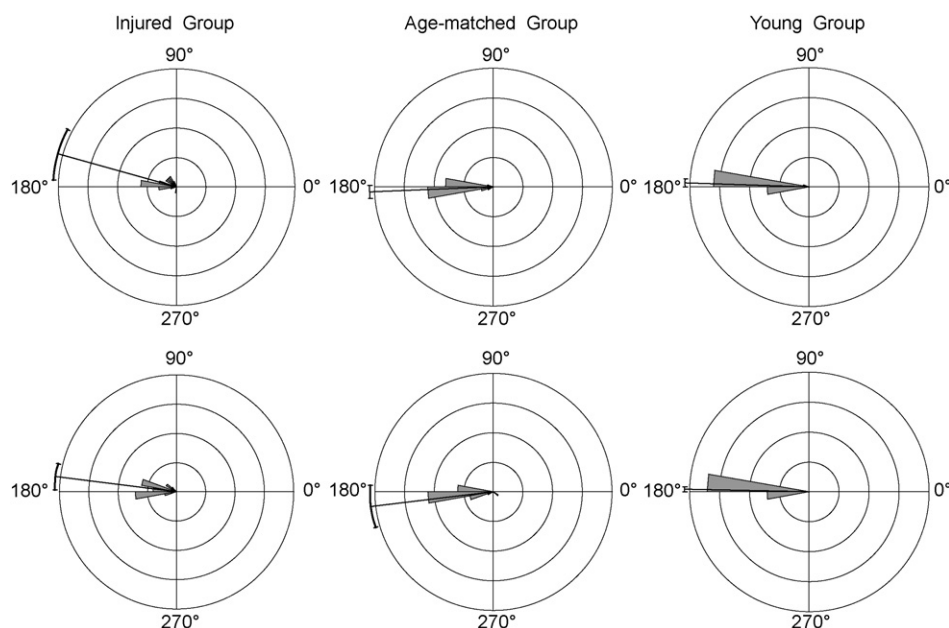


Fig. 3. Circular diagram showing the occurrence of relative phase values in the 180° pattern for the injured/right leg (up) and the healthy/left leg (down), for the three groups (see legend of Fig. 2 for details).

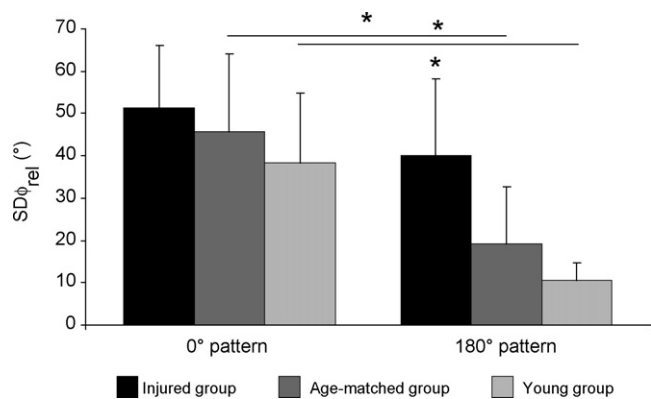


Fig. 4. Mean results of $SD\phi_{rel}$ for the three groups and for each pattern (0° and 180° patterns).

3.3. Pattern stability

The ANOVA performed on the (log-transformed) $SD\phi_{rel}$ values showed a main effect of Group ($F(2,31) = 16.90, p < .001$), Pattern ($F(1,31) = 113.80, p < .001$) and a Pattern \times Group interaction ($F(2,31) = 12.45, p < .001$). Newman–Keuls tests revealed a larger variability for IG compared to YG and AG in the 180° condition (all $ps < .001$). Moreover, the stability was better for the two healthy groups in the 180° condition compared to the 0° condition (all $ps < .001$) whereas there was no difference between pattern conditions for IG (Fig. 4).

3.4. Movement frequency

The analysis of variance performed on movement frequency exhibited a main effect of Group ($F(2,31) = 10.68, p < .001$), indicating that stroke patients were slower than members of the two healthy groups (all $ps < .01$). A main effect of Pattern was also found ($F(1,31) = 22.55, p < .001$) indicating that movement frequency was higher in the 180° condition. No other interaction was significant.

4. Discussion

The aim of this study was to analyze the effects of stroke onto the preferred *in-phase* and *anti-phase* postural coordination documented in healthy participants. We predicted that due to the biomechanical constraints acting on the two modes, the *in-phase* pattern would be problematic for patients. In addition, we expected that a general increase in variability would accompany the changes in postural dynamics due to stroke.

4.1. Anti-phase pattern persistence

For the 180° pattern, patients produced a coordination mode close to the required pattern, although IG patients were less stable than healthy participants for this pattern. This decrease in stability can be explained by a diminution of the underlying attractor strength. This diminution can originate from the modification of the oscillators' properties (significant reduction in movement frequency) rooted in the stroke-related sensori-motor deficits (e.g., diminution of muscular force, asymmetry between legs in muscular tonus [23], or somato-sensorial deficits [24]). A small but significant difference was also observed for the 180° pattern between young and age-matched participants (higher variability for AG), showing the sensitivity of our test to normal ageing. This difference is not responsible for the observed divergence between healthy and hemiparetic patients but witnesses the progressive

degradation of inter-joint coordination during postural sway with age [25].

4.2. In-phase pattern disappearance

A major result concerns the 0° pattern. Mean ϕ_{rel} and AE performance show that patients did not exhibit the *in-phase* pattern when required. They produced instead a coordination mode close to *anti-phase*. In biomechanical terms, producing the *in-phase* pattern requires important CoP displacements in the anterior–posterior axis and greater ankle torque in comparison with the *anti-phase* pattern [13,26]. The well-known fact that stroke patients suffer from an important weakness of ankle muscles [27] leading to a reduction in torque produced at that joint, may explain the disappearance of the *in-phase* pattern. In addition, stability limits and weight-shifting deficits in hemiplegic patients are certainly contributing factors to the difficulty of patients to perform the *in-phase* pattern [5,6]. This result impacts our understanding of postural pattern formation, suggesting that biomechanical constraints play a crucial role in shaping postural dynamics [11], particularly in fragile humans.

4.3. Effect of biofeedback

The only effect observed for the bioFB condition was a less important error for the healthy/left leg when the bioFB information originated from that leg. This result was obtained only for one variable (AE), which is insufficient to conclude for a beneficial effect of one bioFB condition compared to the other. We view this preliminary result as an important avenue for future research because of the potential transfer from the healthy leg to the paretic leg that our experimental task may offer.

5. Conclusion

To conclude, this work reveals important changes in postural dynamics following stroke. Hemiplegia causes the system to evolve from the healthy bi-stable dynamics in which *in-phase* and *anti-phase* patterns are (re-)produced [10] to a mono-stable behavior where only the *anti-phase* pattern remains, associated with a decrease in pattern stability. Biomechanical limitations characterizing our pathological population, (e.g., reduction of the BoS, limited ankle torque) are contributing factors to these changes. Obviously, the observed results are circumscribed within the context of our “imposed” postural task, and extension of these results to other postural situations remains to be analysed. For instance, ankle–hip coordination remained rather unchanged when the supporting surface was translated at various frequencies (e.g., [11]). However, the existence of the two preferred patterns in other postural situations such as during “quiet stance” [28], calls for a possible transfer in daily activities. The consequence of these results for rehabilitation routines and associated clinical tests is under evaluation.

Conflict of interest

All authors have not any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

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