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Exploring coordination dynamics of the postural system with real-time visual feedback

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Abstract

Differential performance over a wide range of possible postural coordination modes was investigated using 16 ankle–hip relative phase patterns from 0° to 337.5°. Participants were instructed to produce each coordination mode with and without real time visual feedback. Feedback consisted of a Lissajous figure indicating the discrepancy between actual and requested ankle–hip relative phase. The results showed: (1) the presence of a unique attractor around the anti-phase pattern (relative phase ≈ 180°); (2) performance was similar with and without visual feedback; (3) the absence of an attractor for the in-phase pattern (relative phase ≈ 20°). The third result is not consistent with previous research in which both in-phase and anti-phase patterns emerged when they were not imposed [B.G. Bardy, L. Martin, T.A. Stoffregen, R.J. Bootsma, Postural coordination modes considered as emergent phenomena, J. Exp. Psychol. Hum. Percept. Perform. 25 (1999) 1284–1301; B.G. Bardy, O. Oullier, R.J. Bootsma, T.A. Stoffregen, Dynamics of human postural transitions, J. Exp. Psychol. Hum. Percept. Perform. 28 (1999) 499–514]. This finding indicates the strong dependency to task variation and instructions of postural pattern formation.

Keywords: Coordination dynamics; Standing posture; Attractors; Ankle–hip relative phase; Closed-loop feedback system

Numerous studies of inter-limb coordination, and especially, of bimanual coordination [8], have revealed the existence of stable patterns of coordination between the cyclic movement of two body segments: in-phase (i.e., 0° relative phase) and anti-phase (i.e., 180° relative phase). These two modes appear to be strong attractors of the dynamics of any bimanual coordination system. The system used to control overall body posture (stance) is more complex, being characterized by many elements interacting inertially in very different ways. Nevertheless, ankle–hip coordination in stance exhibits similar spontaneous coordination modes [2,3]: in-phase motion between ankles and hips for low frequencies/small amplitudes of body movements ($\phi_{rel} \approx 20°$), and anti-phase motion between ankles and hips for high frequencies/large amplitudes of body movements ($\phi_{rel} \approx 180°$). Interesting for the present research is the repeated finding that these two coordinative states of the postural system have emerged out of the very large number of possible combinations of the many degrees of freedom involved in the accomplishment of supra-postural tasks.[1]

Together with a large portion of the bimanual coordination research, these studies on postural coordination have concentrated on the stability properties of in-phase and anti-phase

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[1] In contrast to many studies of bimanual coordination, the relative phase was not mandated by instructions or induced by environmental information (e.g., metronome or Lissajous figure). In our experiments [2,3], standing participants were asked to track with their head a target moving sinusoidally in the antero-posterior axis, so as to nullify the change in distance and the relative phase between head and target. The experimental task is supra-postural in the sense that the goal is not to maintain a particular postural coordination, but to perform the tracking task.

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modes, and on the changes between them under the pressure of a control parameter such as movement frequency [3,8]. The results are important to the neuroscience community because they reveal the self-organized nature of biological systems that may be exploited by the central nervous system in the production of flexible and stable movement patterns.

Some previous research has explored the possible induction of attractors other than in-phase and anti-phase. Yamanishi et al. [16] used a bimanual finger typing task, and asked participants to perform 10 different phase relations between the left and the right index finger (varying by 36° steps from 0° to 324° relative phase). Each performance began with a visual signal specifying the current phase relation (visual metronomes) and ended without the visual signal. As expected, in-phase and anti-phase patterns were the most accurate (smallest error) and stable (lowest standard deviation). More interesting was the tendency to produce these two modes when neighboring patterns were requested; in-phase and anti-phase patterns attracted the other surrounding coordination modes. These results have been reproduced by Tuller and Kelso [14] in a similar task but with continuous visual signal, and by Zanone and Kelso [17] with a flexion-extension task of index fingers. More recently, several studies have shown that task or sensory parameters such as the presence of augmented visual feedback [10,13] or a change in the mechanical or neuromuscular constraints [6] have great consequences in the formation and stability of bimanual coordination modes [5].

In the context of stance, we have demonstrated [1] that people can learn novel ankle–hip coordination (i.e., different from in-phase and anti-phase). However, to capture the complete dynamics of the postural system, it is necessary to scan systematically the entire repertoire of coordinative states (step by step). This is the aim of the present study. We explored the complete range of postural coordination by asking standing participants to execute 16 different ankle–hip relative phase patterns (from 0° to 337.5°). In order to examine the role of enhanced visual feedback on pattern formation and stability, each coordination mode was tested in two conditions. First, visual feedback was provided via a Lissajous figure in which the instantaneous discrepancy between the requested relative phase and the actual relative phase was plotted as a real time trajectory. Second, participants attempted to produce the requested coordination without visual feedback. Based on the theoretical abstract nature of coordination dynamics, as well as on the resemblance between bimanual and postural data in terms of spontaneous dynamics, we expected (i) greater accuracy and stability for spontaneous patterns (in-phase and anti-phase), (ii) attraction of other coordination modes toward spontaneous patterns, and (iii) better performance in the visual feedback condition than in the no visual feedback condition.

Fourteen naïve adults (nine males and five females, mean age of 22 years) participated in this study. Eight participants were assigned to the experimental group and six to the control group. Participants in the experimental group were asked to produce 16 ankle–hip relative phase patterns [0°–22.5°–45°–67.5°–90°–112.5°–135°–157.5°–180°–202.5°–225°–247.5°–270°–292.5°–315°–337.5°]. For each requested relative phase, the coordination pattern was visually presented to the standing participants on a 3 m H × 2 m V projection screen, in the form of a curve plotted in a (0.82 m × 0.82 m) ankle–hip position plane (Lissajous figure). Participants were asked to generate hip-ankle coordination corresponding to the displayed pattern, with two trials for each value of relative phase. Each trial consisted in the completion of 30 cycles of ankle–hip oscillation. In the experimental group, one trial with visual feedback (the visual feedback condition) was followed immediately by a trial with eyes closed (the no visual feedback condition), during which they tried to maintain the same relative phase value without the Lissajous feedback. Participants in the control group performed only the no visual feedback trial for each of the 16 requested patterns. A demonstration of the expected pattern took place at the beginning of each trial, using an animated picture simulating a person in profile performing the requested relative phase. The control group was used to test for order and fatigue effects.

Angular motion of hip and ankle joints was measured with two electro-goniometers placed on the participant's right leg. During visual feedback trials, data from the two goniometers were also used to generate the real time visual feedback in the same ankle–hip configuration plane that had been used to illustrate the requested relative phase pattern, using a closed-loop, virtual reality system (see Fig. 1). Participants were given a 3-min period to become familiarized with the connection between the graphic display and their own body movements. The order of the 16 relative phase values was randomized for each participant in order to minimize neighboring and hysteresis effects.

We computed four dependent variables to characterize the performed coordination: (1) the relative phase, ϕ_{rel}, between ankle and hip movements, (2) the circular standard deviation

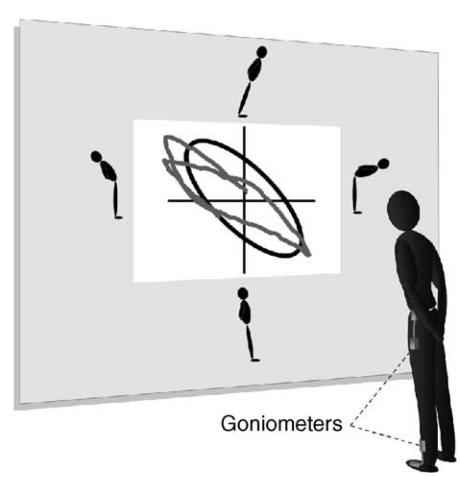

Fig. 1. Experimental design for the visual feedback condition. Participants were asked to match their ankle–hip coordination (grey line) with the dark pattern (in this example, 135° relative phase).

of relative phase, SDϕ_{rel}, (3) the constant error CE (i.e., the difference between the performed and the requested relative phase), and (4) the absolute error, AE. We calculated ϕ_{rel} using a point-estimate method, with one value per cycle. A relative phase between 0° and 180° indicated that the ankles were leading the hips. For each trial, we used all values of ϕ_{rel} to compute SDϕ_{rel}. We computed CE and AE for each cycle of each trial. A positive value of CE indicated an overestimation of the relative phase to produce, and a negative value indicated an underestimation. AE is the absolute value of CE. For all circular variables (i.e., ϕ_{rel}, SDϕ_{rel}, CE, and AE), we used standard circular statistics [4] to calculate the mean vector, the circular standard deviation, and the 95% confidence interval. However, because it is not possible with circular comparison tests to analyze interactions between factors, we also used standard Anovas. With the notable exception of ϕ_{rel}, the range of values for SDϕ_{rel}, CE, and AE are lower than 180° for a same required relative phase. Linear statistics can thus be applied with negligible error on these variables.

Circular means and 95% confidence intervals (CI) for achieved relative phase are presented in Fig. 2 for each of the 16 patterns requested. With two exceptions (22.5° requested – visual feedback; 180° requested – control) the 95% CI never contained the requested phase relation, evidencing the difficulty for the participants to reproduce exactly the requested patterns, with or without visual feedback. However, for the lowest requested patterns, the 95% CI around the mean often contained nearby requested relative phase that were higher than the current requested pattern. Above relative phase values of 157.5° (experimental group), or 202.5° (control group), the 95% CI sometimes contained requested relative phase that were lower than the current requested pattern. The overestimation of the requested phasing below anti-phase and its underestimation near and above anti-phase indicates a dynamical bias near the 180° pattern. The patterns between 270° and 0° appeared to be the most difficult to produce. Indeed, none 95% CI included these requested relative phases for any condition, in either group.

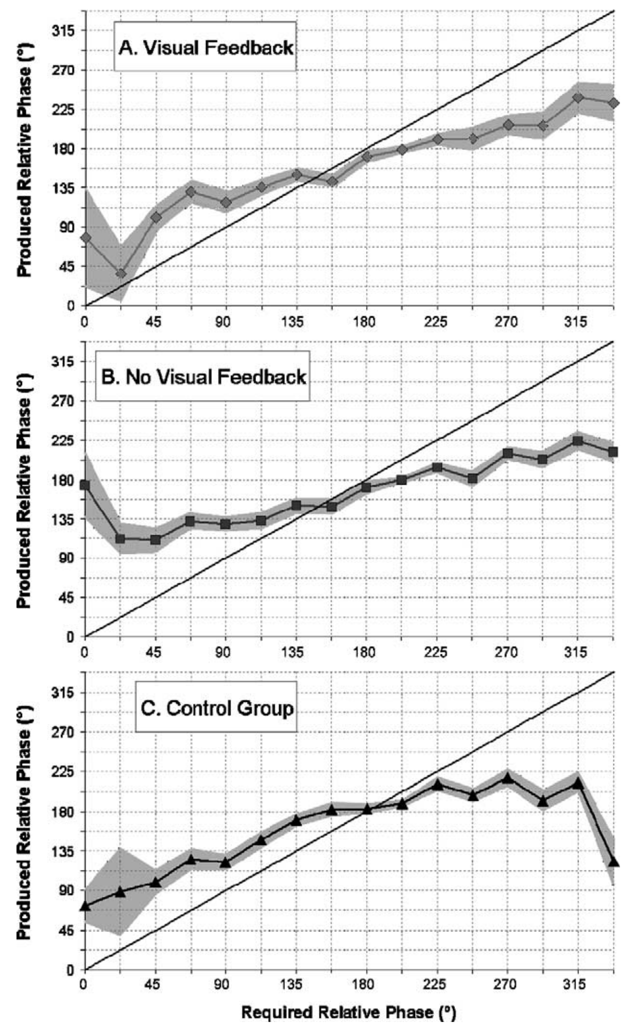

Fig. 2. Mean relative phase (curves with symbols), 95% confidence interval (grey regions), and perfect $x = y$ performance (black line) as a function of requested pattern. (A) Experimental group, visual feedback condition. (B) Experimental group, no visual feedback condition. (C) Control group, no visual feedback condition.

Because the no visual feedback trials for the experimental group always followed the visual feedback trials, fatigue, and/or order effects could be expected to affect postural dynamics. The comparison between control and experimental groups (Fig. 3) would ensure that the effects considered for the experimental group in the subsequent analysis can be attributed to experimental manipulations. We conducted pattern (16) × group (control versus experimental, no visual feedback condition only) ANOVAs with repeated measures on the first factor for CE, AE and SDϕ_{rel}. For CE, there was a significant effect for pattern ($F(15, 180) = 11.28$, $P < 0.05$), not for group ($F(1, 12) = 1.92$, ns) or for the pattern × group interaction ($F(15, 180) < 1$, ns). For AE, the main effect of pattern was significant ($F(15, 180) = 20.55$, $P < 0.05$), but the main effect of group and the interaction were not (each $F < 1$, ns). For SDϕ_{rel}, the main effect of pattern was significant ($F(15, 180) = 9.55$, $P < 0.05$), but the main effect of group and the interaction were not (both $F < 1.2$, ns). These analyses confirm that there were no fatigue and/or order effects (i.e., previous performance with visual feedback had no influence on the no visual feedback condition).

Mean values of CE, AE and SDϕ_{rel} for each requested pattern and in each condition are presented in Fig. 3 for each group. The figure illustrates the main results: (1) accuracy and stability were greatest in the 180°–202.5° range, (2) there was no effect of feedback condition, and (3) there were no differences between control and experimental groups.

For the experimental group, we conducted a pattern (16) × condition (2) repeated measures ANOVA on CE, AE and SDϕ_{rel}. For CE (Fig. 3A), the main effect of pattern was significant ($F(15, 105) = 9.75$, $P < .05$). The main effect of condition and the pattern × condition interaction were not significant (each $F < 1$, ns). For AE (Fig. 3B) the main effect of pattern was also significant ($F(15, 105) = 20.90$, $P < .05$), while the condition effect and the interaction were not (each $F < 1.6$, ns). For SDϕ_{rel} (Fig. 3C), the main effect of pattern

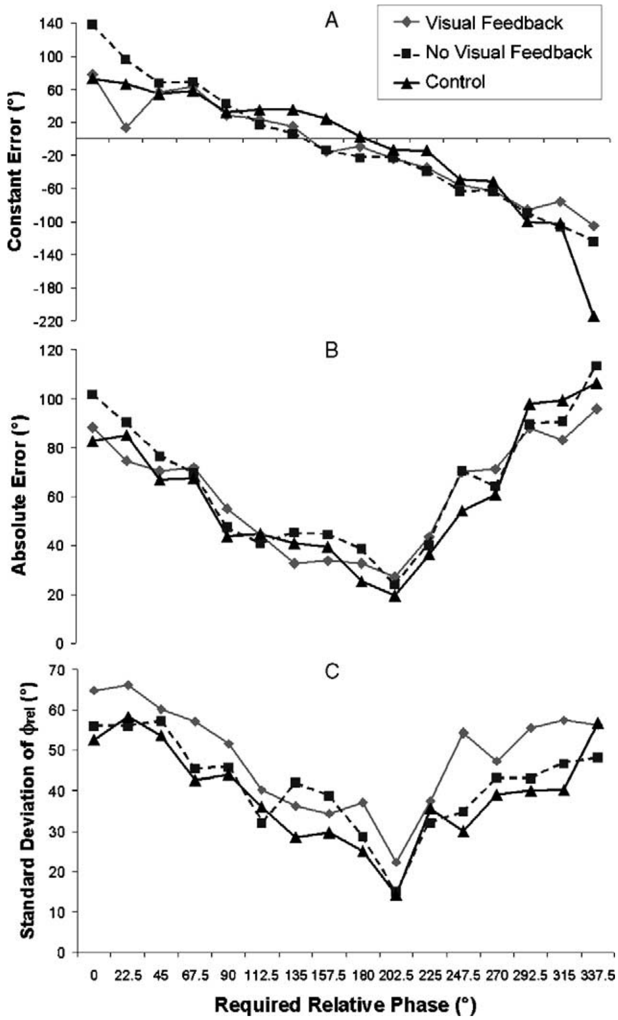

Fig. 3. Variables characterizing the produced relative phase as a function of requested pattern for the experimental group (with and without visual feedback) and the control group (no visual feedback). (A) Constant error. (B) Absolute error. (C) Standard deviation of relative phase.

was significant ($F(15, 105) = 9.86$, $P < 0.05$). The main effect of condition was also significant ($F(1, 7) = 23.03$, $P < .05$), with greater stability for no visual feedback condition (mean $SD\phi_{rel}$ of 41.50°) than for visual feedback condition (mean $SD\phi_{rel}$ of 48.68°). The pattern x condition interaction was not significant, $F(15, 105) < 1$, ns. These analyses confirm a strong attraction of the anti-phase pattern across the entire range of coordination modes tested. The minimum values for AE and $SD\phi_{rel}$ occurred at the requested relative phase of 202.5°, not 180° (see Fig. 3B and C). However, in this condition the actual relative phase produced was 178.5° (see Fig. 2), which was very close to the anti-phase pattern observed by Bardy et al. [2,3].

We compared requested patterns in which the ankle movement tended to lead (requested relative phase from 22.5° to 157.5°) to those in which the hip movement tended to lead (from 202.5° to 337.5°). For the experimental group (visual feedback and no visual feedback conditions), we conducted planned comparisons on CE, AE, and $SD\phi_{rel}$. CE was significantly lower for ankle-lead patterns than for hip-lead patterns, $F(1, 7) = 97.95$, $P < 0.05$. This analysis revealed a tendency to overshoot the requested relative phase when the ankles were leading (mean CE = 21.06°) and to undershoot when the hip were leading (mean CE = −60.56°). AE was smaller for ankle-lead patterns (mean AE = 58.18°) than for hip-lead patterns (mean AE = 70.01°), $F(1, 7) = 12.44$, $P < .05$. When the ankles were leading, the mean $SD\phi_{rel}$ was 47.40°, while it was 42.36° when the hips were leading; the difference was not significant, $F(1, 7) = 2.51$, ns.

The data of joint amplitudes are summarized in Fig. 4. For the experimental group, we analyzed the amplitudes of joint angular movements using pattern (16) × condition (2) repeated measures ANOVAs. For hip amplitude, the main effect of pattern was significant ($F(15, 105) = 8.17$, $P < 0.05$). The main effect of condition was also significant ($F(1, 7) = 10.13$, $P < .05$), with a higher amplitude for no visual feedback condition (mean of 13.33°) than for visual feedback condition (mean of 10.21°). The pattern × condition interaction was not significant ($F(15, 105) = 1.10$, ns). For ankle amplitude, the main effect of pattern was significant ($F(15, 105) = 4.17$, $P < .05$). The main effect of condition ($F(1, 7) = 3.39$, ns) and the interaction were not significant ($F(15, 105) = 1.17$, ns). These results indicate an increase of movement amplitude for both joints for requested patterns close to anti-phase (Fig. 4), and increased hip amplitude in the no visual feedback condition.

We found a general influence of the requested relative phase on performed coordination. Our measures capturing the coordination (ϕ_{rel}, $SD\phi_{rel}$, CE, and AE) indicated that participants did not accurately produce relative phases between 270° and 360° (0°), with constant errors as high as −100°. There was a tendency to overestimate relative phase for requested relative phase below the range [157.5°–202.5°], and to underestimate relative phase above that range, as expressed by the negative slope of constant error over the scan. Thus, in this study there was a unique attractor around anti-phase, that is, a unique coordinative state which attracted the

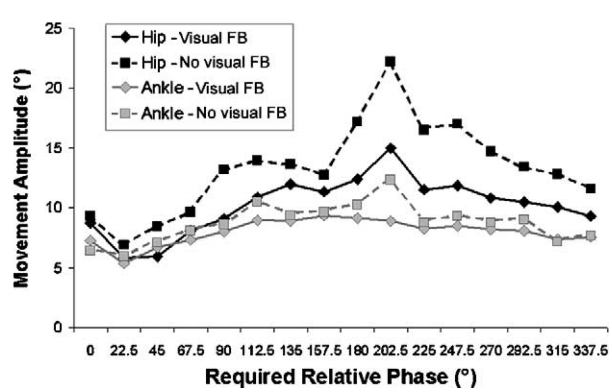

Fig. 4. Mean angular movement amplitude of hips and ankles as a function of requested pattern for the experimental group, with and without visual feedback (FB).

other patterns toward its relative phase value. This finding is complemented by better performance (smaller CE and AE) when the requested relative phase involved the lead of hip movement (relative to conditions in which the ankle lead), illustrating the asymmetrical nature of postural dynamics.

Based on previous research using visual feedback in bimanual tasks [10,13], we expected better performance in the visual feedback condition. However, performance (CE and AE) was similar with and without visual feedback, and stability (SDϕ_{rel}) was better in the absence of visual feedback. Because experimental and control groups did not differ, this result cannot be explained by an order effect of having that condition following the tracking condition. The reduction in stability with visual feedback may indicate that hip and ankle amplitude were severely constrained in the presence of visual feedback, but behaved more as free parameters without it. Because movement amplitude is critical for the stability of coordination dynamics, differences in amplitude between the two conditions may explain the difference in stability. In any event, in our postural coordination task visual feedback did not play the beneficial role observed in bimanual coordination. The absence of interaction between the requested pattern and the visual feedback manipulation for accuracy (CE and AE) and stability (SDϕ_{rel}) suggests a common postural dynamics in the two conditions.

We did not observe a stable in-phase pattern (around $0°$–$45°$). This finding contrasts with previous studies that have observed robust in-phase coordination of the hips and ankles [2,3,11]. Why was it absent in the present study? Perhaps the instruction to execute particular values of relative phase imposed movement frequencies and amplitudes that were different from those involved in the spontaneous in-phase pattern observed in previous research. An effect of frequency seems unlikely, since in our study, subjects were free to take as much time as they wished. An amplitude effect may seem credible. For the requested in-phase mode of $22.5°$, hip and ankle amplitudes ($5.84°$ for hips, $5.40°$ for ankles in the visual feedback condition) were higher than the $3.97°$ for hips and $4.30°$ for ankles reported by Bardy et al. [2]. However, absence of significant interactions between requested pattern and visual feedback for CE, AE or SDϕ_{rel} suggests that the coordination dynamics did not differ when movement amplitude was imposed (visual feedback), and when it was not (no visual feedback).

A more likely explanation is the difference, between the present and previous studies, in subjects' task. In the present study, hip-ankle coordination was dictated by the experimenters. In previous studies the experimenters dictated only a supra-postural task (using head movements to track motion of a visible target), and hip-ankle coordination emerged out of constraints related to the tracking task. The role played by task goal in shaping postural behavior has been at the heart of recent work on vision and stance [12] and postural dynamics [11], showing that subtle variations in task goal and experimental instructions can strongly influence postural behavior.

In the same vein, and quite paradoxically, it has been shown that focusing attention on coordination (internal focus) can disrupt a more natural behavior [7,9,15]. Wulf and Prinz [15] found that performance improved when subjects were asked to concentrate on how their actions affected the environment, relative to when they were told to focus on the movement itself. Similarly, Hodges and Franks [7] suggested that explicit instructions can lead subjects to attempt conscious control over processes that typically are controlled by lower, less cognitive levels of the motor system. Thus, instructions focusing attention on a goal different from the phase relation between the moving limbs may favor the expected coordination. In the present study, the greater stability of the produced relative phase in the absence of visual feedback is consistent with this view.

The present results document the asymmetry of the postural system around one single anti-phase ankle–hip attractor, when the dynamics of the hip-ankle coordination is imposed by the experimenters. Recent studies have shown that bimanual coordination dynamics can be modified by providing suitable visual feedback [10] or by varying neuromuscular-skeletal constraints [6]. In the present study, we influenced postural coordination dynamics by changing the nature of the task. Our results do not support a direct correspondence between constrained postural dynamics, that is, the time-related postural behavior that emerges out of a coalescence of constraints [2,3,11], and imposed dynamics, that is, the postural behavior that is specified by instructions or environmental information. The task-specific behavior of the postural system may be adequately exploited by the central nervous system by modulating appropriately, under specific task-related circumstances, the order parameter for the coordination.

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