

# Postural Coordination Dynamics in Standing Humans

Benoît G. Bardy

Research Center in Sport Sciences, University of Paris Sud XI, Orsay, France

## Abstract

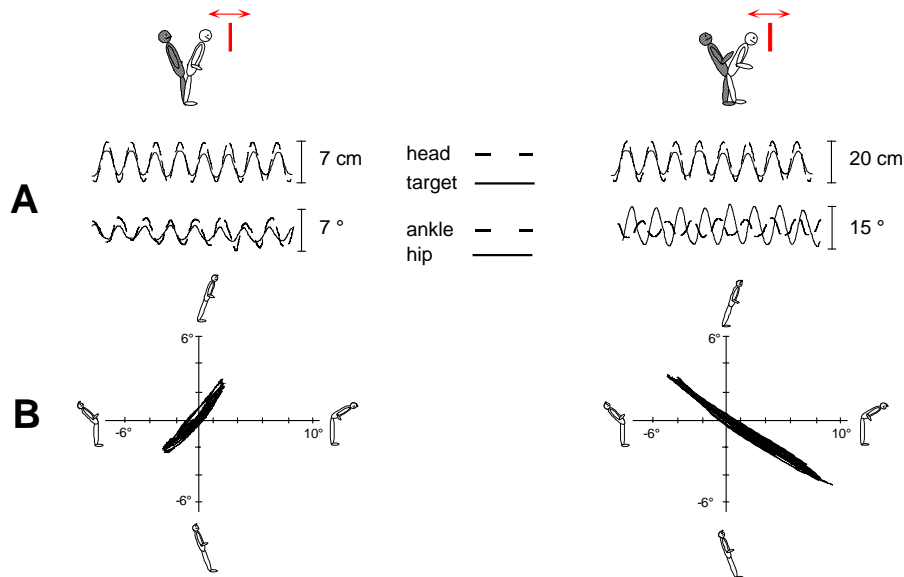
Human stance requires the coordination of multiple joints. This article examines the dynamics of postural coordination modes involving the torso and legs in the control of stance and stance-related activities. Based on data obtained in various experiments using the same postural tracking task, we provide evidence that postural modes (i) emerge out of the coalescence of multiple constraints, (ii) exhibit persistence and changes that are characteristic of self-organized systems, (iii) are modulated by the actor's intention, and (iv) can be learned by modifying the intrinsic dynamics of the postural system. Similarities between postural phase transitions in humans or non-biological phenomena suggest the existence of general and common principles governing pattern formation and flexibility in complex systems, and circumscribe the generality of neurophysiologically-based theories of postural behavior.

## Postural Coordination Dynamics in Standing Humans

One of the major problems facing movement scientists is how humans and other animals coordinate the multitude of degrees of freedom of their bodies, constraining them to act as a single unit in accomplishing behavioral tasks. Standing, walking, reaching, or hitting a moving object are prosaic examples in which successful performance is based upon, and severely constrained by, a set of neuromuscular synergies temporally and functionally assembled for the purpose of the task. In less than two decades, the field of coordination dynamics has demonstrated its robustness as a theoretical framework for posing (at least), and solving (at best) the problem of human coordination. Experimental and theoretical studies have provided evidences for the existence of non linear dynamical principles in the domain of human inter-limb coordination (e.g., Carson et al. 1995; Haken et al. 1985; Kelso 1984; Schönér et al. 1986), intra-limb coordination (e.g., Buchanan et al. 1997; Diedrich and Warren 1995; Kelso et al. 1991), as well as for coordination of limbs with external events (e.g., Dijkstra et al. 1994; Jeka et al. 1997; Schmidt et al. 1990). These studies have concentrated on coordination of individual segments, such as fingers, arms, legs, or head. Surprisingly, virtually no research in pattern dynamics has concentrated on the problem of postural coordination, i.e., coordination between various body parts that underlies our supra-postural behaviors (see however Saltzman and Kelso 1985, and Woollacott and Jensen 1996 for early predictions). In our daily actions such as standing, walking, running or dancing, the very great dimensionality of the body (e. g., some  $10^3$  muscles and  $10^2$  joints for humans) needs to be reduced to a controllable system exhibiting order, that is, stable and flexible postural patterns. In posture research, a great number of neurophysiological and biomechanical studies have evidenced the role of local constraints — central command signals or forces — in organizing patterns of whole-body coordination (e.g., Allum et al. 1993; Corna et al. 1999; Horak and Nashner 1986, McCollum and Leen 1989; Nashner and McCollum 1985; Nashner et al. 1989; Pai and Patton 1997). We argue, however, that these local constraints operate in the context of general principles governing postural pattern formation that remain largely unknown. The present contribution aims at underlying the persistences and changes in human posture that witness these general principles. On the basis of recent experimental work, we provide evidences for similarities between postural coordination in humans and other well-known biological phenomena, suggesting the existence of general and common principles governing pattern formation and flexibility in complex systems. We believe that such an approach circumscribes the generality of neurophysiologically-based or biomechanically-based theories of posture, and can therefore be helpful for building a general theory of postural coordination and control.

## The postural tracking task: a paradigm for investigating postural pattern formation

We have begun to evaluate the multi-segment postural system as a dynamical system, examining modes of coordination that may exist in standing participants between rotations at the ankles and hips. We have focused on the emergence of postural coordination modes that underlie a supra-postural tracking task, as well as on the constraints that shape coordination dynamics (Bardy and Marin 1997; Bardy et al. 1999; Marin, Bardy, et al. 1999, Marin, Bardy and Bootsma 1999). In this series of studies, participants in comfortable bi-pedal stance were instructed to maintain a constant distance and phase between their head and a visual target that oscillated along the line of sight. “Tracking” the target with the head was the specific instruction given to the participants. We measured posture during task performance, and found that participants exhibited only two preferred coordination modes between the ankles and the hips (see Figure 1 for an example). Because of its rhythmical nature (e.g., Yoneda and Tokumasu 1986), postural coordination patterns could be captured by the collective variable  $\phi_{rel}$ , i.e., the relative phase between ankle motion and hip motion. Two values of  $\phi_{rel}$  consistently emerged: An *in-phase* mode, with the two joints moving simultaneously in the same direction ( $\phi_{rel}$  close to  $20^\circ$ ), and an *anti-phase* mode with the two joints oscillating simultaneously in opposite directions ( $\phi_{rel}$  close to  $180^\circ$ ).



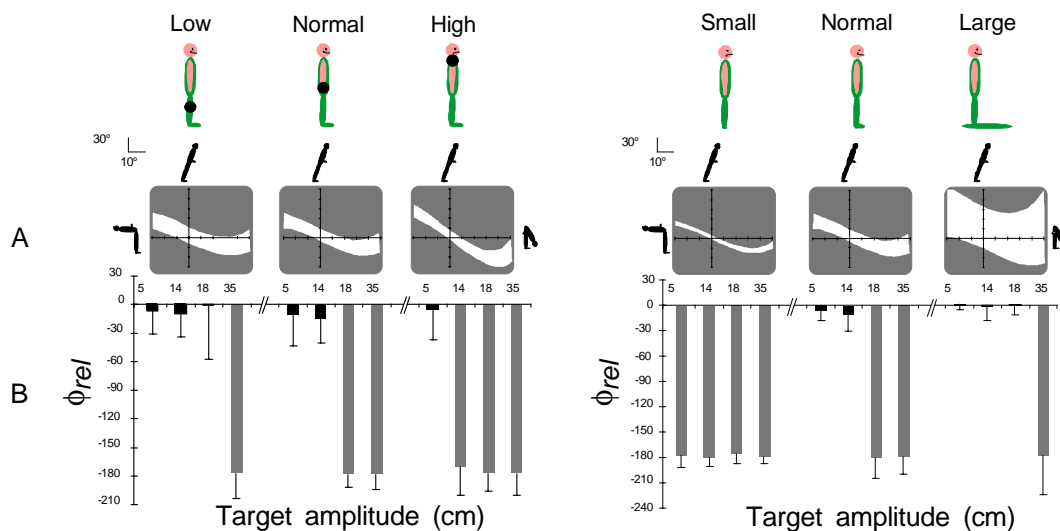
**Figure 1.** The postural tracking task exhibiting in-phase (left) and anti-phase (right) hip-ankle coordination. (A): Time series of fore-aft positions of head and target showing phase locking of the head (target amplitudes are 5 cm (left) and 18 cm (right)), and related in-phase and anti-phase motion of ankles and hips. (B): Corresponding hip-ankle plane. Figure adapted from Bardy et al. 1999.

From a kinematic point of view, the anti-phase mode corresponds roughly to what Nashner and McCollum (1985) have interpreted as a *hip strategy*. However, the in-phase mode does not have a clear equivalent in the neuromuscular approach developed by Nashner and McCollum. This is because the existence of hip rotation outside of the hip strategy, when it has been acknowledged at all, has not been considered to be a defining feature of multi-segment coordination. As we shall see in the following paragraphs, these two postural modes can be viewed as stable patterns of coordinated movements of the various segments of the postural system. Under the pressure of non-linearities, these patterns emerge via a process of self-organization, resulting in a limited number of stable states. Different, interacting, constraints influence the role played by the non-linearities and thus contribute to the emergence of these patterns, and to changes between them (e.g., Haken et al. 1985; Newell 1985). Applying the coordination dynamics research agenda to the study of the postural system, we now precise (i) the

conditions under which these patterns spontaneously emerge, (ii) bifurcate from one to the other, (iii) are modulated by the actor's intention, and (iv) are destabilized by learning a new, non spontaneous, postural pattern.

## Constraints on postural coordination

Experimental evidences concerning the role played by a coalition of constraints on the selective emergence of postural states have been obtained. In studies involving the postural tracking task, we have shown that postural modes emerged from the interaction of body-based, task-based, and environment-based constraints (cf. Newell 1985; Riccio and Stoffregen 1988). By manipulating target amplitude or frequency, as well as the properties of the body (height of the center of mass, length of the feet, global stiffness) and the surface of support (soft, firm, rolling), evidence was provided that performance at the tracking task was coupled with the mechanical requirement of maintaining the center of mass over the feet (Bardy et al. 1999), and that the form of this coupling depended on the interaction with the surface properties (Marin, Bardy et al. 1999) and the overall stiffness of the body (Marin, Bardy and Bootsma 1999). A typical example is given on Figure 2, which illustrates for a set of participants (see Bardy et al. 1999 for details) the effect of changing the height of the center of mass (left figure) or the length of the feet (right figure) on (A) the stability region for stance and (B) the corresponding spontaneous values of the postural relative phase  $\phi_{rel}$  for three amplitudes of the tracked target. As evidenced, a fixed value of a given constraint could produce different modes, depending on the value of other, independent constraints. For example, increasing the height of the center of mass yielded both in-phase and anti-phase modes, depending on the amplitude of target motion. An implication is that no single constraint is sufficient to predict the mode that will appear in a given situation. Previous analyses of multi-segment coordination in the control of stance have concentrated on physical properties of the observer-environment system. Such analyses have exemplified the influence of environmental properties (e.g., support surface length, motion, or compliance; Buchanan and Horak 1999; Horak and Nashner 1986), biomechanical properties of the body (foot length or body size; e.g., McCollum and Leen 1989), or pathological deficits (e.g., Horak et al. 1990). The results reported on Figure 2 confirm that such factors can *shape* the coordination dynamics (e.g., Beek et al. 1995). However, they also demonstrate that these properties cannot fully determine or *specify* the coordination itself. Again, this is because a single mode was used for different biomechanical properties, and different modes were used for the same biomechanical property. It thus appears that postural coordination emerges out of the simultaneous (and sometimes competitive) influence of a variety of qualitatively different constraints.



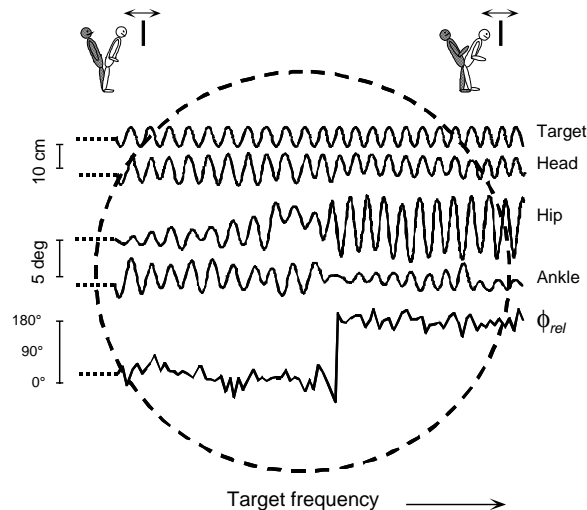
**Figure 2 .** Effects of changes in the location of the center of mass (left), and the length of the feet (right) on (A) the ankle-hip antero-posterior state space, and (B) the ankle-hip relative phase  $\phi_{rel}$ , as target amplitude increases (5, 14, 18, 35 cm). For (A), vertical and horizontal axes represent angular positions of the ankles and the hips,

respectively. Angular positions have been arbitrary limited from  $-30^\circ$  to  $+50^\circ$  for the ankles, and from  $-90^\circ$  to  $+150^\circ$  for the hips. The white area represents the (static) stability region for upright stance, i.e., the region for which the center of mass is maintained above the feet. The height of the center of mass was manipulated by adding a 10 kg mass at the level of the knee or the neck, and the “length of the feet” was manipulated by changing the surface of support (See Appendix in Bardy et al. 1999, for details and equations).

## Self-organization in the postural system

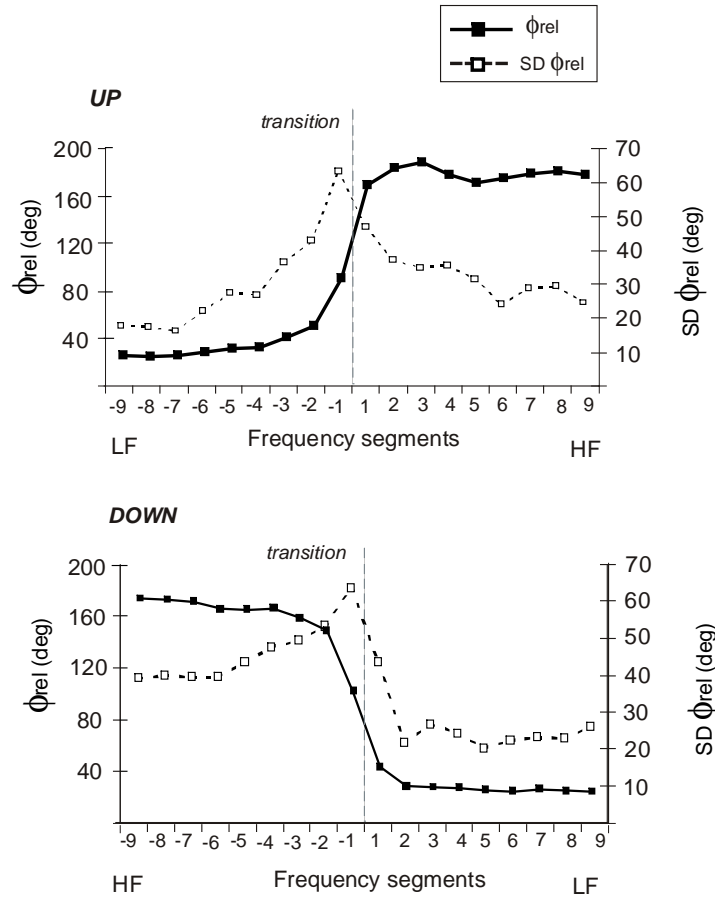
The emergence of only two postural modes of coordination, in-phase and anti-phase, out of the plethora of muscles and joints interacting together and creating a potentially very large number of multi-segmental coordination, is remarkable. It reveals that the high dimensionality of the postural system can be enslaved in, and captured by, a high order variable expressing the low-dimensional dynamics of that system: the relative phase between ankles and hips. Interestingly, the absolute value of  $\phi_{rel}$  differed from  $0^\circ$  in these studies ( $\phi_{rel} \approx 20-30^\circ$ ), indicating that the ankles tended to lead the hips. This departure from pure in-phase mode-locking has not been observed in more or less identical components such as fingers or arms (e.g. Kelso 1984; Schöner et al. 1986) but it has been observed in the context of whole-body coordination (Bardy et al. 1999; Buchanan and Horak 1999). An explanation for this difference may be found in the frequency competition  $\Delta\omega$  between the individual oscillators involved, as evidenced by classical work in inter-limb coordination (e.g., Schmidt et al. 1993; Sternad et al. 1992), demonstrating a systematic shift in the location of basins of attraction when  $\Delta\omega$  differs from zero. The upper and lower parts of the body differing substantially in length, mass, and moment of inertia, non-similarities in their eigenfrequency may be responsible for the different value of relative phase, and for the variability of  $\phi_{rel}$  during in-phase postural coordination.

More recently, we closely examined the self-organized features of these postural modes in the transient region, and discovered that the changes from in-phase to anti-phase (and from anti-phase to in-phase) exhibited characteristics of non-equilibrium phase transitions (Bardy, Oullier et al. 2002). The same postural tracking task was used for this purpose. Standing participants were instructed to follow a moving target with their head. Target amplitude was kept constant (10 cm), but target frequency continuously increased or decreased between 0.05 Hz and 0.80 Hz in steps of 0.05 Hz, playing the role of the control parameter. The main results are summarized in Figures 3 and 4.



**Figure 3.** A zoom on the transition region for one typical record (*Up* condition) showing sustained in phase motion between the target and the head, and a transition from an in-phase to an anti-phase motion of the ankles and hips as target frequency is increased over time. This transition between patterns is highlighted in the change in relative phase  $\phi_{rel}$  of the two joints. Adapted from Bardy, Oullier et al. 2002.

As we increased (*Up* condition) or decreased (*Down* condition) the frequency at which the visual target moved, a frequency-induced loss of stability occurred, yielding *critical fluctuations* in the vicinity of the transition region. Transitions between in-phase and anti-phase modes were abrupt, with no intermediate state, and exhibited *hysteresis*: Transitions from in-phase to anti-phase indeed occurred at a higher frequency of target motion than transitions from anti-phase to in-phase. Finally, we applied an external perturbation, i.e., a shift in the direction in which the target was moving. These perturbations were applied either near to or far from the region in which transitions between modes were known to occur. Each mode was found to be less stable when perturbations were applied close the transition region than when perturbations were applied far from it, as evidenced by a larger relaxation time values in the latter situation.



**Figure 4.** Postural transitions. Means and standard deviations of the point-estimate relative phase  $\phi_{rel}$  (ten participants) as a function of target frequency in Up and Down conditions. Each frequency segment includes a temporal average of  $\phi_{rel}$  over 4 cycles of oscillation, with an overlap of two cycles. *LF* and *HF* refer to low frequency and high frequency segments respectively. Adapted from Bardy, Oullier et al. 2002.

These results have consequences for the development of a general theory of postural control. Consider for instance the well-developed neuromuscular approach according to which postural patterns are behavioral outcomes of centrally programmed neural strategies (e. g., Nashner and McCollum 1985). Some of the results presented above are in concordance with this view. For example, the existence of two postural modes could be understood as resulting from two different neural plans for action. Similarly, abrupt transitions between those patterns could be explained in terms of a sudden shift between these plans. However, other aspects may be less easily explained, like the effects of hysteresis, critical fluctuations, and critical slowing down. Why would the central nervous system choose different

postural modes for identical conditions? Why would the variability of relative phase increase when approaching the centrally-programmed changes in posture? What could be a realistic explanation for the existence of differential stability close and far from the transition region, as evidenced by the local relaxation time analysis? This type of questioning suggests that a general theory of postural transitions cannot be rooted in central mechanisms such as motor programs or solely in mechanical, energetic, or perceptual mechanisms constraining behavior (see Bardy, Oullier et al. 2002). At a more general level, we think that any theoretical approach to posture could benefit from the present results, because the production and regulation of movement could take advantage of the non linearities outlined here (c.f., Rosenbaum 1998). Indeed, these data provide evidences for the existence of self-organization in the postural system, and encourage further examination of the possibility that the interactions between the components of that system may be understood through the physics of non-equilibrium processes.

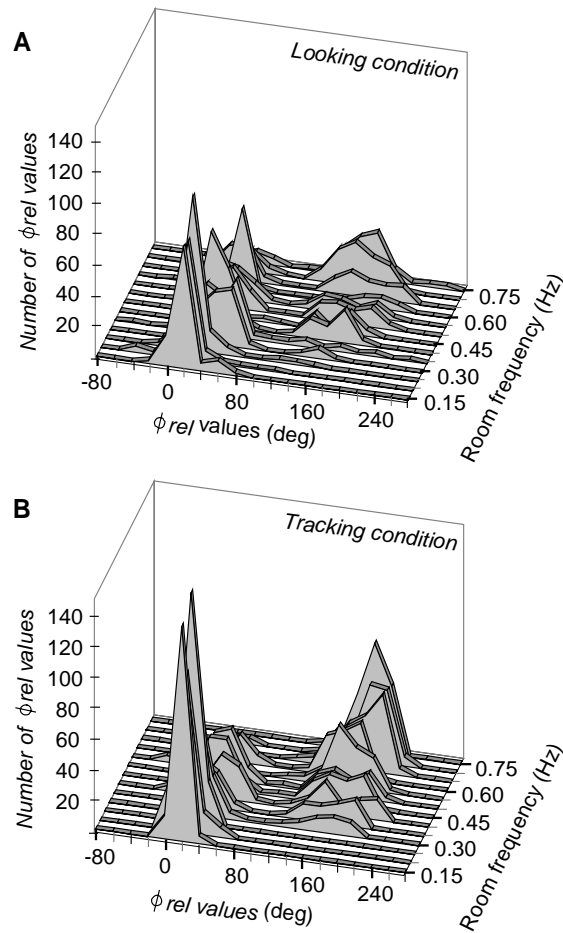
## Supra-postural goals and coordination dynamics

A general characteristic of the studies reported here is that the postural coordination patterns (and the changes between them) are not prescribed by any type of instruction or intention, but emerge “for free” out of the interaction between the intrinsic dynamics of the postural system and a set of constraints acting upon it. This does not mean, however, that the goal of the task has no role to play in the emergence of postural patterns. Postural patterns are fundamentally influenced by the actor’s intention (see Lee, 2003, for related arguments). Riccio and Stoffregen (1988) were among the first to suggest that postural stabilization is not an end in itself, but is valuable only to the extent that it facilitates the achievement of other goals. Stance can be controlled in different ways, which will differentially impact the performance of other behaviors. Thus, success of postural control actions may be most appropriately defined in terms of their impact on the achievement of supra-postural goals. It is meaningless to suggest that postural control is successful only if it minimizes postural sway. Minimal sway will facilitate the achievement of many goals, but not all possible goals. Some goals require body sway to be reduced, such as reading for instance, but other goals require body sway to be increased, such as following the target in our postural tracking task. In one exemplary study that tested the effect of task goal on body sway, Stoffregen et al. (2000) showed that standing participants instructed to search for letters in a text located at eye level exhibited less postural sway than when only instructed to look at a blank target placed at the same location. Among others, this result indicates that tasks that are super-ordinate to the control of posture, named *supra-postural tasks* (Stoffregen et al. 1999) are constraining the amount of sway in standing humans, and it is not unreasonable to assume that postural patterns may also be affected by the goal of the task.

In a different context, the literature on the perceptual control of balance has repeatedly demonstrated the importance of vision and visual coupling for the maintenance of stance (e.g., Lee and Lishman 1975; Schöner 1991; Van Asten et al. 1988) but there have been almost no studies reporting the underlying postural coupling. The body is often considered as an inverted pendulum oscillating around the ankles and actively matching (Schöner 1991), or passively driven by, the optical flow created by body sway. A classical result obtained in these studies is that coupling of postural sway to a moving visual surround decreases non linearly with increases in the frequency of imposed motion, or with increases in the distance to the visible surroundings (e.g., Dijkstra et al. 1992, 1994; Lestienne et al. 1977, Van Asten et al. 1988). One interpretation is that, because the natural frequency of the postural system can be different from the frequency of imposed motion, some decoupling effects between imposed and actual frequency can occur. To our knowledge there has been no analysis of the possible role of postural patterns (in-phase, anti-phase) to the observed changes in visual coupling. The differences that exist in sway amplitude and frequency for in-phase and anti-phase patterns suggests that changes in the amplitude and/or frequency of imposed motion might be accommodated by a change from one postural pattern to another. The shift between these modes could be expected to produce a temporary decoupling of the head from imposed optical flow.

By using the postural tracking paradigm, we recently addressed this issue. We tested the effect of the actor’s intention on the emergence of postural patterns (Oullier et al. 2002). Participants standing in a moving room were instructed either to look at a target fixed on the front wall (*Looking* condition) or to follow the target with their head (*Tracking* condition). No instruction was given about what postural mode to adopt. Room frequency was increased or decreased in steps of 0.05 HZ between 0.10 Hz and 0.75 Hz. Dependent variables included the point-estimate relative phase between ankles and hips as well as gain and phase between motion of the head and motion of the target. Generally, the influence of

task was greater than the influence of frequency, as evidenced by a decrease in both head's amplitude and head-target coupling in looking as compared to tracking. More interesting are the findings illustrated on Figure 5 that reveal several important features of the postural system.



**Figure 5.** Effect of intention (A: looking at a target, B: tracking this target with the head) on the dynamics of postural patterns: Distribution for the two tasks of ankle-hip relative phase values as a function of room motion frequency. Adapted from Oullier et al. 2002.

First, a bi-modal distribution of relative phase values clearly appeared around 20° and 180°, indicating the same type of postural patterns for the two tasks, in-phase and anti-phase. Looking at or tracking a moving target are tasks that play a similar type of constrain on posture, which reveals that these two modes are stable attractors of the dynamics of the postural system. This indicates that the traditional inverted pendulum analogy may not be correct. Adaptive patterns of postural coordination underlie the simple act of looking at a target, as it does for tracking that target. Second, no intermediate state existed between in-phase and anti-phase, and a rapid jump existed for both tasks between in-phase and anti-phase, suggesting a similar two-attractors dynamics underlying looking and tracking. Third, Figure 5 also indicates a more broadly distributed range of relative phase values around 0° and 180° in looking as compared to tracking. This, together with the corresponding lower head-target coupling observed in Looking, argues for the existence of two sub-systems underlying the performance at the tracking task. A head-target system expressing the *visual coupling* with the environment, and an ankle-hip sub-system expressing the *inertial coupling* between the two joints. The head-target system can be captured by the head-target relative phase (as well as cross-correlation and gain between head and target). It is directly influenced by the goal of the task, which can be formalized in dynamical terms in the

differential equation capturing that coupling (e.g., Schöner 1989). The ankle-hip sub-system is captured by the ankle-hip relative phase. It is influencing, and being influenced by, the head-target coupling, in a circular causality. The possibility of modeling the dynamics of the postural system while taking into account the co-existence of these two interacting sub-systems, is now under investigation (Fourcade et al., 2002) and will be detailed shortly in the conclusion. For the present, we believe that these results offer converging evidence for the existence of self-organized phenomena operating at these two levels, and encourage examination of alternative interpretations of findings from studies of relations between posture and vision

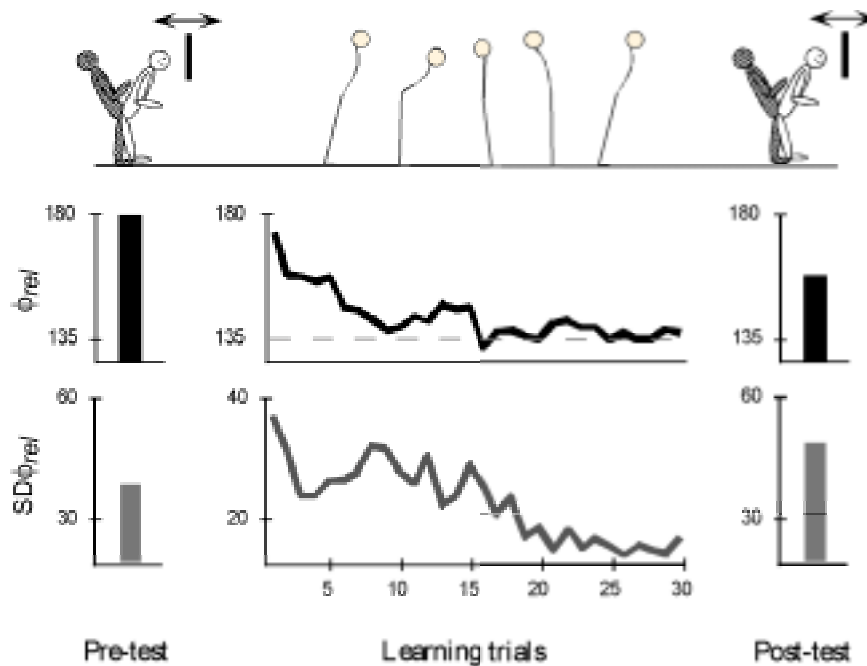
## The dynamics of learning new postures

The process by which humans modify their spontaneous postural patterns to the requirement of new tasks is another important route to explore for the development of a general theory of postural patterns formation. In the context of stance-related behaviors in humans, various general accounts of changes between postural patterns due to learning have been advocated, mostly inspired by the work of Bernstein (1967). Bernstein's account of qualitative changes in movement organization emphasized the non-linear nature of the learning process. A common method for studying these non linearities is through the sequential reducing and releasing (also known as freezing and freeing, respectively) of the body's degrees of freedom (*df*). Learned movements exhibit changes in organization that correspond roughly to the three-stage model of motor learning proposed by Bernstein. Stage 1 consists of reducing the number of peripheral *df* to the minimum that can be controlled. In Stage 2, *df* are gradually released and incorporated in the coordination solution, while Stage 3 consists of exploiting the reactive phenomena existing at the interface between the organism and the environment (see Newell 1996, for a review). Bernstein's theory, although not yet fully tested (Newell and Vaillancourt 2001), has proven to be a robust conceptual framework for describing behavioral changes observed during the acquisition of a wide variety of motor skills involving the postural system, such as dart throwing (McDonald et al. 1989), pistol shooting (Arutyunyan et al. 1968), or ski-like body oscillating (Vereijken et al. 1992).

In addition, experimental and theoretical studies have provided evidence for the operation of self-organizational principles in the domain of learning new human inter-limb coordination (e.g., Fontaine et al. 1997; Zanone and Kelso 1992, 1997; Verschueren et al. 1997; Wenderoth and Bock 2001). At a theoretical level, Schöner (1989, Schöner et al. 1992) has postulated that changes due to learning emerge out of the cooperative or competitive interplay between the initial, well-learned pattern of coordination (the so-called *intrinsic dynamics*) and the dynamic characteristics of the to-be-learned pattern, or *behavioral information*. Experimental results were consistent with this proposal (Zanone and Kelso 1992, 1997). It is to be noted, however, that most of these studies have concentrated on coordination of individual fingers, joints, or arms, and that empirical data in the field of posture or stance are rare. One reason may be that it is not easy to measure how a complex multi-joint system like a human body changes over time. Another reason is that there may be differences in the time scales at which long-term changes occur in the bimanual vs. postural patterns. Whereas the acquisition of a new bi-manual pattern sometimes can take less than fifty trials, learning and stabilizing new postures often involves years of practice, as illustrated by many examples in sport. Preliminary information about changes in postural coordination due to learning has been obtained, however, in a recent study using the postural tracking task (Marin, Bardy and Bootsma 1999). Increasing the frequency of target oscillation produced a transition from the in-phase mode to the anti-phase mode. However, this transition occurred earlier for non-gymnasts than for gymnasts, suggesting that the non-gymnasts might be able to learn to maintain the in-phase mode at higher frequencies. The delay in phase transition in gymnasts was attributed to an increase in both their global muscular stiffness, resulting from the co-activation of posterior and anterior muscles acting at the main joints, and in the gain of the stretch reflex (Fitzpatrick et al. 1992). In addition, expertise was found to interact with other constraints (e. g., those defined by the task and the properties of the surface of support), yielding specific coordination modes adapted to the rules of the tracking task.

Based on these earlier results, we recently conducted a series of experiments in which the design and analysis allowed to assess the changes due to learning as the result of the competitive interplay between the initial pattern of coordination and the characteristics of the to-be-learned pattern (Bardy, Faugloire et al. 2003; Faugloire & Stoffregen, 2003). In these experiments, standing participants were instructed to learn a new phase relation between the ankles and the hips. The body reorganization during the acquisition of this new postural pattern, as well as the destabilization of the intrinsic dynamics

consecutive to learning, was assessed. The methodology involved a pre-test/learning/post-test design. The pre-test and the post-test involved the postural tracking task, with target motion of constant amplitude (10 cm) and various frequencies (from 0.25 Hz to 0.65 Hz). In the learning period, participants were instructed to learn a new phase relation between ankles and hips, namely 135 degrees. They did not execute the tracking task. They stood in the middle of the laboratory, looking straight ahead with the arms crossed in the back, and moved their body in a way to reproduce the requested relative phase pattern, at a natural, i.e., not constrained, amplitude and frequency. 30 trials consisting of 10 body oscillations were recorded for each participant. A feedback was given to them every 3 trials, consisting of a state space (an ankle-hip plane) illustrating the discrepancy between the performed and the desired (135°) postural pattern. Figure 6 illustrates the main results for a group of 14 participants (Bardy, Faugloire et al. 2003). Although there were differences between participants in terms of learning and rate of destabilization, learning a postural relative phase of 135 degrees did occur, as evidenced by the migration over trials of the current relative phase in the direction of the to-be learned pattern, by the decrease in its standard deviation (Fig 6, middle), and by the decrease in movement time. Moreover, an interesting finding was the destabilization effect due to learning, witnessed by the difference in both the spontaneous relative phase (here 180 degrees) and its variability between the pre-test and the post-test. Overall, participants exhibited a postural coordination at the post-test that was in between the initial, spontaneous, pattern (180 degrees) and the learned pattern (135 degrees). Complementary findings were recently obtained in the examination of the links between sport expertise and the learning of a novel pattern postural coordination, reflecting the competition between the dynamics of the novel and pre-existing patterns (Ehrlacher et al. 2003). Although preliminary, these results strongly suggest that learning a new, non-spontaneous, postural pattern requires the reconfiguration of the intrinsic dynamics of the postural control structure compatible with the operating constraints, and the discovery (and stabilization) of a new equilibrium between the constituents of the movement performed.



**Figure 6.** The effects of learning a new relative phase (135°) on the stability of a spontaneous postural pattern (180°). Learning is evidenced by a change in the relative phase  $\phi_{rel}$  toward 135° and a decrease in its variability (middle). The destabilization due to learning is evidenced by the change in initial  $\phi_{rel}$  in the direction of the to-be-learned pattern between the pre-test (left) and the post-test (right), as well as in the increase in its variability  $SD\phi_{rel}$ . Adapted from Bardy, Faugloire et al. 2003.

## Conclusion

We believe that the postural tracking task provides a general and useful paradigm for investigating the non linear dynamics of human posture. The main signatures of self-organization observed with this paradigm (including critical fluctuations, bifurcation, hysteresis, and critical slowing down) should be considered as important features that need to be taken into account in a general theorization of postural control. In addition, the findings that these self-organized modes are (i) emerging out of a coalition of intrinsic, environmental, and intentional constraints, and (ii) destabilized by the learning of a new postural mode, open the possibility of integrating concepts such as perception, learning, expertise, or intention, in the language of postural dynamics. Recently, we created a mixed, or ‘compound’, model of human posture that captures these non-linearities (see Fourcade et al., 2003, for a preliminary treatment). The model is composite in the sense that it is a mechanical model, that is linking joints and segments, with units of mass and length, that can produce the self-organized signatures observed at the behavioral level. The human body is represented with two non-deformable segments, one representing the head-trunk system rotating around the hips, the other representing the thigh-legs system rotating around the ankles, in a double-inverted-pendulum system. Stiffness and damping terms acting at the two joints have biologically plausible values. Oscillations of the body are produced by a constant-amplitude torque acting at the ankles, counterbalanced by a resistive torque acting at the hips in order for the feet to be kept in contact with the ground. Interestingly, simulations of the double pendulum indicate the presence of two ankle-hip coordinative patterns accompanying the continuous increase of target frequency (in phase, anti-phase), as well as the presence, with appropriate initial conditions, of critical fluctuations, bifurcation, hysteresis, and critical slowing down. Thus, this accuracy suggests that it is possible to root the general organizational principles accompanying movement control into the biomechanical (or neuro-physiological) substrates of specific biological systems, such as the postural system. It also suggests that an intermediate position between pure structural models —searching for structural and causal explanations of behaviors — and pure phenomenological models —searching for abstract and general principles of (self-)organization (c.f., Beek et al., 1995) can be useful for modeling human posture and movement.

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