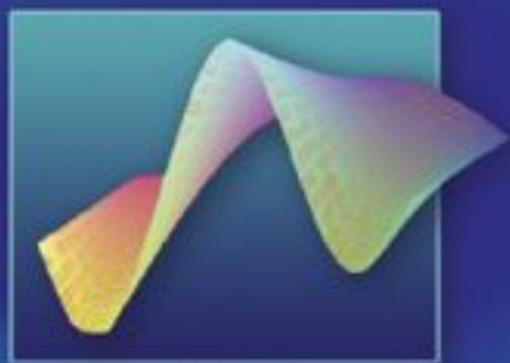
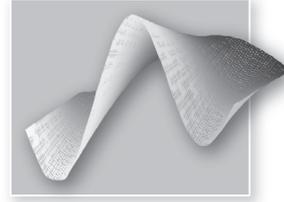


Movement System Variability



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Chapter 2



Variability in Postural Coordination Dynamics

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Editors' Overview

Research on the use of vision for controlling posture is examined, showing how it has focused on (1) neurophysiological processes underlying the intrinsic coordination in posture and (2) the importance of informational coupling in achieving the control of stance. This chapter aims to overview recent research in this area, particularly emphasizing the relationship between intentionality and variability in shaping the dynamics of intersegmental coordination during stance. It is argued that data on modulating a pattern of coordination for postural control reveal the influence of local constraints such as intentions and forces, whereas transitions between patterns reveal self-organization processes at work. Focusing on the small number of postural control strategies identified in previous work, the ankle and hip strategies, it is proposed that there is a need to examine the coordination between these two key joints in maintaining upright postural control. In particular, variability in coordination between the ankles and hips is proposed as a functional relationship designed to maintain upright posture during suprapostural tasks. The findings discussed in this chapter support a new perspective on the dynamics of whole-body coordination during postural control, signaling that there is no primary role solely for neural, mechanical, or muscular mechanisms, as has been espoused in previous research. Many constraints interact to shape postural behavior in humans, and variability in the postural system plays a functional role in adapting to perturbations.

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One of the major problems that movement scientists have to face is how humans (and animals) coordinate the multiple degrees of freedom of their bodies, constraining them to act as a single unit in accomplishing behavioral tasks (Kelso, Southard & Goodman, 1979). To achieve control, the high dimensionality of the body must be reduced to a system exhibiting order, that is, stable and flexible patterns of coordination (Bernstein, 1967). In research on the control of standing posture, many neuro-physiological (e.g., Nashner & McCollum, 1985) and biomechanical studies (e.g., Winter, 1990) have demonstrated the role of local constraints (e.g., forces, central command signals) in shaping patterns of whole-body coordination. These local constraints play a key role in the emergence of preferred postural coordination patterns. They operate in the context of self-organization principles governing coordination, postural pattern formation being no exception. Until recently, this more general level of organization remained largely unstudied in the field of postural coordination (however, see Saltzman & Kelso, 1985, for early suggestions). Typically, the influence of local constraints is assessed through the modulation of a behavioral pattern, while self-organization is revealed in changes between patterns (Haken, 1977). In the present chapter, we discuss recent studies that have focused on the dynamics of human postural coordination. Based on these studies, we argue that multi-joint control of standing posture exhibits typical signatures of self-organized systems.

Maintainance of upright stance depends upon stable control of the posture of the head and body. On earth this implies that the support surface, that is, the surface on which one is standing, can support the body mass. From a purely mechanical point of view, there is balance when the sum of the gravito-inertial forces acting on a body is compensated by an opposite and equal reaction force applied from the support surface. Such a rule would apply to the postural system if it were static, but this is not the case. The human body is a multi-joint system that offers a (potentially) unlimited number of combinations of motion at different joints spontaneously and continuously oscillating at low frequency and low amplitude (Yoneda & Tokumasu, 1986). The spontaneous oscillations are centered around the direction of balance (Ricchio & Stoffregen, 1988; Stoffregen & Ricchio, 1988). The high order of complexity defining the postural system and the constraints that are applied to it, such as ground reaction and gravity, generate a large amount of variability at different levels of observation (Newell & Corcos, 1993). Controlling such a system is therefore difficult and requires reduction of its dimensionality (Kay, 1988).

Ambiguity of the Neurophysiological Approach to Postural Coordination

Nashner and McCollum (1985) proposed that amongst the many possible relations between joints or muscles, the maintenance of stance commonly relies on

a small number of *postural strategies*. These strategies are muscular synergies that reduce the high dimensionality of the postural system mainly involving relationships between the muscles recruited in movements of the ankles and hips. Nashner and McCollum proposed that in most situations humans use one of two postural strategies. In the *ankle strategy*, control of balance is achieved by producing muscular torques around the ankle joint to counterbalance gravito-inertial torques acting on the body. The ankle strategy is thought to be chosen to regulate perturbations at low frequencies (under 0.2 Hz; Nashner, Shupert, Horak & Black, 1989) or at low sway amplitudes (under 20°; McCollum & Leen, 1989). In the *hip strategy*, gravito-inertial torques are counteracted by rotations of the hips (these are generally accompanied by rotations of the ankles in the opposite directions). Nashner and McCollum argued that the hip strategy would be used to counter perturbations at higher frequencies (>2.5 Hz) and/or amplitudes (>20°).

The concept of ankle and hip strategies has met with wide acceptance. One reason for this may be that Nashner and McCollum's (1985) approach succeeds at (conceptually) reducing the dimensionality of the postural system (cf. Kay, 1988). At the muscular and joint levels, hip and ankle strategies compress a high-dimensional postural space with many degrees of freedom requiring coordination into a low-dimensional space with only a few degrees of freedom to be mastered (cf. Bernstein, 1967; Turvey, 1990). The strategies permit minimization of behavioral variability arising from the large amount of movement created by combinations between limbs and joints. Postural synergies might be used to reduce the number of degrees of freedom of the body, in which case the system would become less variable and easier to control. Another reason for the appeal of hip and ankle strategies may be experience of the use of the hips for postural control. Most people are familiar with the sudden fore-aft motion of the hips that can occur when the body is perturbed. Common examples include a sudden lurch in a subway train or stance on a balance beam, each of which commonly produces noticeable bending at the hips.

Despite its widespread acceptance, the concept of hip and ankle strategies (Nashner & McCollum, 1985) presents some ambiguities. For the purpose of this chapter, the emphasis will be put on one of these ambiguities (for a more extensive discussion on this topic see Bardy, 2004 and Bardy, Marin, Stoffregen & Bootsma, 1999). It is often assumed that in an ankle strategy there is no rotation at the hips. This idea is accepted and reported in many areas of postural research including sensorimotor control (Gurfinkel, 1973; Horak & Nashner, 1986; Nashner et al., 1989), pathology (Horak, Nashner & Diener, 1990), and biomechanics (McCollum & Leen, 1989). This assumption contrasts with the original description of postural strategies by Nashner and McCollum (1985, p. 140), who stated that the ankle strategy rotation takes place "primarily" rather than exclusively about the ankle joint. For instance, hip rotation is evident in their graphical example of an ankle strategy (Nashner & McCollum, 1985, figure 5a, p. 141). In addition, empirical studies have consistently shown

some degree of rotation at both ankles and hips (Bardy et al., 1999; Horak & Nashner, 1986, figure 7; Horak et al., 1990, figure 4; Marin, Bardy, Baumberger, Flückiger & Stoffregen, 1999; Oullier, Bardy, Bootsma & Stoffregen, 1999; Stoffregen, Adolph, Thelen, Gorday & Sheng, 1997). This suggests that in most cases there is motion at both joints. Given this empirical fact, why do researchers and theoretical models (e.g., Kuo, 1995) assume that in the ankle strategy there is no rotation at the hips?

One way to answer this question is to assume that in the ankle strategy, rotation around the hips is uncontrolled noise, having no specific function in postural control (e.g., Horak & Nashner, 1986; Nashner & McCollum, 1985). Such an assumption may be influenced by the ambiguity that exists in the operational definition of both ankle and hip strategies. In empirical studies, ankle and hip strategies have been differentiated on the basis of their respective muscle activity, joint movements (e.g., Buchanan & Horak, 1999; Horak & Nashner, 1986; Nashner & McCollum, 1985), and forces generated by postural activity with respect to the support surface (e.g., Buchanan & Horak, 2001; Horak & Nashner, 1986; Horak et al., 1990; Ko, Challis & Newell, 2001). Definitions of the ankle and hip strategies at these three levels of behavioral analysis are not equivalent, resulting in ambiguity about whether ankle and hip strategies are defined in terms of muscle activity, kinematics, or kinetics. When there is a strong correlation between activities at the different levels of analysis, the definitional ambiguity is not a problem. However, under many normal circumstances the relations between these levels are equivocal, nonlinear and therefore extremely complex (see Bernstein, 1967; Tuller, Fitch & Turvey, 1982 for theoretical discussions and Bonnard, Pailhous & Danion, 1997 for an experimental illustration). For instance, authors observe some hip muscle activities in an ankle strategy (Nashner & McCollum, 1985) while there is no hip motion if the ankle strategy is defined in terms of forces (nonsignificant shear forces can be detected in an ankle strategy; cf. Horak et al., 1990).

Kinematic Analysis of Dynamic Patterns in Postural Coordination

Mixing levels of behavioral analysis when trying to understand movement coordination can lead to misunderstanding (Bernstein, 1967). Following early analyses (Saltzman & Kelso, 1985; Woollacott & Jensen, 1996), Bardy and colleagues have focused on the kinematics of postural coordination (Bardy et al., 1999; Marin et al., 1999a; Oullier et al., 1999). This analysis of multi-segment postural coordination is consistent with the dynamical systems approach (Beek, Peper & Stegeman, 1995; Kelso, 1995; Kugler, 1986; Riccio, 1993; Turvey, 1990). Bardy and colleagues assume that if ankle and hip movements are involved in the control of upright stance, then it is appropriate to analyze coordination (i.e., relative displacement) between these two joints. It would

not be so much the degree of involvement that determines the type of postural organization adopted, rather the way in which the movements of the different joints are coordinated. In this case, their respective movements might not be a simple random motion that can be neglected but could be sensible and coordinated movements. Hence, variability in behavior can be a source of information that helps in understanding the underlying dynamics of a system (see Fuchs & Kelso, 1994). The variability between coordination of the (ankle and hip) joints should therefore be considered to be useful and functional for the scientist (and possibly for the standing person). A natural variable for characterizing modes of coordination in postural coordination dynamics is the relative phase ϕ_{rel} between movements of the hips and of the ankles. The phase of one joint captures both its position and its velocity. This means that the relative phase ϕ_{rel} of two joints reduces four degrees of freedom to one. The coordination between the hip and the ankle can therefore be summarized in ϕ_{rel} . Hence, with a single value of this (collective) variable, the organizational state of the system can be known at any time. Such a variable has been used in a variety of studies involving coordination to an external event (Jantzen, Steinberg & Kelso, 2004; Kelso, DelColle & Schöner, 1990; Lagarde & Kelso, 2004; Oullier, Jantzen, Steinberg & Kelso, in press), inter- and intra-limb coordination (de Guzman, Kelso & Buchanan, 1997; Diedrich & Warren, 1995; Kelso, 1984, 1995; Kelso, Buchanan & Wallace, 1991; Kelso & Zanone, 2002; Salesse, Oullier & Temprado, in press) as well as interpersonal coordination (Oullier, de Guzman, Jantzen & Kelso, 2003; Richardson, Marsh & Schmidt, 2005; Schmidt, Carello & Turvey, 1990; Temprado, Swinnen, Carson, Tourment, & Laurent, 2003). In recent studies, Bardy and colleagues have identified two basic patterns (modes) of coordination between hips and ankles (Bardy et al., 1999; Marin et al., 1999a; Marin, Bardy & Bootsma, 1999; Oullier et al., 1999): an *antiphase* mode characterized by a relative phase close to 180°, in which the hips and ankles move in opposite directions, and an *in-phase* mode of coordination characterized by a relative phase around 20°, in which the hips and ankles move in the same direction. In the next section, we describe several experiments that illustrate these findings.

Postural Coordination Emerges from the Interplay of Different Constraints

Riccio and Stoffregen (1988; see also Newell, 1986) suggested that postural organization emerges from the interaction of constraints operating, respectively, at the level of the participant, the environment, and the task. This contrasts with researchers who have argued that the adoption of postural strategies solely depends upon the effects of a single constraint. For example, it has been proposed that the effect of environmental properties alone can influence the organization strategy (Horak & Nashner, 1986; McCollum & Leen, 1989). At the surface of support, an ankle strategy produces mostly torque while a

hip strategy produces mostly shear forces. For this reason, Horak and Nashner (1986) as well as McCollum and Leen (1989) suggested that all surfaces that have low resistance to shear, such as slippery surfaces, require the use of the ankle strategy for maintaining upright stance. In contrast, a hip strategy should be used on surfaces that have low resistance to torque, such as foam or a narrow beam (Nashner & McCollum, 1985). These assertions are consistent with the findings of some studies previously mentioned, but several other studies have produced counterexamples. For instance, Stoffregen et al. (1997) found that some fourteen-month-old children maintained stance on a soft surface (foam rubber) without detectable rotation at the hips. Conversely, in some children, hip rotation was observed during stance on a low friction surface. These examples suggest that a single constraint (in this case, environmental) is not sufficient to explain the adoption of a given postural strategy. This is true also for constraints imposed by properties of the participant. For example, according to Horak and Nashner (1986), the effective length of the feet can be the main constraint that influences the selection of postural strategies. When standing on a narrow beam, a person's toes and heels are unsupported, reducing the effective length of his/her feet. Horak and Nashner (1986) found that the coordination between hips and ankles was affected by varying the length of the support surface. Marin et al. (1999a), however, found that, thanks to their expertise, gymnasts can sway about the ankles while standing on a beam when moving at low frequency. Thus, reduction in effective foot length does not always mandate a reliance on hip rotations for postural control.

Classical analyses of multi-segment control (e.g., Nashner & McCollum, 1985) have concentrated on properties of the environment and the person, such as forces (torque and shear), surfaces (soft, slippery, and short, etc.), biomechanics (foot length and height of the center of mass, etc.), and joints (ankle, hip). Marin et al. (1999a) considered an additional category of constraints: the goal of the task in which participants were engaged. Indeed, posture is often analyzed in the context of quiet stance, that is, when postural control is the primary or sole activity. However, from an ecological point of view, quiet stance does not represent ordinary posture (Stoffregen, Smart, Bardy & Pagulayan, 1999). Outside the laboratory, upright posture is rarely maintained for its own sake, but rather it facilitates the achievement of *supra-postural* tasks such as looking, walking, and manual manipulation (Balasubramaniam, Riley & Turvey, 2000; Balasubramaniam & Wing, 2002; Bardy & Laurent, 1998; Bardy, Warren & Kay, 1996; Danion, Duarte & Grosjean, 1999; Riccio & Stoffregen, 1988). Accordingly, the research conducted by Bardy and colleagues examines postural control in the context of an explicit supra-postural task.

Bardy et al. (1999) and Marin et al. (1999a) claimed that the emergence of hip-ankle coordination cannot be the result of only one of these types of constraint (body properties, support surface, and task) but instead a function of the interactions between them. In studies that we discuss in the following sections (Bardy et al., 1999; Marin et al., 1999a,b; Oullier et al., 1999), par-

Participants were instructed to move their heads so as to track the back-and-forth oscillations of a computer-generated target moving in the anterior–posterior axis; the aim of the task was for the participants to maintain a constant distance between their head and the target. In their first experiment, Bardy et al. (1999) added mass at different body locations in order to manipulate the height of the body's center of mass (creating *normal*, *high*, and *low* conditions of center of mass height). For each height of the center of mass, participants were asked to follow four different amplitudes of target oscillations that simulated 5, 14, 18, and 35 cm peak-to-peak displacements of the object (see figure 2.1a). There were three main results. First, for each condition only two stable values of ϕ_{rel} were observed: $\approx 20^\circ$ and $\approx 180^\circ$. This result confirmed that there was rotation about the hips in all conditions. The observation that hip movements were coordinated with ankle movements militates against interpreting the hip movements as noise. Second, as figure 2.1a illustrates, under similar conditions increasing target amplitude (across conditions) was associated with a change in the value of ϕ_{rel} from 20° to 180° . Third, the selection of in-phase ($\phi_{\text{rel}} \approx 20^\circ$) or antiphase ($\phi_{\text{rel}} \approx 180^\circ$) coordination emerged from the interaction of the location of the center of mass and the target amplitude. These results confirmed the hypothesis that the emergence of a coordination mode depends on the interaction between tasks and body properties.

In their second experiment, Bardy et al. (1999) varied the effective length of feet (creating conditions of *normal*, *short*, and *long* feet). For the *long* condition, participants wore a pair of shoes similar to skis, whereas for the *short* condition participants' feet were tied to a beam 40% shorter than the length of their feet. As in the previous experiment, there were three main results. First, in each condition only two coordination modes were found ($\phi_{\text{rel}} \approx 20^\circ$, $\phi_{\text{rel}} \approx 180^\circ$) (see figure 2.1b). This indicated that there was functional hip movement in all conditions. Second, for the normal and long foot length conditions, increasing the target amplitude produced a shift from in-phase to antiphase coordination. In the short foot length condition, antiphase coordination was observed for all values of target motion amplitude. These findings were consistent with the results of Horak and Nashner (1986). Third, shifts between coordination modes depended on the interaction between the target amplitude and the length of feet (see figure 2.1b).

Marin et al. (1999a) varied the friction and rigidity of the support surface, and crossed these variations with changes in the amplitude of the target motion (see figure 2.2). In the *standard* condition, participants stood barefoot on a flat, rigid floor. In the *foam* condition, they stood on a gymnastic mat (23 cm thick), and in the *roller* condition, they wore roller skates (ankle motion was not restricted). The results showed once again that 20° and 180° of ϕ_{rel} were found (see figure 2.2), suggesting that hip and ankle moves were not nonfunctional noise. On the *standard* surface, ϕ_{rel} of 20° was observed with target amplitude below 30 cm, with ϕ_{rel} of 180° for target amplitudes greater than 35 cm. For the two other surfaces, the amplitude of target oscillation did not influence

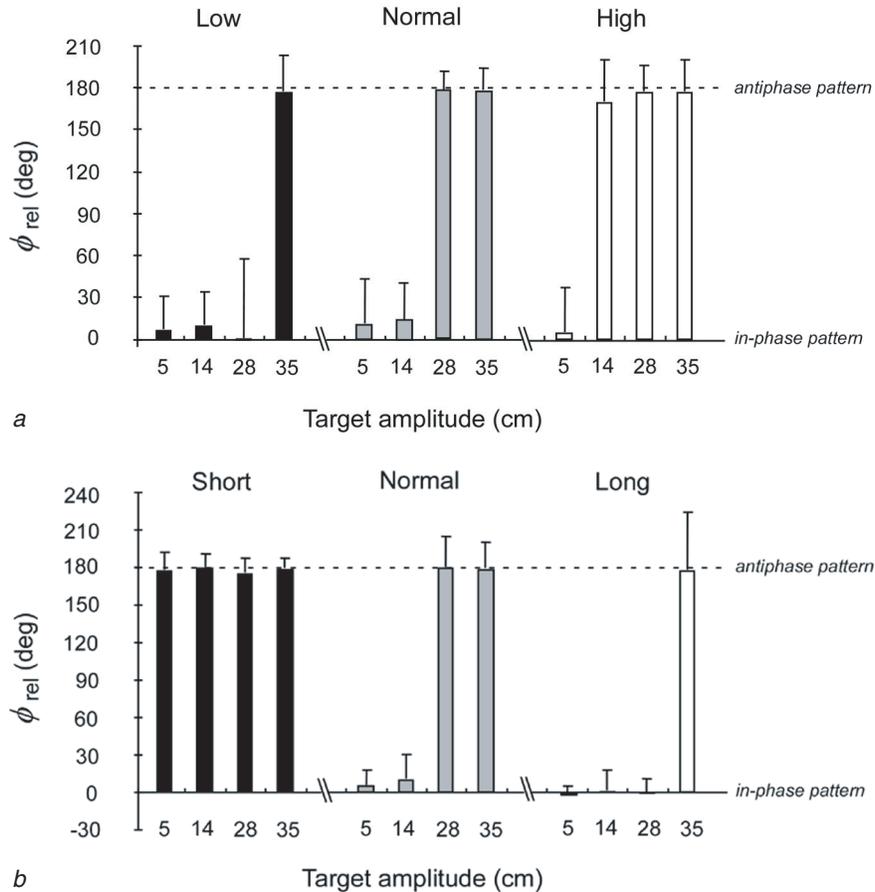


FIGURE 2.1 (a) Effects of cross-manipulating the height of the center of mass (low, normal, and high) and the amplitude of sway (5, 14, 28 & 35 cm) on the circular mean of ϕ_{rel} ; (b) Effects of cross-manipulating the length of the support surface (short, normal, and long feet) and the amplitude of sway (5, 14, 28 & 35 cm) on the circular mean of ϕ_{rel} .

From B.G. Bardy et al., 1999 "Postural coordination modes considered as emergent phenomena," *Journal of Experimental Psychology: Human Perception and Performance* 25: 1284-1301. Copyright © 1999 by the American Psychological Association. Adapted with permission.

coordination. In the *roller* condition, participants always adopted the in-phase coordination, while in the *foam* condition, the antiphase pattern was always observed (figure 2.2). Taken together, the results of Marin et al. (1999a) and Bardy et al. (1999) clearly reveal that postural coordination emerges from the interaction of different constraints.

These studies confirm that the ankles and the hips are coordinated and that the hip-ankle coordination is functional in the control of stance. Only

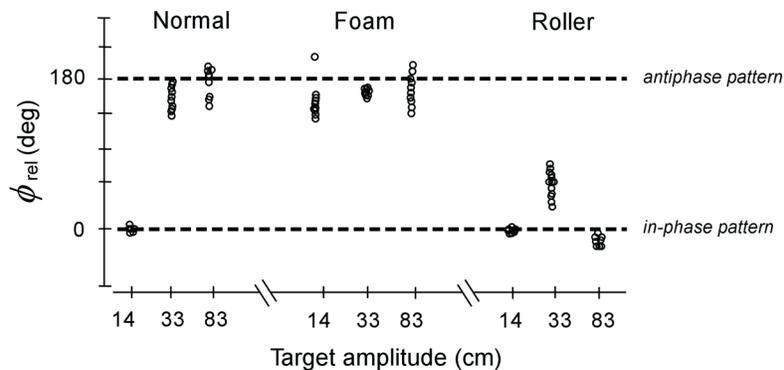


FIGURE 2.2 Effects of varying the surface of support (*normal*, *foam*, and *roller*) on the circular mean of ϕ_{rel} as a function of target amplitude (14, 33, and 83 cm) and the surface of support.

Reprinted from *Human Movement Science* Vol 18, L. Marin et al., Interaction between task demands and surface properties in the control of goal-oriented stance, pgs. 31-47, Copyright 1999, with permission from Elsevier.

two modes of coordination (in-phase or antiphase) were observed, and the emergence of these modes depended on the interaction of task-, and environment-based constraints. In their experiments, Bardy et al. (1999), Marin et al. (1999a) and Oullier et al. (1999) have either manipulated the nature of the surface of support and the amplitude or frequency of target movements to investigate the emergence of the postural coordination modes and their stability. For each trial, participants were asked to oscillate their heads back and forth at constant values of the control parameter (amplitude or frequency of target movements). The different values of the control parameter that were tested enabled the researchers to show that the stability of each mode depended on the coalition of constraints applied to the standing human similarly to what has been reported in other studies on coordination between a limb and an external event (e.g., Kelso, Fink, DeLaplain & Carson, 2001; Lagarde & Kelso, 2004) and interpersonal coordination (e.g., Oullier et al., 2003). This stability can be quantified in terms of the variability of the relative phase between the hips and the ankles, ϕ_{rel} . The variability of ϕ_{rel} was low for extreme values of the control parameter, in other words, for very large or very low amplitudes (Bardy et al., 1999) and very high or very low frequencies (Oullier et al., 1999). When the values of the control parameter were in between these extremes, an increase of variability could be observed. According to the dynamical systems theory (Kelso, 1995), Bardy and colleagues assumed that this increase of variability was due to being in the vicinity of the region of transition from one coordination pattern to another. The variability of the relative phase between the ankle and the hip therefore provided information about the organization of the system. Nevertheless, this remained an assumption since the design of these experiments (Bardy et al., 1999; Marin et al., 1999a) did not directly address this

point. Indeed, control parameters remained constant within a trial and were varied only on a between-trials basis. One other point in common among these experiments is that participants were always asked to intentionally track the target with their heads. The possible question of the influence of intention on modulating the dynamics of postural coordination had never been addressed. This is why Oullier, Bardy, Stoffregen, and Bootsma (2002) tested the stability of the coordination modes while continuously varying the control parameter within a trial and having participants perform two different tasks involving intentional and nonintentional sway in the experiment. The question behind Oullier et al.'s (2002) study was to know whether intention (to sway) could affect the variability of the relative phase between the ankles and the hips. These results are summarized and discussed in the following section.

Intention (to Sway) Modulates the Stability of Postural Coordination

Oullier et al. (2002) asked participants either to track the back-and-forth oscillations of a target (e.g., Bardy et al., 1999; Marin et al., 1999a; Oullier et al., 1999) or merely to look at it as it moved (Stoffregen, 1985; Stoffregen et al., 1999; Oullier, Bardy & Bootsma, 2001). In controlling stance, looking at the target favors rotation of the body about the ankles (Stoffregen et al., 1999), whereas tracking it favors in-phase or antiphase coordination between the ankles and hips depending on the frequency of the target (e.g., Marin et al., 1999b). Both looking and tracking, however, require an adaptive intrinsic (ankle and hip) coupling between the segments of the postural system, and both require an adaptive visual coupling between the body and the target (Oullier, Bardy & Bootsma, 2001). Research relating vision to stance has repeatedly demonstrated the importance of visual coupling for the achievement of stance (e.g., Schöner, 1991), however little is known regarding how intention modulates the dynamics of both the visual coupling and the postural coordination. A hypothesis to explain postural sway that has enjoyed a wide acceptance in the literature on postural control is that humans control body sway by attempting to minimize retinal slip (e.g., Lee & Lishman, 1975). However this is not sufficient to understand the dynamics of the underlying coordination. The dynamic coupling of vision and intrinsic coordination in the postural system must be taken into account (Dijkstra, Schöner, Giese & Gielen, 1994). This is why studying the relative influences of the postural and the visual systems is useful to understand the coupling between postural coordination and the nature of the task. Standing in order to look at a target or in order to track it with the head are tasks that impose different constraints on the postural system. In contrasting by using looking and tracking tasks, the goal was to understand how intention to move could influence postural coordination and modulate its variability. Results revealed that the visually based coupling between motion of the head and of the target

(attached to the front wall of a moving room in which participants were standing to perform the tasks) was influenced by the frequency of target motion and by intention to move or not (tracking versus looking). Frequency and intention had a significant effect on all of the dependent variables that were used to assess head-room coupling¹. The influence of intention was consistently greater than the influence of frequency. The results illustrate the role of supra-postural tasks in modulating motion of the body as indicated by the effects of the type of task on several dependent variables. Even when the amplitude of the target matched the amplitude of natural oscillations of the body, tracking induced larger amplitudes of head movement than merely looking at it. Consistent with this, both target-head and ankle-hip couplings were stronger in the tracking task. Changes in these couplings were observed as functions of the type of task and the oscillation frequency of the target. Increasing target frequency was accompanied by decreasing visual coupling during both looking and tracking tasks, although coupling remained stronger during tracking. The looking task was associated with reductions in target-head and ankle-hip couplings. In this context, the task effect (i.e., the effect of differences in intention) is regarded as illustrating the relative weakness of coupling in the task of looking.²

Bardy et al. (1999) documented the emergence of two preferred modes of postural coordination when participants used voluntary movements of the head to track motion of a target in the anterior–posterior axis. Oullier et al. (2002) found that similar modes emerge whether participants track the target, or merely look at it. Thus, the ankle-hip coordination underlying the maintenance of upright stance was found to be qualitatively similar whether performing a looking or a tracking task. This result is illustrated by the emergence of in-phase and antiphase modes of postural coordination, as shown in figure 2.3 by the bimodal distribution of ϕ_{rel} values for each task. Thus, coordination dynamics underlying the maintenance of upright stance appears similar with or without the intention to sway. This result raises doubts about the widely accepted distinction between quiet stance and deliberate sway (e.g., Creath, Kiemel, Horak, Peterka & Jeka, 2005).

Oullier et al.'s (2002) results also have clear implications for research on the visual control of stance. Implicitly or explicitly, the body is often considered as a simple inverted pendulum oscillating about the ankles and actively matching

¹ Oullier et al. (2002) computed and analyzed the movement amplitude, cross-correlation, frequency overlap and the relative phase between the target and the head and between the ankle and the hip.

² Some of the results relating to coupling between target and head differ from previous research relating vision and stance. For instance, the tracking task Oullier et al. (2002) studied closely resembled the one used by Bardy et al. (1999). However, in the findings of Oullier et al. (2001, 2002) the coupling between stimulus and head was stronger and the relative phase between target and head was lower than the values reported by Bardy et al. (1999). The differences across studies might have arisen from a difference in the means used to generate optical flow. Oullier et al. (2001, 2002) used a moving room to generate flow while Bardy et al. (1999), Marin et al. (1999a, b) and Oullier et al. (1999) generated flow using tri-dimensional computer graphics and video projection. The different results are consistent with the hypothesis of Stoffregen, Bardy, Merhi and Oullier (2004) that coupling of body sway with optical flow imposed by the experimenter may vary with the technology used to generate the flow (see also Faugloire, Bardy, Merhi & Stoffregen, 2005).

the optical flow created by body sway (Schöner, 1991) or passively driven by this flow. Results of Oullier et al. (2002) indicate that the inverted pendulum analogy may not be correct, for adaptive patterns of postural coordination underlie the simple act of looking. Whether changes in ankle-hip coordination may influence the coupling of head movement to the visual environment remains an open question. The fact that in-phase coordination between ankle and hip emerged under conditions of slow motion of the visual surrounds and antiphase coordination under conditions of rapid motion may or may not be related to the finding reported in this experiment and in earlier studies that the strength of coupling between motion of the room and head decreases with increasing frequency (e.g., Dijkstra, Gielen & Melis, 1992; Dijkstra et al., 1994; Lestienne, Soechting & Berthoz, 1977).

Interestingly, the looking and tracking tasks seemed to exhibit differences in stability, as suggested by the smaller number of in-phase peaks in figure 2.3 and the systematically larger circular deviation of relative phase in the *looking* condition (Oullier et al., 2002). These results suggest the variability of the relative phase is modulated by the intention to sway. Such a result corroborates the assumption that intention should be considered as a modulating factor of the intrinsic dynamics of the postural system similarly to the way it modulates bimanual coordination (Kelso, 1995; Scholz & Kelso, 1990). In the results reported by Oullier et al. (2002), the variability of the coupling between the ankle and the hip also provided information about the nature of visual coupling.

Another important aspect of the data presented in figure 2.3 is the deep valley between the two distribution peaks. This valley represents the absence of transient modes of coordination between the in-phase and the antiphase patterns. This valley (visible separately on figures 2.3a and b) suggests that there must have been a sudden change in coordination mode in each of the (looking and tracking) tasks. Once again (see figure 2.1 and Bardy et al., 1999), when a control parameter was increased, the variability of the ankle-hip relative phase increased, announcing the imminent transition. The higher the variability of ϕ_{rel} , the closer the transition. It is clear from figure 2.3 that the observed bi-modal distribution of relative phase is congruent with a phase transition between postural patterns. However, the methods used by Bardy et al. (1999), Marin et al. (1999a) and Oullier et al. (2002) did not allow the researchers to determine the nature of the transition or the role of the variability of the order parameter in the phase transition. This is because transitions occurred between rather than within trials and so were neither observed nor manipulated as such.

Dynamics of Postural Transitions

The sharply bi-modal distribution of relative phase into two values (figure 2.3) suggests that there is no transient mode of coordination between the in-phase and the antiphase patterns. The values of the relative phase reported by

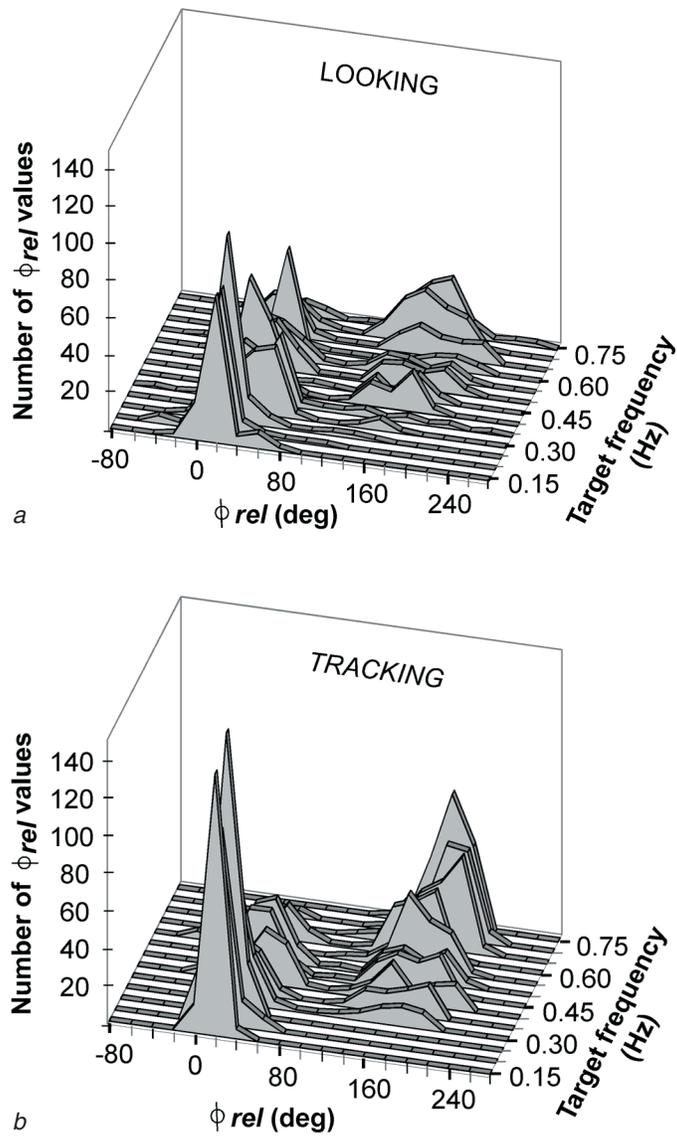


FIGURE 2.3 Distribution of values (in 20° frequency bins) for the ankle-hip relative phase ϕ_{rel} as a function of the target oscillation frequency. Depending on the experimental condition, participants were asked to (a) simply watch the target oscillating in the anterior–posterior plane (*looking* condition) or (b) track it with the head (*tracking* condition). In both conditions, two modes of coordination emerged for the peak distribution: in-phase (about 20°) and antiphase (about 180°).

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Oullier et al. (2002) suggest that a transition should occur but do not indicate why the system changes from one postural pattern to the other. A direct study of postural transitions was still necessary. In this section we review previous attempts to understand how the postural system changes from one mode of coordination to the other. We then report recent research in which this question is directly addressed.

In their research, Bardy and colleagues have examined the existence of postural patterns, focusing on the number and type of patterns, and on the conditions under which each pattern occurs. While this approach has yielded much information about postural patterns, it has provided little knowledge about the dynamic, real-time shift from one coordination mode to another (for recent reviews see Horak & MacPherson, 1996; Woollacott & Jensen, 1996). For example, Horak and Nashner (1986) observed that different control strategies were used on different support surfaces, but they limited their study to situations in which the pattern of multi-segmental coordination was stable. They did not attempt to document the process by which the postural control system dynamically reorganized itself within trials. This may be because transitions between states have often been considered to derive from the states themselves (Bardy, 2004). In other words, it was assumed that changes between states could be understood in terms of the characteristics of stable states. Bardy, Oullier, Bootsma and Stoffregen (2002) argued that four general perspectives of change between postural patterns occur in the context of controlling upright stance.³ We discuss each of these perspectives next.

First, postural transitions can be considered as a way to minimize the metabolic cost associated with controlling stance. Hoyt and Taylor (1981) argued that preferred locomotory states are characterized by the minimization of energy expenditure. If such an observation is transposed to posture, shifts from one postural pattern to another might occur when, as conditions change, the current pattern becomes less efficient than some other pattern, where the efficiency is defined in terms of the amount of energy expended in achieving the goal (Sparrow & Newell, 1998). Corna, Tarantola, Nardone, Giordano and Schieppati (1999) reported that participants standing on an oscillating platform switched from a single to a double inverted pendulum pattern as platform frequency increased and that this switch reduced the effort required to maintain stability. Minimization of effort may help shape postural patterns, but it is not sufficient to trigger changes between patterns. This is because there are many situations in which maintenance of upright stance is not the sole goal of postural control. Stance is not maintained solely for its own sake but, often, it aids in the achievement of supra-postural tasks such as lifting, throwing, or looking (Stoffregen et al., 1999). The argument is that when controlling stance, people aim to minimize energy expenditure, as is consistent with efficiently

³In this section, we present different accounts of postural control separately. This is done solely for clarity. The reader should not regard the different accounts as being mutually exclusive.

performing suprapostural tasks. It is believed that there is a trade-off between achieving the lowest metabolic cost and achieving the goals of suprapostural tasks (Newell, 1986; Riccio & Stoffregen, 1988; Sparrow & Newell, 1998). Diedrich and Warren (1995) demonstrated that walk-run transitions are not governed solely by energetic considerations; in the vicinity of the transition region there is not a one-to-one correspondence between the different gait patterns adopted and their metabolic costs. Thus, explaining the transition between coordination modes exclusively in terms of energy minimization would be incomplete.

The second possibility is that the switch from one postural state to another is determined by mechanical limits on the states involved. Mechanical limits may be characterized in a variety of ways, such as limits on the forces and torques applied at the support surface (Horak & Nashner, 1986; Marin, 1997; Pai & Patton, 1997) or at the joints (Yang, Winter & Wells, 1990), limits on the intrinsic frequency of postural patterns (Buchanan & Horak, 1999; McCollum & Leen, 1989), or limits on the amplitude of body movements tolerated by these patterns (McCollum & Leen, 1989; Riccio & Stoffregen, 1988). There is evidence that mechanical properties of the body and/or the environment constrain the appropriateness of particular postural patterns. Nevertheless, a theory of postural transitions based solely on mechanical factors would be inadequate. This is because there is not a one-to-one correspondence between mechanical conditions and patterns of postural control. A given set of mechanical properties can give rise to more than one coordination mode (Bardy et al., 1999; Krizkova, Hlavacka & Gatev, 1993; Marin et al., 1999a; Stoffregen et al., 1997). Conversely, different types of mechanical properties can give rise to a single coordination mode. These effects occur because posture is not constrained solely by mechanical properties of the individual and its environment, but is simultaneously constrained by additional factors (e.g., Oullier, Bardy, Stoffregen & Bootsma, 2004). Thus, the question of postural coordination modes and the transitions between them cannot only be assessed with Newtonian mechanics (Beek et al., 1995).

A third possibility is that transitions between postural patterns may result from changes in the information available to the central nervous system. A large body of research on sensory loss, or sensory deficit, has been interpreted as indicating that a change in postural coordination can be caused by changes in the information available for the actor (Allum, Honegger & Schicks, 1993; Buchanan & Horak, 1999; Corna et al., 1999; Horak, et al., 1990; Horstmann & Dietz, 1988; Kuo, Speers, Peterka & Horak, 1998; Nashner et al., 1989). Other researchers have examined the relationship between postural control, a response, and the optical consequences of body sway, considered as a stimulus to the postural control system. Simulation of the optical consequences of body sway leads to direction-specific postural responses during stance (van Asten, Gielen & Denier van der Gon, 1988), postural oscillations (Mégrot, Bardy & Dietrich, 2002; Oullier et al., 2002, 2004), walking (Bardy et al., 1996; de Rugy,

Taga, Montagne, Buekers & Laurent, 2002; Warren, Kay & Yilmaz, 1996), and running (Young, 1988). Again, however, the methodology used in these studies was designed to test for the existence of functionally specific postural adjustments and not for characterizing transitions between different types of adjustments. Thus, while perceptual information certainly influences the organization of posture, its exact role in the organizational processes underlying the formation of postural patterns is not clear at present. The study of postural transitions requires different methodologies.

Fourth and last, postural transitions may be understood within the broader context of the dynamical systems theory (Kelso, 1995; Turvey, 1990). This approach has motivated strong interest in phenomena that occur in the vicinity of the regions of transition from one coordination mode to another. These regions may reveal general principles governing pattern formation that are not directly accessible via the study of the patterns themselves (Fuchs & Kelso, 1994). This does not, of course, imply that biomechanical, metabolic, or informational properties have no influence on the emergence of postural coordination modes (Bardy et al., 1999; Buchanan & Horak, 1999) or on transitions between modes. Rather, the causes of transitions are not to be sought in each of these properties alone (Diedrich & Warren, 1995).

Bardy et al. (2002) argued that modes of postural coordination may function as attractors in the postural state space and that changes between these different modes may be characterized as nonequilibrium phase transitions between attractors (e.g., Saltzman & Kelso, 1985; Woollacott & Jensen, 1996). The neurophysiological and biomechanical studies described above are consistent with the idea that local constraints participate in shaping patterns of whole-body coordination. However, these local constraints operate in the context of general principles governing postural pattern formation that remain largely unknown (Saltzman & Kelso, 1985). Whereas the influence of local constraints is typically assessed through the modulation of a behavioral pattern, self-organization is revealed in changes between patterns (Haken, 1977). The macroscopic variables, the order parameters, that emerge from the (nonlinear) interaction between the various degrees of freedom reveal interesting features. The collective variable that has been used by Bardy and colleagues to describe the behavior of the postural system is the ankle-hip relative phase, ϕ_{rel} . The behavior of ϕ_{rel} in the vicinity of phase transitions can reveal whether or not ϕ_{rel} is an order parameter for postural coordination. In studying transitions between postural coordination modes, Bardy et al. (2002) used the tracking task in which participants were instructed to use head movements to track the oscillations of a visible target along the fore-aft axis of the body. Using preliminary results (Oullier et al., 1999), a method was developed for observing transitions from one postural mode of coordination to another. The heart of this method was varying the frequency of target oscillations within trials (e.g., Kelso, Scholz & Schöner, 1986).⁴ Studies of bimanual coordination have characterized coordination modes (in-phase and antiphase) as attractors in

the phase space. Given this characterization, Bardy et al. (2002) hypothesized that postural transitions occur when one attractor (i.e., coordination pattern) becomes less stable than the other. Bardy et al. (2002) sought to identify five typical hallmarks of dynamical systems (Kelso, 1995; Kelso, Scholz & Schöner, 1988; Turvey, 1990): (i) at least two stable attractors defined by two different values of the order parameter ϕ_{rel} . When a non-specific control parameter (here, the oscillating frequency of the target) is continuously varied, a sudden shift from one attractor to the other should occur. This shift is called (ii) a *phase transition* (see Kelso, Schöner, Scholz & Haken, 1987). In the vicinity of the phase transition, a loss of stability expressed in (iii) *critical fluctuations* (an increase of variability in the order parameter ϕ_{rel}) should be observed (Scholz, Kelso & Schöner, 1987). The value of the control parameter at which transitions occur should be different for transitions from antiphase to in-phase than for transitions from in-phase to antiphase (if any). This is called (iv) *hysteresis* and reveals the tendency of the (postural) system to remain in its current state as long as possible before switching to a different pattern. Hysteresis therefore reveals the sensitivity of the system to initial conditions, i.e., to its own history. Finally, the best way to test the stability of a system is to perturb it (Kelso, 1995), and for this reason Bardy et al. (2002) designed a second experiment that permitted us to analyze the relaxation time (i.e., the time the system needs to return to its initial state after perturbation). If the increase in variability of ϕ_{rel} when approaching the transition region indeed denotes loss of stability, then the relaxation time should be smaller when the system is far from the transition and larger when it is near the transition. This effect is called the (v) *critical slowing down*, i.e., an increase of the relaxation time in the vicinity of the phase transition (Scholz et al., 1987).

Bardy et al.'s (2002) results revealed two values of ϕ_{rel} , each of which tended to predominate in a certain region of the control parameter space (figure 2.4). At low frequencies of target oscillation the ankles and hips moved in-phase, while at higher frequencies of target motion antiphase oscillations were observed. The interesting feature here is that not only do these results corroborate Bardy et al.'s (1999) results on the identification of two coordination modes, but the fact that these modes emerge even when the control parameter is varied on a within-trial basis.

⁴Bardy et al. (2002) varied the frequency of target oscillation in a stepwise manner and in two conditions. In the *up* condition, frequency increased from 0.05 Hz to 0.80 Hz in steps of 0.05 Hz. In the *down* condition, it decreased from 0.80 Hz to 0.05 Hz in similar steps. Each frequency step lasted for 10 oscillation cycles, for a total of 160 cycles per trial. In the procedure Bardy et al. (2002) used before computing dependent variables, 18 segments were defined for each trial: nine before and nine after the transition. Each segment included the mean values of the dependent variables for four cycles, with an overlap of two cycles (see Kelso et al., 1986, for a similar analysis). The use of 18 segments was imposed by the large variability among participants in the frequency at which transitions occurred, and the 18 segments corresponded to the maximal range including data points from all participants at all frequencies. Second, segments were aligned across each participant on the first cycle following the transition. Overall, this procedure resulted in the analysis of a limited portion of the ascendant or descendant run corresponding to 5 to 6 frequency steps. At the same time, the procedure promoted a detailed analysis of the behavioral organization (and its changes) in the transition region.

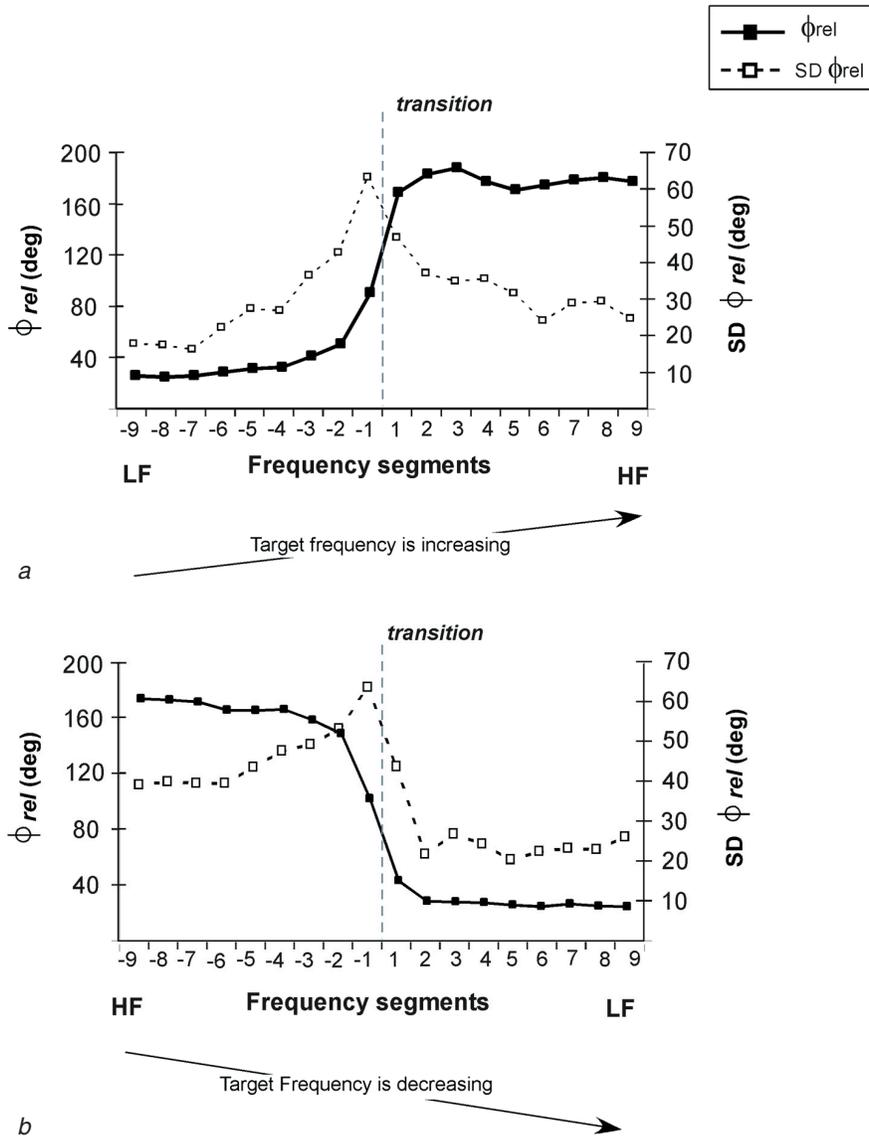


FIGURE 2.4 Postural transitions, point estimate circular mean, and deviation of ϕ_{rel} in the (a) up (frequency increasing) and (b) down (frequency decreasing) conditions. Each segment includes a temporal average of ϕ_{rel} over four cycles of oscillation, with an overlap of two cycles. LF and HF refer to low frequency and high frequency, respectively.

From B.G. Bardy et al., 1999 "Postural coordination modes considered as emergent phenomena," *Journal of Experimental Psychology: Human Perception and Performance* 25: 1284-1301. Copyright © 1999 by the American Psychological Association. Adapted with permission.

The second dynamical hallmark that Bardy et al. (2002) observed was that small, stepwise changes in the frequency of target oscillation lead to sudden shifts between coordination modes. The data illustrate the rapid nature of this transition. Eighty percent of the transitions occurred within a single cycle (overall mean = 1.2 cycles). This was true despite the fact that there was high inter-subject variability of the control parameter value at which transitions occurred (Oullier et al., 1999). When the frequency of the target was increased the system switched from in-phase to an antiphase coordination and, conversely, when the control parameter was decreased transitions from antiphase to in-phase were observed systematically. The variability of ϕ_{rel} was small when the system was far from transition, but as the system approached transition variability markedly increased (see figure 2.4). This progressive increase of the variability of ϕ_{rel} reached a peak in the region of transition. The variability data reveal the loss of stability in the current mode of coordination. After the transition the variability of ϕ_{rel} returned to lower values (Bardy et al., 2002). This is the phenomenon referred to as critical fluctuations.

The fourth hallmark observed was hysteresis, that is, the fact that transitions from in-phase to antiphase (figures 2.4a) and from antiphase to in-phase (figure 2.4b) did not occur at the same value of the control parameter. Hysteresis was found in 80% of the transitions, revealing the tendency of the system to remain in its current state by delaying the switch from the mode of coordination losing stability to a more stable one. As noted earlier, Bardy et al. (2002) found that increasing the frequency of target oscillation lead to a switch from in-phase to antiphase and that decreasing target frequency lead to a switch from antiphase to in-phase. This result differs from studies of unimanual (e.g., Kelso et al., 1990) and bimanual coordination (e.g., Kelso et al., 1986, 1988), in which transitions have been found only with increasing frequency. The stability of the in-phase mode in bimanual coordination explains why there is no switch to the antiphase mode, which is less stable. Bardy et al.'s results therefore suggest that the stability of the two modes of postural coordination is sufficiently similar for the transition to occur in both directions (in-phase to antiphase and antiphase to in-phase).

In a separate experiment, Bardy et al. (2002) investigated the stability of postural coordination both close to and far away from the region in which transitions between coordination patterns occurred. The authors did this by introducing a perturbation in the motion of the target to be tracked and by varying the location of the perturbation relative to the transition region.⁵ Then, the relaxation time was calculated. Relaxation time was found to be shorter for

⁵The transition frequency TF was determined separately for each participant. In four experimental conditions, the frequency of target oscillation was set at a constant value, either far from the participant's TF ($TF - 0.30$ Hz, $TF + 0.30$ Hz) or close to it ($TF - 0.15$ Hz, $TF + 0.15$ Hz). Thus, in the two conditions of low frequency ($TF - 0.30$ Hz, $TF - 0.15$ Hz), participants were expected to exhibit in-phase coordination, while in the conditions of high frequency ($TF + 0.15$ Hz, $TF + 0.30$ Hz), participants were expected to exhibit antiphase coordination.

perturbations that occurred when the system was far away from the transition region. This finding is consistent with the concept of critical slowing down. Relaxation times were also compared for the in-phase and antiphase patterns. The relaxation time was found to be shorter for the in-phase pattern which appeared to be more stable than the antiphase one.

Nature of the Transitions Between Postural Coordination Patterns

In two experiments, Bardy et al. (2002) examined self-organized properties of postural coordination. Two postural coordination modes (in-phase and antiphase) were observed and changes between modes exhibited characteristics of nonequilibrium phase transitions, including differential stability, critical fluctuation, bifurcation, hysteresis, and critical slowing down. One implication of these results is that the ankle-hip relative phase ϕ_{rel} can serve as the order parameter of the postural system. The results are consistent with a dynamical systems approach of the multisegment control of stance, in which postural states behave like attractors in the postural space and changes between states behave like self-organized, nonequilibrium phase transitions between attractors. This transition appears to be from a mono-stable (fixed point) state to another mono-stable state, with a marginal bi-stable region in between. The bi-stable region appears when the control parameter reaches a critical value, that is, when the system can adopt either of the two modes of coordination. It appears that the variability of the order parameter is high before the transition, and it determines if the system switches to another mode. The bi-stable region is also the hysteresis region. Observation of these hallmarks leads to the hypothesis that the transition was a saddle-node type of bifurcation (Kelso, Ding & Schöner, 1992) rather than a Hopf bifurcation (Buchanan & Horak, 2001). The phase transition observed in postural coordination contrasts with that reported in studies of bi-manual coordination (Haken, Kelso & Bunz, 1985; Schöner & Kelso, 1988) that have reported transitions from bi-stable states (two fixed points) to mono-stable states (one fixed point). The dynamics of transitions between coordination modes seem specific to the properties of the system and the level at which the system is analyzed.

Variability in Self-Organization of Postural Coordination

Bernstein (1967) pointed out that there is not a one-to-one correspondence between movement and muscular, mechanical, or neural activity; this statement is known as the *equivocality principle*. This is why Bardy and colleagues

have concentrated on a higher-order collective variable (ϕ_{rel}) defined at the kinematic level. Hip-ankle relative phase captures the order of the postural system in the space of a low dimensional state (Bardy, 2004; Bardy et al., 1999). At any time, a single (order) parameter, ϕ_{rel} , provides information about how the upper body moves relative to the lower body. One of the consequences of Bernstein's equivocality principle is that abrupt changes at the level of the movement trajectory may not exist at different levels of observation of the postural system, such as the muscular activity. Recent research reports that under diverse environmental, task, and body constraints, postural movements serving goal-directed supra-postural behavior exhibit typical signatures of self-organization (see Bardy, 2004 for a review). Bardy et al. (2002) used two indices of postural stability to investigate the dynamics of postural coordination. In their first experiment, changes in the variability of the ankle-hip relative phase (during a trial) showed a decrease in stability as the transition point was approached. This result was confirmed in their second experiment by analyzing local relaxation time following perturbations of the visual target. As predicted, the relaxation time was greater near the region of transition. Hence, changes in postural coordination were accompanied by a loss of stability in the order parameter (expressed by critical fluctuations and critical slowing down).

In all the studies presented in this chapter, variability was considered to be functional, and its analysis provided a better understanding of the behavior of the postural system. When focusing on the postural coordination modes *per se*, differences of variability between the two patterns were found, also variability of ϕ_{rel} increased when approaching the region of transition. Interestingly, under minimal constraints, for many values of the control parameter either of the two coordination modes could be adopted, depending on the situation (Bardy et al., 2002; Oullier et al., 2002). This result suggests that a general theory of postural transitions cannot be solely rooted in central mechanisms, such as motor programs, nor, for that matter, in mechanical, energetic, or perceptual mechanisms. If that were the case, then for each value of each parameter (or combination of parameters) there would be one specific postural state to be adopted by the system. But as Fuchs and Kelso (1994) pointed out, self-organization is expressed in the vicinity of the region of phase transition. By definition, when the system is in the marginal region of bi-stability it can adopt either one of the two coordination patterns. The marginal region is where the variability of the order parameter plays its most important role, since what was considered in previous studies as noise is the factor that causes the system to switch to another mode of coordination. Depending on the increase or decrease of the control parameter (Bardy et al., 2002), the change in the surface of support (Marin et al., 1999b; Oullier et al., 2004), body properties (Bardy et al., 1999), or the intention to sway (Oullier et al., 2002, 2004), the variability of the relation between the hips and the ankles is changing and will be determining the organization of the postural system.

Unique Aspects of Postural Coordination

In line with previous studies of bimanual coordination (Haken et al., 1985; Schönér & Kelso, 1988), and locomotion (Diedrich & Warren, 1995, 1998), two preferred stable patterns were observed in the experiments on postural coordination dynamics: an in-phase mode ($\phi_{\text{rel}} \approx 20^\circ$) and an antiphase mode ($\phi_{\text{rel}} \approx 180^\circ$). Like the bi-manual and locomotor systems, the postural system is multi-stable. Multi-stability refers to the existence of multiple qualitatively distinct patterns in a state space, each of which is stable over a coalition of constraints that shapes its dynamics (Kelso et al., 2001; Lagarde & Kelso, 2004; Oullier et al., 2003). Despite the many similarities in the coordination of the manual, locomotor, and postural systems, there are differences. The most obvious are the values for the coordination patterns that were found by Bardy and colleagues, which differ from the usual 0° and 180° of non-postural coordination (Kelso, 1995). In their studies of postural coordination dynamics, the in-phase mode exhibited a value close to 20° (i.e., the hip is lagging). This difference in the order parameter may arise from the nature of the oscillators involved in postural control. While both hands of a person are primarily coupled at the neural and perceptual level (Kelso, 1995), movements of the trunk and legs have a reciprocal mechanical effect on each other. This coupling might be one of the reasons why there is a 20° relative phase in the in-phase mode (see Fourcade, Bardy & Bonnet, 2003).

Conclusion

Many areas that can modulate the stability of postural coordination remain to be explored, such as the effect of learning (e.g., Faugloire, Bardy & Stoffregen, submitted; Kelso & Zanone, 2002; Ko, Challis & Newell, 2003), development (e.g., Marin & Oullier, 2001), attention (e.g., Monno, Chardenon, Temprado, Zanone & Laurent, 2000), expertise (Bardy, Faugloire & Fourcade, in press) or the interaction with another person (e.g., Oullier et al., 2003). Taken together the studies reported in this chapter support an interpretation of the organization of multi-segmental postural control that does not rely exclusively and primarily on neural, mechanical or muscular mechanisms, but rather a perspective where postural coordination dynamics emerge from a coalition of constraints of different nature (Oullier et al., 2004).

Although many researchers still consider variability in postural sway as only stochastic noise (e.g., Kiemel, Oie, & Jeka, 2002), the experiments reported in the present chapter suggest that variability often serves as a functional component of the postural system rather than noise, at least at the kinematics level. The self-organized features of the postural system are highly associated with variability of the order parameter. The resemblance of human postural phase transitions to self-organizational phenomena found in other biological and

nonbiological systems (Kelso, 1995) raises questions about the necessity of appealing primarily to local constraints in understanding whole-body movement, and reinforces the hypothesis of general and common self-organization principles governing pattern formation in complex systems in which variability (modulated by a coalition of constraints) plays a key functional role.

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