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Interaction between task demands and surface properties in the control of goal-oriented stance

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Abstract

Standing subjects were asked to track the fore-aft motion of a target with their heads. Three support surface conditions (standard, foam, rollers) were crossed with three amplitudes of target motion. The relative phase ϕ_{rel} between angular motion of ankles and hips was analyzed. Two preferred patterns emerged; close to in-phase ($\phi_{\text{rel}} \approx 0°$), and close to anti-phase ($\phi_{\text{rel}} \approx 180°$). On the solid surface increasing target amplitude produced a change from in-phase to anti-phase coordination. There were no amplitude-related changes in hip–ankle relative phase on the rollers where only in-phase coordination was observed, or the foam (only anti-phase coordination). We conclude that (1) hip–ankle relative phase is useful for describing postural coordination, (2) 0° and 180° are two spontaneous coordination modes in the hip–ankle postural space, and (3) these modes emerge differentially under the mutual pressures of task and support surface properties.

Keywords: Posture; Coordination; Constraint; Stance; Surface; Relative phase

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1. Introduction

Research on multi-segment coordination of posture has emphasized the role of two basic postural strategies in the control of stance (Horak and Nashner, 1986; McCollum and Leen, 1989; Nashner and McCollum, 1985; Riccio and Stoffregen, 1988). 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. In the *hip strategy*, gravito-inertial torques are counteracted by rotations of the hips (these usually are accompanied by rotations of the ankles, in the opposite direction). In this paper we have two main aims. The first is to provide evidence in support of a new analysis of postural coordination (Bardy et al., in press). The second is to show that the emergence of postural coordination modes is influenced by supra-postural tasks and not just by body-based or surface-based properties. Recent research has examined interactions between voluntary tasks and variations in dynamics of the body (Bardy et al., in press; Marin et al., in press). In the present study we examine interactions between voluntary task and properties of the support surface.

1.1. Postural coordination modes

Our first aim is to evaluate further a new operational analysis of multi-segment postural coordination (Bardy et al., in press). In both theoretical and empirical studies hip and ankle strategies have been defined in a variety of qualitatively different ways; at the level of the forces applied to the supporting surface (e.g., Horak and Nashner, 1986; Horak et al., 1990), at the level of neuro-muscular activity (Horak and Nashner, 1986; Nashner and McCollum, 1985), or at the level of kinematics of joint movement (Krizkova et al., 1993; McCollum and Leen, 1989; Riccio and Stoffregen, 1988), with definitions often being used simultaneously or interchangeably (e.g., Horak and Nashner, 1986; Nashner and McCollum, 1985). Although, these three levels of activity are related, there is no direct correspondence between neuro-muscular activity, force production, and body movement (Berkinblit et al., 1986; Bonnard et al., 1997; Riccio and Stoffregen, 1988). A similar pattern of muscle activity can produce different movements in different situations. Conversely, a given movement can be produced by different patterns of muscular activity.

This poses challenges for the view that the control of posture can be directly based on mechanical, or neuro-muscular activity (McCollum and Leen, 1989; Nashner and McCollum, 1985). In addition, it suggests that the three types of definitions used by Nashner and McCollum (1985) may be interchangeable only for a limited set of circumstances. One way to respond to this would be to restrict the definition of postural control strategies to a single level of activity. Here we define and analyze postural activity at the level of kinematic properties of the organism–environment system (e.g., Riccio and Stoffregen, 1988; Reed, 1988). The primary motivation for a kinematic definition is that the utility of postural control actions is evaluated in terms of these kinematics (e.g., maintaining or losing balance, as opposed to applying particular forces or contracting particular muscles). Despite the variable relation between muscles activity and applied forces, on the one hand, and the kinematics of posture, on the other, people appear to be highly skilled at producing the desired kinematic results (maintenance of stance). Our approach is an attempt to develop a single definition that is useful across a wider range of postural situations.

Our metric is defined in terms of relative movement of body joints. We will concentrate here on motion about the ankles and the hips. While it is widely accepted that a hip strategy may include rotation at the ankles, it is often assumed that in the ankle strategy there is no rotation at the hips. Indeed, in some treatments of the ankle strategy the body is modeled as an inverted pendulum, rotating about the ankles (Gurfinkel, 1973; Horak and Nashner, 1986; McCollum and Leen, 1989). However, in empirical studies hip rotation is often apparent in the ankle strategy (e.g., Horak and Nashner, 1986, Fig. 7; Nashner and McCollum, 1985, Fig. 7). If ankle and hip strategies each involve movement about both joints, then it may be possible (and appropriate) to analyze *coordination* between the ankles and the hips. A natural candidate for characterizing modes of coordination in postural control is the relative phase between hips and ankles (ϕ_{rel}). ϕ_{rel} has been used as a collective variable summarizing coordination in a variety of non-postural movements, involving both inter- and intra-limb coordination (see Kelso, 1995 for a review). In a recent study, Bardy et al. (in press) analyzed the relative phase between hips and ankles (ϕ_{rel}) in standing participants who were asked to track a visual target with their heads. Two coordination modes were found to emerge consistently; an in-phase pattern, with the ankles and the hips moving simultaneously in the same direction (ϕ_{rel} close to 0°), and an anti-phase pattern, with the ankles and hips rotating simultaneously in opposite directions (ϕ_{rel} close to 180°). Participants were also found to switch from in-phase mode to anti-phase mode as a result of interactions between task-based and body-based constraints. At the kinematic level the anti-phase pattern is coherent with Nashner and McCollum's description of the hip strategy (Nashner and McCollum, 1985). However, the in-phase pattern fails to support the inverted pendulum analogy, and suggests that hip rotation may play a functional role in the ankle strategy. In the present study we sought to extend these findings to determine whether in-phase and anti-phase patterns can be reliably elicited on different surfaces of support.

1.2. Interaction between task demands and surface properties in the achievement of stance

At the surface of support an ankle strategy produces mostly torque while a hip strategy produces mostly shear forces (Horak and Nashner, 1986; McCollum and Leen, 1989; Yang et al., 1990). For this reason, it has been proposed that an ankle strategy should be used on surfaces that have low resistance to shear, such as a slippery surface, while a hip strategy should be used on surfaces that have low resistance to torque, such as a narrow beam (Nashner and McCollum, 1985). This latter prediction was verified by Horak and Nashner (1986), who reported hip control in response to perturbations during stance on a surface shorter than the foot. However, there are counter-examples to both predictions. Krizkova et al. (1993) reported sway about the ankles when adult subjects were standing on a soft surface. Similarly, Stoffregen et al. (1997) found that some 14-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 empirical findings suggest that the emergence of multi-segmental postural coordination may be more complex than is commonly believed. This does not undermine the general assertion that postural control strategies should be influenced by environmental properties (Nashner and McCollum, 1985), but it does suggest the need for systematic investigation of the kinds of dynamics that influence stance. To date, analyses of multi-segment control (e.g., Nashner and McCollum, 1985) have concentrated on dynamical properties of the environment and the person, such as forces (torque and shear), surfaces (soft, short, etc.), and joints (ankle, hip). In the present research we consider an additional category of constraints. We report a study in which postural responses were influenced not only by properties of the support surface, but also by the goal of an intentional task in which participants were engaged (cf. Riley et al., 1997; Stoffregen et al., in press). In this study, the emergence of hip–ankle coordination modes was a function of the interaction between properties of the support surface and the task.

In many studies of postural control (e.g., Blaszczyk et al., 1993; Dijkstra et al., 1994; Masson et al., 1995), the participants' sole task is to maintain stance (i.e., keep the center of mass over the feet). This maintenance of bio-mechanical stability is described as *quiet stance*. However, stance is not only maintained for its own sake, but also because of other behaviors that it affords, such as looking, locomoting, manual manipulation, and so on. It can be argued that stance is useful primarily to the extent that it facilitates these other behaviors (e.g., Robinson, 1972; Tobias, 1982). This suggests that functional (performance-related) needs of supra-postural tasks might influence the manner in which stance is controlled (Bardy et al., 1996; Riccio and Stoffregen, 1988; Riley et al., 1997; Slobounov and Newell, 1994 Stoffregen et al., in press). Consider the simple case of a person standing on an extended, rigid surface. Due to bio-mechanical constraints, movement solely about the ankles is effective only for small rotations; about 5–10° (McCollum and Leen, 1989). For a person 1.75 m tall, this would correspond to a fore-aft excursion of the head of roughly 20 cm. Thus, an in-phase coordination between ankles and hips may be adequate for tasks in which the desired amplitude of head motion is within this range. By contrast, anti-phase motion of the two joints can facilitate much larger excursions of the head. Thus, when task performance calls for large excursions of the head we might expect an anti-phase mode to emerge. More generally, postural coordination may be task-specific (Bardy et al., in press; Riccio and Stoffregen, 1988; Slobounov and Newell, 1994).

Next, consider how postural control could support large A-P head movements on different surfaces. On a high-friction, non-rigid surface (e.g., a foam) or a short surface (e.g., a beam), large amplitudes of head motion can be achieved through an anti-phase mode, a pattern of coordination that would also be promoted by the reduced resistance of the surface to torque. In these cases task and surface constraints *converge* toward the emergence of an anti-phase mode. By contrast, on rigid, low-friction surfaces (e.g., ice, or while wearing roller skates), task and surface constraints can *diverge* towards conflicting coordination modes, with large-amplitude head movements favoring an anti-phase mode and low friction favoring an in-phase mode. Could people resolve these conflicting properties, and if so, how? Given the risk of falling associated with large head movements during stance on low-friction surfaces, we might predict that performance on the supra-postural task would be sacrificed to the maintenance of stance, and hence that surface-specific coordination modes would 'dominate' task-specific modes. One alternative would be a trade-off between the two constraints; a partial reduction in task-related head movements coupled with a partial reduction in bio-mechanical stability.

In the present study, we attempted to create situations in which constraints imposed by the support surface and constraints imposed by the supra-postural task either converged toward the same coordination mode (either in-phase or anti-phase) or diverged towards conflicting coordination modes. Participants stood on surfaces that differed in friction and firmness, and were asked to produce head movements to track the fore-aft sinusoidal displacement of a visual target. We varied task-based constraints on coordination by varying the amplitude of target motion. In general, the instruction to match the amplitude of head movements to the amplitude of the target should tend to favor an in-phase mode for small amplitudes, and an anti-phase mode for large amplitudes. As noted above, however, the surface manipulation should also tend to favor an in-phase mode on a firm but frictionless surface, and an anti-phase mode on a frictive but non-rigid surface. The results indicated that hip rotation was present in all conditions, and suggested that neither task-based nor surface-based parameters were dominant in postural coordination, but that coordination modes emerged as a functional trade-off of the two types of constraint.

2. Method

2.1. Design and procedure

The target to be tracked was a frontal square that oscillated in depth at 0.2 Hz, depicting a flat, rigid object 87 cm horizontal (H) × 99 cm vertical (V), subtending a mean visual angle of 21° V × 18° H. Displays were generated on a 486 personal computer expanded with an image processing system (Kontron K8000) at a frame rate of 25 Hz, and presented on a rear-projection screen (1.38 m H × 1.78 m V) using a SONY VPH 1270 video projector. Participants ($N = 12$) stood barefooted with their arms crossed across the chest. They were asked to track target oscillations with the head, to move the head in phase with the display, and to match the depicted amplitude (Fig. 1(A)). Three support surfaces were crossed with three target amplitudes. The *Standard* surface was a metal panel placed on the floor. The *Foam* surface was a gymnastic mat (0.23 m thick) that was placed on the panel. In

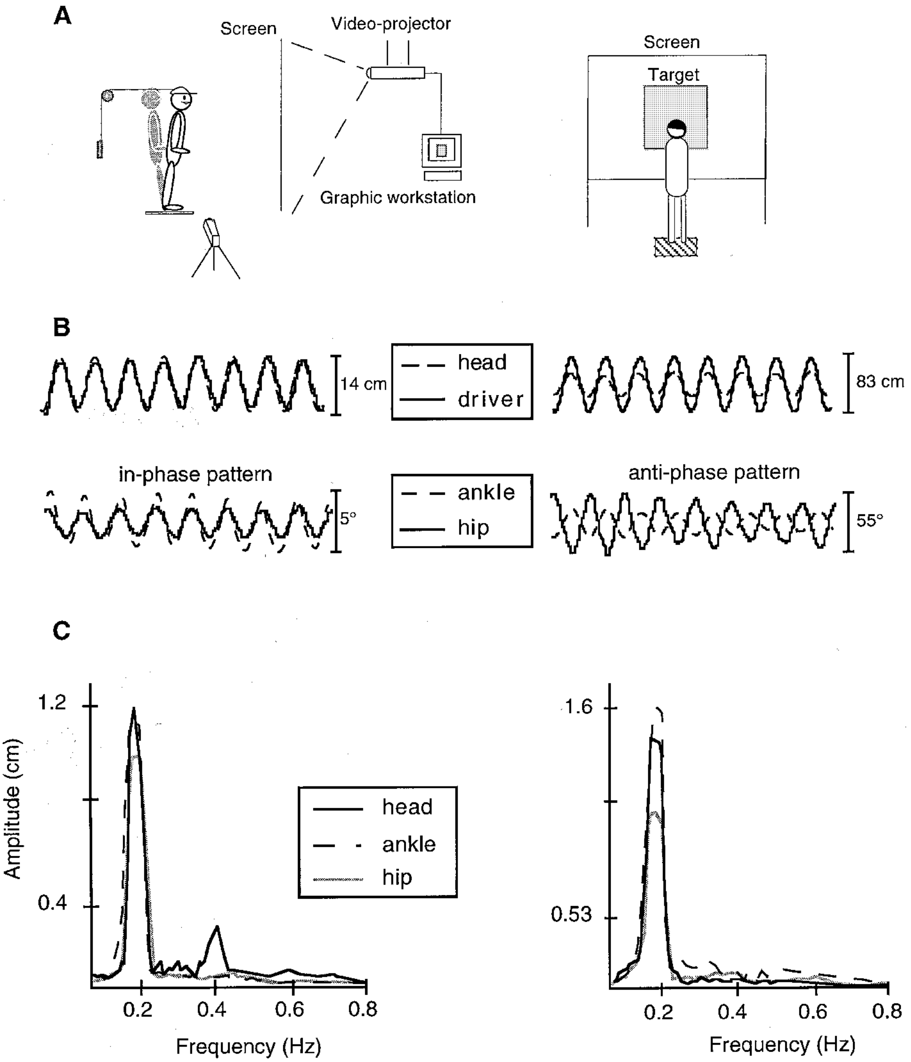

Fig. 1. Analysis of two representative trials (standard surface) illustrating an in-phase (left) and anti-phase (right) hip–ankle coordination: (A) apparatus; (B) time series of fore-aft positions of head and target showing phase locking of the head (target amplitudes are $A = 14$ cm (left) and 83 cm (right)), and corresponding in-phase and anti-phase motion of ankles and hips. (C) amplitude spectra for the same trials, showing peaks at the target frequency (0.2 Hz) and very little activity above 0.4 Hz.

the *Roller* condition, participants stood on the panel while wearing roller skates: Ankles were free to move and participants were 7 cm higher above the ground than in the other conditions. Participants were instructed to keep both toes and heels (or wheels) in continuous contact with the support surface, and to remain within an area marked on the surface (0.3 m × 0.5 m). For each surface, there were three peak-to-peak amplitudes of target motion; 14, 33, and 83 cm. On each trial, the display was presented for 80 s to allow the participant to achieve a steady-state entrainment, and data were collected over the next 40 s. Trials were blocked by surface condition (counterbalanced for order) and presented in an order randomized within blocks for amplitude. A familiarization period included 3 min of practice while standing on standard surface with the display oscillating at various amplitudes. There was one trial per condition, for a total of 108 trials.

2.2. Data acquisition and variables

The task was to track the oscillating display using voluntary movements of the head. Fore-aft head movement was measured at 100 Hz through a potentiometer linked by a constant-weighted thread attached to the head. Data collection began at the onset of a target oscillation cycle, so that the phase lag between the target and the head ($\phi_{\mathrm{t-h}}$) could be determined. For each trial, the peak-to-peak amplitude A_{h} of head motion was calculated, and the time series of head and target oscillations were cross-correlated. The resulting R value provided an estimate of the strength of the coupling between the target and the head. Perfect performance on this task would produce a target–head cross-correlation of unity, with a gain of one and a phase lag of zero.

Postural coordination patterns that occurred during this tracking task were also analysed. Body movement was recorded at 50 Hz using an Ariel video motion analysis system. The camera, placed on the right side of the participant, recorded the position of LEDS (5 mm in diameter) at the right shoulder (top of the acromion), hip (tubercle of the iliac crest), knee (lateral femoral condyle), ankle (lateral malleolus), and toe (lateral aspect of the fifth metatarsal). Hip and ankle angles were computed on the basis of the LED positions, and the mean hip–ankle relative phase (ϕ_{rel}) was obtained by subtracting ankle phase from hip phase for each trial. Both individual phases were obtained from an FFT analysis of the displacement data at the target frequency (0.2 Hz). A value of $\phi_{\mathrm{rel}} \approx 0°$ indicates that the ankles and the hips are moving in the same direction, and was defined as an in-phase mode of coordination. A value of $\phi_{\mathrm{rel}} \approx 180°$ indicates that the ankles and the hips are moving in the opposite direction, and was defined as an anti-phase mode. Any positive value of ϕ_{rel} between 0° and 180° indicates that the hips are leading the ankles. For instance, a value of ϕ_{rel} of 45° indicates that the hips are preceeding the ankles with a phase lag of 45°.

Thus, the dependent variables were (i) the peak-to-peak amplitude A_{h} of the head in the antero-posterior direction, (ii) the cross-correlation R between the target and head in that direction, (iii) the phase lag $\phi_{\text{t-h}}$ between target and head, and (iv) the hip–ankle relative phase ϕ_{rel}. Full circular statistics were used for computing means and standard deviations of $\phi_{\text{t-h}}$ and ϕ_{rel} (Batschelet, 1981). Raleigh tests of non-homogeneity with 95% confidence intervals were used in order to determine whether phases were randomly distributed over trials or significantly clustered around a mean value, and Watson–Williams F tests were used to analyze circular variables. Because only one 40 s trial was registered in each condition, all the standard deviations reported refer to inter-individual variabilities.

3. Results

Mean amplitude of head movement, target–head gain, cross-correlation between target and head, as well as target–head lag and hip–ankle relative phase are presented in Table 1. The gain (column 2) has been included to scale the head amplitude to the target amplitude. Fig. 1(B) illustrates trials from a typical subject, showing motion of the target, head, ankles and hips. Fig. 1(C) illustrates the Discrete Fourier Transform (DFT) for these trials, indicating a major peak at the target frequency of 0.2 Hz and very little activity above 0.4 Hz. Four important points should be noted. First, the magnitude of responses was influenced by the target amplitude and the support surface. Second, stance on the foam surface produced positive phase lags between target and head, whereas the rollers produced negative phase lags. Third, two major coordination modes emerged, an in-phase mode ($\phi_{\text{rel}} \approx 0°$) and an anti-phase mode ($\phi_{\text{rel}} \approx 180°$). Fourth, increasing the amplitude of target motion produced a shift from in-phase to anti-phase mode on the standard surface, but there were no target-related changes in phase on the other surfaces. We discuss these results in turn.

Cross-correlation: Table 1 (column 3) indicates the existence of a reliable coupling between target and head under all conditions. With one exception – Roller surface, Small Amplitude (Newman–Keuls, $p < 0.01$) – the strength of the coupling between target and sway was remarkably high (i.e., greater than 0.9). This indicates that participants had no problem in responding to the visual target.

Table 1
Means (SD) across participants

Support	Amplitude (cm)	A_h (cm)	Gain	R	ϕ_{t-h} (deg)	Raleigh phase r	ϕ_{rel} (deg)	Raleigh phase r
Standard	14	11.54 (0.04)	0.82	0.98 * (0.02)	−0.28 (6.95)	0.99 *	−0.51 (1.36)	0.99 *
	33	22.82 (0.03)	0.69	0.96 * (0.03)	−0.99 (9.36)	0.98 *	−165.36 (13.45)	0.97 *
	83	37.13 (0.07)	0.44	0.95 * (0.04)	−0.39 (11.15)	0.97 *	−179.01 (21.56)	0.93 *
Foam	14	15.35 (0.03)	1.09	0.95 * (0.03)	12.58 * (6.8)	0.98 *	−150.33 (21.54)	0.92 *
	33	22.31 (0.04)	0.67	0.96 * (0.01)	14.81 * (6.49)	0.98 *	−166.88 (5.18)	0.99 *
	83	35.74 (0.05)	0.43	0.96 * (0.01)	18.57 * (9.75)	0.95 *	−177.63 (23.55)	0.91 *
Rollers	14	11.35 (0.04)	0.81	0.40 * (0.08)	−12.43 * (10.19)	0.97 *	−2.71 (1.87)	0.99 *
	33	19.88 (0.06)	0.60	0.93 * (0.03)	−14.9 * (9.67)	0.98 *	44.78* (19.7)	0.94 *
	83	31.36 (0.07)	0.37	0.92 * (0.02)	−20.44 * (10.09)	0.97 *	−8.92 (6.73)	0.99 *

A_h = peak-to-peak head amplitude. Asterisks indicate that: for R, cross-correlations between target and head differed from zero; for ϕ_{t-h}, target–head phase lag differed from 0°; for rs, the Raleigh tests of non-homogeneity for phases were statistically significant; and for ϕ_{rel}, hip–ankle relative phase differed from 0° or 180°. * $p < 0.05$.

Sway amplitude: On average, participants adapted their head motion amplitude to the target amplitude (Table 1, columns 1 and 2), with a gain of about 0.66. A two-way RM ANOVA (Amplitude × Surface) on the peak-to-peak amplitude of head motion revealed a main effect for target amplitude, $F_{(2,\,22)} = 150.05, p < 0.01$, accounting for 75% of the total variance. However, a significant effect of support surface was also found, $F_{(2,\,22)} = 5.84, p < 0.01$, 3.5% of the total variance, as well as an amplitude × surface interaction, $F_{(4,\,44)} = 8.02$, $p < 0.01$, 11% of the total variance, indicating a more subtle effect of the target amplitude. Sway amplitude was reduced under the roller conditions; this occurred mainly with the two large target amplitudes (post-hoc Newman–Keuls, $p < 0.01$). Thus, when standing on the rollers subjects minimized body sway, favoring the maintenance of stance over matching the target amplitude.

Target–head phase: The mean phase angle ϕ_{t-h} between target and head was similar for the three target amplitudes (Table 1, column 4) and was significantly clustered around a mean, indicating a preferred phase angle. Significant differences, however, were found to exist between surface conditions. While the mean phase was around 0° on the standard surface (Mean = 0.5; SD = 9.1), it was positive on the foam (Mean = 15.3°, SD = 7.7), and negative on the rollers (Mean = −15.9°, SD = 10), as indicated by the 95% confidence interval for the observed phase angle, which contained 0° phase only on the standard surface. Watson–William tests performed on the mean $\phi_{\mathrm{t-h}}$ confirmed this result and revealed significant differences between standard and foam conditions, $F_{(1,\,34)} = 9566$, $p < 0.01$, and between standard and roller conditions, $F_{(1,\,34)} = 7234$, $p < 0.01$. When standing on the standard surface, participants moved in phase with the display. They anticipated it on the foam, and followed it on the rollers.

Hip–ankle relative phase: Column 6 of Table 1 shows the mean hip–ankle relative phase ϕ_{rel} and Fig. 2 details the value of ϕ_{rel} for each participant in the nine experimental conditions. ϕ_{rel} was found to be significantly clustered around a mean (Table 1, column 7), thus indicating a preferred phase angle. With one exception – Rollers, Medium amplitude – two values of relative phase are apparent: close to 0° (i.e., in-phase coordination), and close to 180° (i.e., anti-phase coordination), as indicated by the 95% confidence interval for

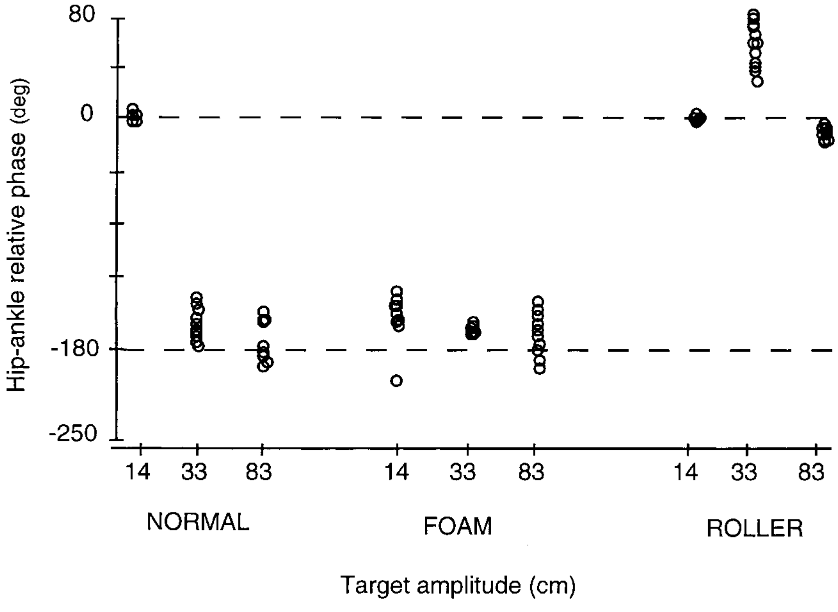

Fig. 2. Mean relative phase ϕ_{rel} for the 12 subjects as a function of target amplitude and support surface.

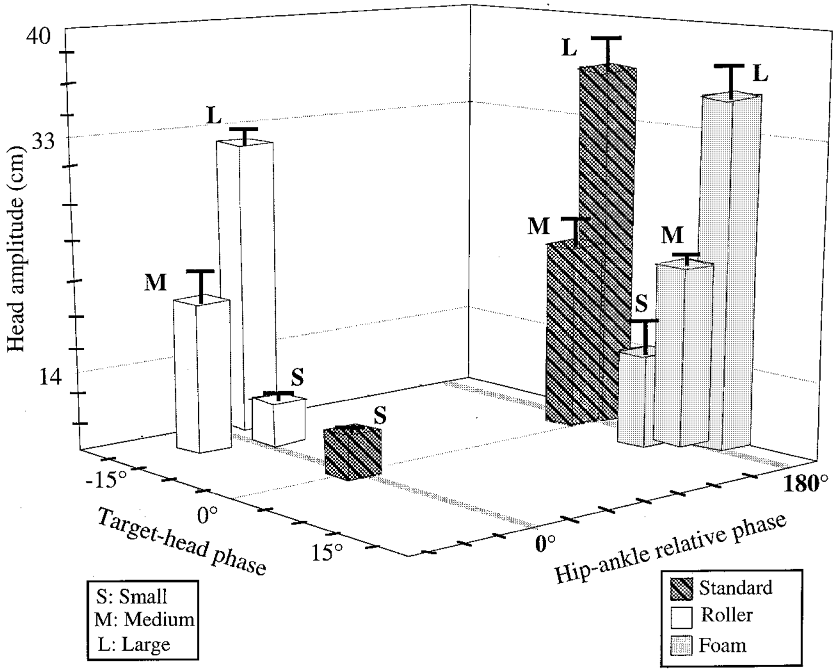

Fig. 3. 3-D summary of the results, illustrating the evolution of head amplitude as a function of both hip–ankle relative phase and target–head phase lag.

the observed phase angle, which contained 0° or 180° phase in all but this condition. On the standard surface ϕ_{rel} was at 0° for the small target amplitude, but switched to almost 180° at higher amplitudes. There were no target-related changes in phase on either of the other surfaces.

The data are summarized in Fig. 3, in which sway amplitude is plotted as a function of the target–head phase lag and hip–ankle relative phase. The figure shows the separation of postural coordination into two preferred modes ($\phi_{\mathrm{rel}} \approx 0°$ and $\phi_{\mathrm{rel}} \approx 180°$), and how these modes were emerged differentially depending on both the target amplitude and the support surface.

4. Discussion

The amplitude and surface effects found on hip–ankle relative phase indicate that participants were able to control their body configuration with respect to constraints imposed simultaneously by the visual tracking task and the support surface. The non-rigid surface produced anti-phase coordination and the roller surface produced in-phase coordination (with one exception), regardless of the amplitude of target or head motion. These findings are inconsistent with the argument that postural coordination is influenced solely or primarily by the amplitude of imposed motion. The amplitude of target motion influenced hip–ankle relative phase only on the standard surface, where both in-phase and anti-phase patterns were observed. This finding moderates the argument that sway about the ankles should always be observed on surfaces that resist torque, regardless of perturbation amplitude (Diener et al., 1988). By contrast, all three findings are consistent with the idea that multi-segment coordination in postural control emerges from interactions between constraints imposed by the support surface and those imposed by the task.

4.1. Postural coordination modes

One of the main findings of the present study is the existence, in eight of the nine conditions, of two preferred coordination modes, $\phi_{\mathrm{rel}} \approx 0^\circ$ and $\phi_{\mathrm{rel}} \approx 180^\circ$. These two modes have also been observed when amplitude of voluntary head movement has been crossed with variations in the length of the feet and the height of the center of mass (Bardy et al., in press). The robust appearance of these two modes across such wide variations in support surface and task demands supports the contention that relative phase between ankles and hips may be a useful descriptor of postural coordination subserving goal-oriented, continuous movements. Inter- or intra-limb relative phase has been shown to characterize coordination in discrete (e.g., Schöner, 1990) and continuous movements (e.g., Kelso, 1984; Diedrich and Warren, 1995; Turvey, 1994). Thus, the use of ϕ_{rel} in analyzing hip–ankle coordination during stance can be understood as a natural outgrowth of general models of the dynamics of coordination in motor control (c.f., Saltzman and Kelso, 1985, 1987). Obviously, the use of ϕ_{rel} to characterize postural modes of coordination depends upon the existence of some degree of rotation at both the hip and ankle joints, a result that was found for all surface and target amplitude conditions. The presence of functional hip movements in the in-phase mode may have been facilitated by our use of periodic stimulation, and the presence of an explicit voluntary task. If so, this would underscore the value of expanding the range of situations in which multi-segment postural control is studied.

Our findings confirm the hypothesis that postural patterns can be viewed as patterns of coordinated movements of the various segments of the postural system (Bardy et al., in press). Under the pressure of both internal and external constraints, these patterns emerge in such a way that a limited number of states exist (e.g., Kelso, 1995). The value of $\phi_{\mathrm{rel}} \approx 45°$ that was observed in the Roller-Medium amplitude condition indicates that other modes might exist. This is consistent with the broader literature on coordination dynamics (cf., Zanone and Kelso, 1992). It is also consistent with the notion of mixed, or intermediate, ankle–hip strategies (Nashner and McCollum, 1985). It is to be noted, however, that the large variability observed in this condition makes it difficult to determine whether the 45° pattern is a consequence of our experimental manipulations or the result of inter-individual variability.

4.2. Converging and diverging constraints

The results of this experiment are consistent with the view that postural modes emerge from the interaction of body-based, task-based, and environment-based constraints (cf. Newell, 1985; Riccio and Stoffregen, 1988). By manipulating head amplitude and support surface, we provided evidence that goal-directed behavior, such as the tracking task used here, is coupled with the mechanical requirement of maintaining the center of mass over the feet, and that the form of this coupling depends on the interaction between task and surface. We have proposed that task and surface constraints can converge to favor a unique postural coordination mode – as in the non-rigid surface / large target amplitude conditions – or diverge to favor opposite postural coordinations – as in the rolling surface / large target amplitude conditions. In the first case (i.e., converging constraints on the foam) the main result was a shift in ϕ_{rel} from 0° to 180°, with no change in coupling strength or head amplitude as compared to the standard condition. In other words, participants were able to perform the task on the non-rigid surface by adapting postural patterns in a surface-specific manner. In the second case (i.e., diverging constraints on the rollers), the main result was a trade-off between the two constraints, as evidenced by change in coupling strength, head amplitude, and ϕ_{rel}. The adoption of a torque-resistant, in-phase mode in the small amplitude condition allowed the participants to match the target amplitude, but with some phase decoupling during the trial, as indicated by a low correlation ($R = 0.4$) as compared to the other conditions. In the medium amplitude condition, this trade-off was evident in participants' attempt to shift ϕ_{rel} (about 45°), with a higher coupling strength ($R = 0.93$) but a lower gain (≈0.60). Finally, in the large amplitude condition, a surface-specific in-phase pattern (ϕ_{rel} close to 0°) emerged that produced high coupling strength ($R = 0.92$), but with a very small gain (≈0.37). This indicates that participants were more concerned with the mechanical requirement of keeping their balance than with performing the requested task. With this last exception, however, these data show a subtle trade-off between the two factors, rather than a general dominance of either surface properties on task properties.

5. Conclusion

The present findings suggest that postural control can be understood on the basis of collective functional units of action (e.g., Saltzman and Kelso, 1985) and that the phase relations between segments composing the postural system can be used to analyze postural coordination modes. Additional work is needed to investigate the dynamics of these modes, as well as transitions between modes. Results obtained recently (Bardy et al., in preparation) indicate that transitions between postural modes resemble second-order phase transitions, exhibiting loss of stability, bifurcation and hysteresis. The results of the present study are also consistent with the idea that motor coordination, in general, emerges out of the simultaneous interaction between constraints imposed by the environment, the body, and the goals of behavior (McGinnis and Newell, 1982; Newell, 1985; Riccio and Stoffregen, 1988). This view reinforces the importance of investigating postural control in the context of purposive action. Future research should investigate the properties of the interaction between the different classes of constraints. One way to do this would be to examine postural control on different surfaces in the presence of a manual task, such as catching, which would require fast, high-amplitude adjustments to posture.

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