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Full Length Article

Transitions of postural coordination as a function of frequency of the moving support platform

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ABSTRACT

This study was set-up to investigate the multi-segmental organization of human postural control in a dynamic balance task. The focus was on the coupling between the center of mass (CoM) and center of pressure (CoP) as a candidate collective variable that supports maintaining balance on a sinusoidal oscillating platform in the medial-lateral (ML) plane and was continuously scaled up and then down across a frequency range from 0.2 Hz to 1.2 Hz. The CoM-CoP coordination changed from in-phase to anti-phase and anti-phase to in-phase at a critical frequency (~0.4 Hz to 0.6 Hz, respectively) in the scaling up or down of the support surface frequency, showed hysteresis as a function of the direction of frequency change and critical fluctuations at the transition region. There was evidence of head motion independent of CoM motion at the higher platform frequencies and a learning effect on several of the dynamic indices over 2 days of practice. The findings are consistent with the hypothesis of CoM-CoP acting as an emergent collective variable that is supported by the faster time scale motions of the joints and their synergies in postural control.

1. Introduction

Recent studies have shown that in quiet standing the maintenance of an upright stable posture in balance tasks is regulated by multiple joint motions of the body (Alexandrov, Frolov, Horak, Carlson-Kuhta, & Park, 2005; Federolf, Roos, & Nigg, 2013; Hsu, Scholz, Schöner, Jeka, & Kiemel, 2007; Wang, Ko, Challis, & Newell, 2014) rather than motion at the ankle joint only as provided by the standard inverted pendulum model (Winter, 2009). However, the nature of the organisation of these multiple joint space degrees of freedom (*dof*) in postural control in both quiet standing and dynamic postural balance tasks remains an open and challenging theoretical and experimental question. This is because coordination is a characteristic expression of biological systems that leads to adaptive relations that are task dependent across the multiple *dof* defined over multiple scales of space and time (Bernstein, 1967; Gelfand & Tsetlin, 1962; Kelso, 1995).

There have been a number of studies of the coordination of body effectors that afford stability in the act of quiet standing posture (e.g., Massion, 1994; Nashner & McCollum, 1985) and also dynamic postural balance under both discrete (Gu, Schultz, Shepard, & Alexander, 1996; Hughes, Schenkman, Chandler, & Studenski, 1995) and continuous oscillatory (Buchanan & Horak, 1999, 2001; Ko, Challis, & Newell, 2014, 2003) motion of the base of support. In quiet standing two pri-

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mary postural coordination modes traditionally have been identified. One mode is that of an ankle strategy where the postural system is viewed as an inverted pendulum (Winter, 1995). The second mode is a hip strategy where the hip motion maintains the postural stability (Nashner & McCollum, 1985). An integrated ankle-hip coordination mode has also been proposed (Horak & Nashner, 1986).

Other terms have been used for postural coordination modes in the moving platform protocol such as ride pattern (Buchanan & Horak, 1999), inverted pendulum pattern (Horak & Nashner, 1986) and rigid mode (Ko, Challis, & Newell, 2001) that all characterize the coordinative behavior to maintain postural stability on a moving support surface. Similarly, head fixed pattern (Buchanan & Horak, 1999), buckled pendulum and ankle-knee-hip mode (Ko et al., 2001) have been used to describe related postural coordinative phenomena in dynamic postural balance tasks. Collectively, these studies have revealed qualitative change in the coordination of the joint space *dof*s by perturbing the postural system of quiet stance through manipulations of the platform surface of support and/or perceptual information (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999; Buchanan & Horak, 1999) available.

Bardy et al. (1999) provided evidence that ankle-hip motion was the collective variable in a suprapostural standing task. Ko et al. (2014) provided evidence that the relative phase of CoM-CoP motion along AP could be considered as a collective variable for the task of upright postural stance (Bardy et al., 1999; Kelso, 1995; Mitra, Amazeen, & Turvey, 1998). By definition, a collective variable is a higher order low dimensional variable that captures the overarching pattern of spatial and temporal details among the *dof* of the movement system. It is a construct that holds parallels to the role of macroscopic variables in other systems frameworks of essential variables (Gelfand & Tsetlin, 1962) and order parameters (Haken, 1983; Haken, Kelso, & Bunz, 1985).

The postulation of CoM-CoP relative phase as a collective variable follows in part from the definition of CoM itself as an emergent macroscopic property that captures the motion of the point where the weighted relative position of the distributed mass of the body sums to zero. And, CoP can be considered as another emergent macroscopic variable given that it represents the location on the surface of support of the global ground reaction force. Thus, the CoM-CoP relation (as in a relative phase measure) can be considered a dynamic macroscopic postural property reflecting the global organization of the postural system defined over the individual, environment and the task. The postulation of CoM-CoP as a collective variable in upright standing has, therefore, intuitive face validity from an understanding of the biomechanics of the task (Winter, 2009). In the view of coordination dynamics, the motions of the joint *dof* and synergies are in support of the stability of the macroscopic collective variable that are themselves reciprocally constrained by it (Kelso, 1995).

The dynamic postural balance task with its multiple joint *dof* affords a distinction, unavailable with a bivariate bimanual set-up, between the postulated collective variable and the neuromuscular synergies and individual joint motions. A moving platform that sinusoidally oscillated in the anterior-posterior (AP) plane provided an experimental manipulation as a control parameter to scale the postural coordination patterns under different parameter regions of the state space (Ko et al., 2014). It was found that the CoM-CoP coordination changed from in-phase to anti-phase and anti-phase to in-phase at a certain frequency of the support surface, showed hysteresis as a function of the direction of the frequency change and higher variability (critical fluctuations) at the transition region. The time scales of the changes in the coupling synergies of joint motions were shorter than that of the CoM-CoP couple. This pattern of findings is consistent with the proposition of CoM-CoP being the collective variable in that task.

The movement systems approach to collective variables, synergies and individual joint motions provides a way to distinguish and reveal the functional roles of the multiple *dof* (Gelfand & Tsetlin, 1962; Kelso, 1995; Mitra et al., 1998) rather than assuming that each operate in the same way. As noted a postulation of coordination dynamics is that there is reciprocal control between the slower time scale of the collective variable and the synergies in the regulation of movement and posture that can be distinguished in the scaling of a control parameter (here platform frequency). This distinction between the roles of the variables (motions of joints, synergies and collective variable) can be more directly investigated in the multiple *dof* case of postural control than the bivariate case of bimanual finger control.

In the present study we investigated how the postural system regulates the *dof* when the surface of support is subjected to a sinusoidal oscillating medial–lateral (ML) platform motion. The ML motion in dynamic balance postural tasks is organized differently both anatomically and mechanically from AP postural motion in that it is driven by hip motion (Winter, 2009) and affords adaptive anti-phase postural control between the two leg/feet subsystems (Wang & Newell, 2012). Nevertheless, we investigate if the dynamical principles supporting motion of the candidate collective variable, synergies and joint motions in ML are the same as those to platform sinusoidal translations in AP (Buchanan & Horak, 2001; Ko, Challis, & Newell, 2013), in spite of the different anatomical and physiological constraints to postural motion in each dimension.

We examined the hypotheses that the CoM-CoP and head-CoP couplings would abruptly shift from in-phase (at both quiet standing and low platform frequencies) to anti-phase at higher frequencies of platform motion but that practice would reveal the independence of head motion from that of CoM, particularly at the higher platform frequencies (Ko et al., 2013; Ko & Newell, 2015). The 2 days of practice allowed us to contrast the persistent and transient changes in properties of the candidate collective variable and other macroscopic candidates (Head-CoP, ankle-hip), in addition to the synergies and joint motions as a function of platform dynamics. Given the adaptation of a preferred postural coordination for each platform frequency (Ko et al., 2001), we also investigated whether the frequency at which the critical fluctuations emerged from the CoM-CoP transition was a function of body scale properties (Kugler & Turvey, 1987), using the body mass index (BMI) or Quetelet index derived from body mass and height. In this body-scaling framework, the mass-length pendulum-like prop-