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# Postural Stability Variables for Dynamic Equilibrium

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## Abstract

Experiments on the maintenance of postural stability on flat stationary support surfaces (quiet standing) that show only limited modes of the potential configurations of balance stability have dominated investigations of balance in quiet upright standing. Recent studies have revealed coordination properties of the whole body in maintaining dynamic postural stability with the application of moving platform paradigms. This paper examines properties of candidate collective variables for postural control within the dynamic systems framework. Evidence is discussed in this paper for: (i) self-organization properties of dynamic postural balance; (ii) enhanced variability and entropy prior to a phase transition between center of mass and center of pressure coupling; (iii) co-existence of intermittent postural control strategies that oscillate between periodic to chaotic transitions to maintain upright postural balance. These collective findings indicate postural attractor dynamic states progressively emerge to the changing task constraints of a moving platform revealing insights into the deterministic and stochastic properties of the multiple time scales of human postural behavior.

### Keywords

Upright Balance; Dynamical Systems Theory; Coordination Dynamics; Postural Stability

## 1. Introduction

The maintenance of postural equilibrium in quiet upright standing is coordinated across multiple body joint synergies, as shown in several studies (1–4). An intriguing operational paradigm is the organizational nature of these multiple joint degrees of freedom (*dofs*) in dynamic postural balance tasks; due to the fact, that coordination is a characteristic expression of biological systems that leads to adaptive relations task dependent across the multiple degrees of freedom defined over multiple scales of space and time (5–8).

Several studies on postural coordination and control and its relation to postural equilibrium during static quiet upright standing (9,10). Additionally, dynamic postural balance under

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both discrete (11,12) and rhythmic oscillatory support surface motion (13–16) have been done. Primarily, three modes of postural coordination have been identified in quiet standing – (i) ankle strategy - postural system is viewed as an inverted pendulum (17), (ii) hip strategy - hip motion regulates the postural stability (10), and (iii) integrated ankle-hip coordination strategy (18). Additional strategies to supplement these characterizations have been used to identify postural coordination patterns in the moving platform protocol such as a ride pattern (13), inverted pendulum pattern (18) and a rigid mode (16) that represent the overall coordinative behavior to maintain postural stability on a moving support surface. Furthermore, a head fixed pattern (13), buckled pendulum and ankle-knee-hip mode (16) have been utilized to describe the related postural coordinative phenomena in dynamic postural balance tasks. These studies have collectively revealed a qualitative change in the degrees of freedom of joint space can be induced by perturbing the postural system of quiet stance through systematic scaling the support surface motion (16,19,20).

A collective variable by definition is a higher order low dimensional variable that captures the overarching pattern of spatial and temporal details among the degrees of freedom of the movement system (21). It holds parallel construct with the role of macroscopic variables in other systems' constructs of essential variables (6) and order parameters (22,23). As a collective variable, the postulation of relative phase between center of mass and center of pressure follows in part from the definition of center of mass 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. Additionally, another emergent macroscopic variable to be considered is center of pressure, given that it represents the location on the surface of support of the global ground reaction force. Hence, the relative phase relation between center of mass and center of pressure dynamics can be considered a dynamic macroscopic postural property reflecting the global organization of the postural system defined over the constraints encompassing individual, environment, and the task. Therefore, as a collective variable, the postulation of center of mass and center of pressure has intuitive face validity from an understanding of the biomechanics of the task (24). Even in a closed skill (25) of the platform dynamic balance task, a contrasting hypothesis is that visual information from a stable head dynamic in support of a supra-postural task demand specifies the global structure to the macroscopic organization of the postural coordinative structure (26). The systematic scaling and maintenance of the center of mass and center of pressure relative phase in the dynamic balance task may indeed be driven by other perceptual – action coupling dynamics (27).

Both platform driven perturbations in anterior-posterior and medial-lateral planes of motion and self-initiated medial-lateral movements in the ski-simulator task are reviewed here under the lens of dynamic postural investigations. Ko et al. (2014) investigated whether the relative phase of the center of mass and center of pressure motion along anterior-posterior could be considered as a collective variable for the task of upright postural stance (7,21,28). On the other hand, Dutt-Mazumder and Newell (2017) examined similar evolving postural balance phenomena in the medial-lateral axis of upright stance (29). Dutt-Mazumder and Newell (2017) investigated the changing organization of center of mass to the platform motion in the learning of the ski-simulator task that is self-perturbed (30). Key points are drawn from these studies in sections organized under the dynamical systems approach to posture and movement.

## 2. Standard deviation of center of mass and center of pressure coupling increase prior to critical fluctuation

Unlike a bivariate manual set-up, the dynamic postural balance task with its multiple joint degrees of freedom affords a distinction that has unique features between the postulated collective variable and the neuromuscular synergies. A translating platform that oscillates sinusoidally along the anterior-posterior plane provided an experimental manipulation as a control parameter to systematically scale the postural coordination patterns under different parameter regions of the state space (15). The center of mass and center of pressure 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. Within the time scales, the coupling synergies of joint motions were shorter than the coupling of center of mass and center of pressure.

Rather than assuming each operate in the same way, 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 degrees of freedom (6,7,21). Coordination dynamics postulates 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). Unlike the bivariate case of bimanual finger control, the distinction between the roles of the variables (motions of joints, synergies, and collective variable) can be more directly investigated in the multiple degrees of freedom case of postural control.

## 3. Recurrent postural control strategies co-exist

The coordination and stability of the postural system during the act of quiet upright standing has been investigated through several studies (9, 10). Likewise, studies have been done on postural control in a discrete perturbation dynamic postural balance task (11,12), supra-postural bimanual task (32), and continuous oscillatory platform motion (13,16,33). Center of mass motion to that of platform motion remained in-phase, or transitioned to anti-phase as a function of the platform frequency in both anterior-posterior (15) and medio-lateral (29) moving platform postural tasks. Preliminary evidence from these results indicate the relative coupling of center of mass - an emergent macroscopic property with respect to the oscillatory platform motion could be considered as a collective variable for upright postural stance task (15,34).

Another hypothesis of coordination dynamic is that by systematic scaling of a control parameter (e.g., platform frequency), it is possible to discern the intermittent postural control strategies while maintaining the same upright balance task. Theoretically, the reciprocal control between the slower time scales of the emergent collective variable and the faster time scales of the local synergies (35–38) in the regulation of movement and posture should indicate these episodic postural control patterns (39,40). The distinct role between the variables (joint synergies and collective variable) is fundamental to understanding the coordination and control of the multiple degrees of freedom case of postural control. Prior studies on oscillatory platform motion over various time scales have demonstrated the convergence towards and divergence away from stable postural coordination between center of mass and platform motion (29,33). Chaotic dynamics (41,42) and fractal properties of postural motion during upright quiet standing (43,44), and human locomotion (45) have also been illustrated in studies. However, to provide us a closer insight into the postulated intermittent coupling of center of mass-platform oscillators, their nature of emerging attractor states, the duration of trapped attractor states, and systematic scaling of platform frequency should be considered.

## 4. Summary

To conclude, the review discusses the properties of candidate collective variables for postural control within the dynamic systems framework. We have discussed the evidence for self-organization properties of dynamic postural balance along with enhanced variability and entropy prior to a phase transition between center of mass and center of pressure coupling. We also elaborated on the co-existence of intermittent postural control strategies that oscillate between periodic to chaotic transitions to maintain upright postural balance. These collective findings indicate postural attractor dynamic states progressively emerge to the changing task constraints of a moving platform revealing insights into the deterministic and stochastic properties of the multiple time scales of human postural behavior.

In the future, subsequent work on systematic manipulation of center of mass and center of pressure with oscillating platform paradigm should consider active dynamics of the arm motion during the task performance. In our previous studies, we excluded the arm motions to reduce the number of *dofs* of the whole body to simplify the postural control model. However, arm motions play an important role in a postural balance task and influence the dynamics of center of mass and center of pressure motion, including the preservation of balance stability.

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