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COLLECTIVE VARIABLES IN DYNAMIC POSTURAL STABILITY

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Aviroop Dutt-Mazumder

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The dissertation of Aviroop Dutt-Mazumder was reviewed and approved* by the following:

Karl M. Newell
Emeritus Professor of Kinesiology
Dissertation Adviser
Chair of Committee

John H. Challis
Professor of Kinesiology

Kristina A. Neely
Assistant Professor of Kinesiology

Peter C.M. Molenaar
Distinguished Professor of Human Development and Family Studies

Stephen J. Piazza
Professor of Kinesiology
Graduate Program Director of the Department of Kinesiology

*Signatures are on file in the Graduate School

ABSTRACT

This study investigated aspects of Bernstein's (1967) postulates on the degrees of freedom (*dof*) problem and the degenerate pathways through which coordination patterns are acquired in skill acquisition. The central focus was an investigation of the proposition that the postural system controls a collective variable to realize the demands of the task. The experimental paradigm used a set of dynamical support bases including a tilted platform (Experiment 1), a sinusoidal translating support surface (Experiment 2), and a ski-simulator (Experiment 3) to address the organization of redundant individual (*dof*) in the control of upright standing balance tasks. It was hypothesized that the set of experiments would further augment our understanding regarding the mechanisms involved in the control of posture in such dynamic base of support tasks among humans.

The collective pattern of findings is consistent with the conclusion that the coupling of center of mass-center of pressure (Experiments 1 and 2) and the coupling of center of mass-platform (Experiment 3) act as a collective variable. This was supported by the faster time scale motions of the joints and their synergies and reflects the structural integrity of the system for dynamic postural stability across the conducted experiments. Furthermore, the center of mass and head reflect independent motions in the postural tasks. The findings reveal that for multi-joint postural tasks, the collective variable adopts two stable coordination patterns in-phase or anti-phase as a function of the scaling of a control parameter.

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CHAPTER 1: INTRODUCTION

Background

Whilst maintaining an upright posture, the relevant supporting muscles are required to stabilize the moving body, and ensure that the body is balanced through the vertical projection of the center of gravity lying within the base of support (Rothwell, 1994). The fundamental problem of skill acquisition reflects how both coordination and control of the body are achieved to provide solutions to a new movement problem. Drawing from Bernstein's (1967) postulates on degrees of freedom (*dof*), the degenerate pathways through which coordination patterns are acquired are of paramount importance to the study of motor skill.

Different levels of analysis (physiological, neurological and biomechanical) pertaining to *dof* have been applied to investigate postural coordination patterns. Typically, in the field of motor control the focus has been the kinematics of local joints such as ankle and hip motions, as past research have considered these aforementioned joints as the prime candidates to reduce the dimension of the *dof* in dynamic postural control (Hong & Newell, 2006a; Horak, Nashner, & Diener, 1990; Vereijken, van Emmerik, Whiting & Newell, 1992). Furthermore, studies from a dynamical systems perspective have considered the ankle and hip joints as the collective variable of the postural control system (Bardy, Oullier, Bootsma & Stoffregen, 2002; Martin, Cahouët, Ferry & Fouque, 2006) because the dynamics of the ankle and hip joints demonstrate the characteristics of a non-equilibrium phase transition as a function of a linear scaling of the control parameter (Haken, Kelso, & Bunz, 1985).

The fundamental work on bimanual finger coordination by Kelso (1984; 1995) provided the foundation for the role of non-equilibrium phase transitions, yet the findings cannot be clearly re-imposed on postural control mechanisms since the later need to account for the multiple *dof* arising from the multiple joint linkages. Thus, a priori it would be limiting to consider that ankle-hip coupling solely controls whole body coordination. Rather, emergent variables such as the center of mass, the center of pressure need to be considered to understand the mechanisms of postural control in a dynamic task.

Although analysis of the motions of *dof* at each level is beneficial, one has to be prudent when dealing with the analysis at different levels of the system, since the *dof* become increasingly numerous and cumbersome considered from the macroscopic to microscopic levels. To cater to the problem of these large numbers of *dof* a sound strategy needs to be employed. One approach is to demarcate the differences between the biomechanical Bernstein (1967) and dynamical *dof* (Mitra, Amazeen & Turvey, 1998; Newell & Vaillancourt, 2001). The former deals with biomechanical joints in kinematic space whereas the latter is inspired by attractor dynamics and characterizes the dynamics of the inter-limb pattern.

The dynamical *dof* needs to be scrutinized to understand the behavior of postural coordination as a function of practice trials. In a typical complex system comprising a large number of mechanical *dof*, the analysis of the dynamical *dof* might provide valuable insights to the procedural organization of the mechanical *dof* and how the organization of the system dynamics changes under certain constraints (environmental, organism, and task) (Newell, 1985). The overall crux of postural system dynamics is related to the determination of a collective variable as a function of these constraints that will be discussed in a later section (Gelfand & Tsetlin, 1962; Haken et al., 1985; Newell, & Vaillancourt, 2001).

The aim of this dissertation is to investigate the organizational properties of postural coordination patterns such as dynamical *dof* on different dynamic balancing support surface (tilted platform, moving platform and ski-simulator) and to capture coherently the postural control on these varied surfaces. We further intend to explore the identification of collective variables and study the scaling effects across practice trials that encompass the changes to the organization of multiple *dof*. The study design and corresponding results will provide further evidence to understand the complexity of the *dof* problem in human movement system. In the following sections, we discuss the development of skill acquisition theories and build a framework to investigate the fundamental variables that reflect behavioral changes as a function of practice from a dynamic postural control setting.

Focus of the Dissertation

The role of collective variables has been of significant interest in the framework of dynamical systems theory for motor development, learning and control (Kelso, 1995; Mitra et al., 1998). Typically, a collective variable, also called order parameter or essential variable, is considered as a macroscopic variable that characterizes the fundamental organization and structural integrity of emerging patterns in complex systems. An important aspect of a collective variables is its capacity to reduce the dimension of the original components that describes the system ensemble of multiple individual *dof*, often over several levels of analysis.

It is in this context that the general hypothesis examined here is that CoM-CoP coupling is a candidate collective variable for dynamic balance tasks (Ko, Challis, & Newell, 2014; Wang, Ko, Challis, & Newell, 2014). Although the notion of a collective variable has been central in the experiments of bimanual coordination with two *dof* (Haken et al., 1985; Kelso, 1995) it has not been assessed in whole body coordination tasks that require the configuration of many joint space *dof*. It has been argued that it is only in this latter situation that we can get an operational separation of collective variables and synergies (Wang et al., 2014).

The problem of controlling the multiple *dof* of a postural system is hypothesized to be implemented in only a few collective variables that will lead to the maintenance of stability on an unstable base of support. It is this concept of the collective variable that is the subject of this investigation across the three proposed experiments on dynamic balance in tilted platform, moving platform, and ski-simulator tasks. A related issue is how the collective variable differentiates between experienced and novice performers and how the collective variable may transition as a function of practice and prior skill level. In the proposed studies, we will test several hypotheses applying different tools of analysis that are outlined in detail in the subsequent pages of the experimental outline.

Firstly, we will investigate if the collective variable and motion of the synergies and components qualitatively differs from self-generated movement of the ski-simulator task and the machine imposed motion of a moving platform. The analysis of coordination dynamics at the different categories of collective variable, synergy, and component, would enable us to advance our understanding of movement coordination in maintaining balance on an unstable platform. Overall, the essence of this dissertation would be to investigate, to use the theory and experimental strategies of coordination dynamics (Kelso, 1995), aspects of whole body coordination under the influence of a dynamic base of support and study the collective variables enslaving the emerging coordination patterns with practice.

Secondly, we will test the prediction on how the behavior of collective variable candidates such as the coupling of the center of mass (CoM – the point at which all the mass is concentrated) and the center of pressure (CoP – the point of application of the ground reaction force vector), CoM-CoP, CoM-Platform, Head-CoP and Head-Platform differs from the local synergistic components such as ankle-knee, ankle-hip and knee-hip as a function of different frequencies of an oscillating moving platform. Thirdly, we will study how the coupling of CoM-CoP (candidate collective variable) changes as a function of practice and skill level based on the prior experience of performers and their intrinsic dynamics (Thelen & Spencer, 1998).

The proposed cohort of experiments will help us to evaluate the different pathways of harnessing multiple *dof* that relates to the fundamental aspects of acquiring efficient whole-body coordination in a redundant task. An understanding of this issue will help us to investigate the core elements of coordination and what aspects need to be addressed for skill acquisition purposes. We will utilize several quantitative and qualitative analysis techniques including relative phase and phase portraits to investigate coupled variables that potentially qualify as a candidate collective variable for the given task (Kelso, 1995).

CHAPTER 2: LITERATURE REVIEW

Understanding movement

Movement is expressed in many forms. According to developmental biologists, some forms can be regarded as genetically defined or inherited (self-differentiated), such as the way in which people alternate movement of limbs while maintaining postural stability or responsive reflexes during the onset of a sudden perturbation. Here, the patterns of actions appear to be determined by genetic makeup, through growth and development, where these actions appear to be quite stereotypical for members of the same species (Kauffman, 1993). Another class of movements can be thought of as learned such as performing oscillating movements on a ski-simulator, postural control on a moving or tilted platform and manipulating a grasp based on affordances. These learned movements are often termed as skills. They are not inherited and mastering them typically requires long periods of practice and experience.

Guthrie (1952) proposed a significant terminology for skill, where he defined skill as the ability to produce some result with maximum certainty and maximum outlay of energy, or of time and energy. Skills are especially critical to the study of human behavior as they are involved in operating machines, controlling vehicles, preparing meals and so on. The major goal is to understand the variables that determine motor performance proficiency and that are most important for learning of movement behaviors (Schmidt & Lee, 2013). With the introduction of the information processing framework, the motor behavior field seemed to undergo a transition from a task orientation, which focuses primarily on the effects of variables on the performance or learning of certain motor tasks (or both) to a process orientation that support or produce movements (Pew, 1974).

Discontinuities in motor learning

Learning is a critical part of our existence that is a process of acquiring the capability for producing skilled movements. That is, learning is the set of underlying events, occurrences or changes that happen when practice enables people to become skilled at some task and occurs as a direct result of practice or experience. It cannot be observed directly as the processes leading to changes in behavior are internal and are usually not available for direct examination. Rather one must infer the processes of learning by the changes in behavior that can be observed. A synthesis of these aspects produces the following definition: Motor learning is a set of processes associated with practice leading to relatively permanent changes in the capability of movement (Schmidt & Lee, 2013). In this sense, the goal of practice for the learner is change the organization this internal state so that the capability for skill will be maximum in future attempts.

Another feature of motor learning is that it is relatively permanent; something lasting occurs when one engages in practice and learns some activity. On skill learning, this distinction is important because it rules out the changes that can come from a variety of temporary performance factors. For example, skills can appear to improve if the person is oriented in the right direction or motivation is temporarily high or a drug is administered to enhance the performance. Each of these changes in behavior will probably vanish when the temporary effect of the mood, for example, wears off. Thus, we should not attribute these changes to behavior to motor learning, because they are not sufficiently persistent.

We think of learning as having the goal of improving our behavior on a particular movement (e.g. slalom-skiing), but broader benefits of practice should also be recognized. One of these is the extent to which practice on one task contributes to the performance of another related skills (generalizability). Our capability to perform a task like skiing is not based on one particular sideways oscillation. Rather, we appear to be able to use a generalized array of intrinsic skiing movements by adhering to certain appropriate parameters that would enable one to maintain dynamic balance and improve the efficiency of the sideways movement. In this sense, we can measure the effectiveness of a practice session not only by how well the particular skills are acquired but also by how well other similar skills (that are not practiced) are acquired. This would involve measuring performance on other similar skills in a transfer or retention test. The acquisition condition producing the most effective performance in this transfer or retention test would be judged as having the highest generalizability (Schmidt & Wrisberg, 2004).

The conception of learning as a continuous process has been supported by statements in favor for the classical power law (Snoddy, 1926), which describes the evolution of performance as a power function of the duration of the number of trials practiced (Crossman, 1959). That motor learning is continuous was raised by Newell (1991), who portrayed the process of learning as discontinuous, nonlinear and marked by deep qualitative behavioral reorganizations. It was concluded that continuous descriptions of learning are mainly the reflection of methodological artifacts. The requirements regarding motor coordination were quite low and unlike what occurs in most real life situations possibly did not necessitate the acquisition of new patterns. A second argument concerned the short duration of most studies, which rarely went beyond the very first adaptation to the task and as such did not allow qualitative modifications of the behavior to appear. Third, performance was indexed in those experiments by errors or chronometrical measures, and such outcome indices are ill-suited to reveal possible alterations in the underlying processes during learning. Finally, the power law was supported by group learning curves, and the averaging process could be suspected to eliminate possible discontinuities at the individual level.

It has been shown that there is a qualitative difference between the behavior adopted by participants during the first trials of an experiment and the most skilled behavior adopted after some practice sessions (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). The novice behavior, which exploited a highly nonlinear stiffness function and a Rayleigh damping function, allowed participants to preserve a dwelling time close to the extrema of the oscillations to control the postural adjustments necessary to manage the motion reversals. Later in practice, the skilled behavior characterized by a 'van der Pol damping function' seemed necessary to produce simultaneously high frequencies and large amplitudes. These behaviors appeared to differ qualitatively, corresponding, respectively, to different limit cycle organizations, which provide useful insights concerning the causes underlying the adoption of a given behavior or the transition to another coordination mode.

Dynamical systems approach to skill acquisition

There have been several postulates on skill acquisition such as artefactual-machine perspective (Lintern & Kugler, 1991), Adams's (1971) closed-loop theory of motor learning and Schmidt's (1975) schema theory of discrete motor learning. However, the framework of dynamical systems theory applied to skill acquisition has recently demonstrated a promising perspective and lays the foundations of common functional principles that illustrate the interaction of the many independent *dof* or components that vary over space and time with the environment. Typically, dynamical systems are adaptive where constraints serve to form orderly and stable relationships among the many *dof* at different levels of the system. Various sub-systems in a dynamical network provide multiple examples of 'degeneracy'(Edelman, & Gally, 2001). The ability of elements that are structurally different to perform the same function or yield the same output. The process of co-adaptation has been used to explain how sophisticated biological systems evolve and adapt their behavior to satisfy long-term, evolutionary constraints (Kauffman, 1993). Relevant *dof* are driven by the coordination between the synergies, which also influence the macroscopic behavior of dynamic systems, i.e., circular causality (Kelso, 1995). A dynamical system has a fixed relation to nonlinearity.

According to dynamical systems theory, a slight perturbation in the present state (e.g. a moving platform) can evolve and lead to unpredictable states of the whole body coordination. However, in the long term, the randomness of the system is said to ascribe to a chaotic attractor once the system has reached a stable state (i.e. no more exchange of energy between the sub-systems). Some stable states exist within dynamical systems (metastability), where the constraints imposed on the system gives rise to its present state (Schöner, Zanone & Kelso, 1992). Thus, different functional movement patterns can achieve a performance goal under specific environmental circumstances (Seifert, Button, & Davids, 2013).

Coordination has been defined as the way in which the *dof* become constrained into temporary assemblages of muscle synergies (coordinative structures) so that only a few ‘free’ variables remain. ‘Control’ is the manipulation of these ‘free’ variables; whereas skill refers to the assignment of ‘optimal’ (on the task goal) values to the controlled variables (Kugler, Kelso & Turvey, 1980; Newell, 1991). The problem of skill acquisition is regarded as the problem of how both coordination and control of the body are achieved in providing solutions to a new movement problem. The ways in which patterns of coordination are acquired should, therefore, be of fundamental importance to the study of motor skill acquisition.

Skill acquisition was described as a search for the optimization of the coordination and control function of the variables specifying essential features of the skill (Fowler & Turvey, 1978). When a subject explores the perceptual-motor workspace, critical regions in the field are continuously created and annihilated. As this gives rise to a variety of information states, search strategies can be used by the subject to explore and locate attractor and gradient regions (specified by low energy requirements) of the dynamical properties of the perceptual-motor workspace. Some experiments have shown such exploratory behavior to be highly structured and effective rather than being completely random or trial and error (Newell, Kugler, van Emmerik & McDonald, 1989). As a general result of practice, the highly variable performance that characterizes the novice is seen to give way to performance that, on a macro-behavioral scale, can be remarkably stable.

Attempts have been made to describe or model the changes that take place during learning with varying degrees of success. Two problems are encountered. Firstly, most of the theories and models developed tend to task highly specific – cyclical, discrete, slow and fast movements. Secondly, the more complex a task becomes regarding *dof* involved in its performance, the greater usually the gap between observation and theory, or the less rigorous the link between experiment and theory. Elaborating further on the importance of meaningful and informative variables, it is proposed that the problem of changes during learning can be investigated by deriving low dimensional variables at the appropriate level of description. These variables capture the essential aspects of the high-dimensional *dof* involved in a particular action, and can be used to describe the changes observed over the practice period.

In the dynamical approach, it is stressed that the appropriate level of analysis should be the task comprising in the present case, both the apparatus and the performer. This implies three different kinds of low-dimensional variables that can be derived: variables that are couched in subject-related terms, in apparatus related terms, and regarding the interaction between the subject and the apparatus. When these following variables capture the fundamental relation between the performer and the apparatus they are characterized as collective variables that can differentiate between different coordinative modes. After these three kinds of low dimensional variables have been defined, they can subsequently be used as landmarks for other observables like limb configurations.

Degeneracy and the *dof* problem

The human movement system, by its multiple *dof* is characterized by a potentially large action repertoire and hence encompasses the ability to reach a goal (detailed in outcome terms) in many different ways (degeneracy). In defining coordination as the process of mastering numerous *dof* of the moving limbs and simultaneously converting it to a controllable system, Bernstein (1967) laid the foundations for a movement theory based on the reduction of functional *dof* that explicitly includes the acquisition of movement coordination. It was realized that attempts to provide a solution to a new movement problem require that the many initial *dof* available need to be constrained such that control over the movement system is regained. Only when the total number of the 'to be controlled' variables is greatly reduced, can a person reorganize the control of the movement apparatus in a way appropriate to the movement problem at hand. A severe reduction in the number of controlled *dof*, however, has an important disadvantage wherein the resulting organization loses some of the flexibility and adaptability that are the characteristic of generic human behavior. It is perhaps for this reason that Bernstein predicted that once the system is under control, part of the constrained *dof* will be released again and incorporated into the movement organization in order not only to enhance the motion possibilities but at the same time produce the efficiency and economy of the energy expenditure of the moving system.

Another feature of motor learning is the issue of redundancy. Redundant and non-redundant coordination tasks are typically defined regarding the spatiotemporal (kinematic) relation amongst the body segments. Typically, redundant coordination tasks comprise multiple number of potential coordination solutions that could be adopted to meet the demands of the task goal. On the other hand, non-redundant coordination tasks encompass specific patterns of coordination between two effectors for the ongoing task goal. As consequence, non-redundant tasks often involve two *dof*, and the coordination dynamics of the two effectors is primarily restricted to either in-phase or anti-phase patterns. Bimanual coordination investigations that have outlined non-redundant coordination tasks illustrated that the coordination pattern of the two index fingers switched from anti-phase ($\varphi_{rel} = 180°$) to in-phase ($\varphi_{rel} = 0°$) pattern as a function of an uniform increment of oscillation frequencies. Yet, the phenomena is not reversed if the two fingers are initiated to oscillate from an in-phase coordination pattern or even by uniformly decreasing the oscillation frequency of the two fingers (Haken et al., 1985; Kelso, Scholz, & Schöner, 1988). On the contrary redundant tasks typically involve multiple *dof* such as postural control, locomotion, reaching a target, pitching and so on where the task goal is not restricted to certain specific coordination patterns.

Several studies have been performed to assess the *dof* problem and redundancy in a moving support surface. A classic study examined the issue underlining the freezing and freeing of biomechanical *dof* (Vereijken et al., 1992). It was reported that in the early phases of learning, joint angles of lower limb and torso displayed little movement (low standard deviation of angular motion). Joint couplings were high (high correlation between angles). Over practice, angular movement increased, and cross-correlation decreased. Also, movement amplitude increased with trials while frequency initially decreased & later increased. Early in practice, the magnitude of cross-correlation ranged between moderate and high, indicating tighter couplings between joints were indeed formed to reduce the control problem. Joint control became increasingly independent.

Thus, regarding skill learning, there was an initial freezing of *dof* to constrain the excessive *dof* necessary to accomplish the task. Later on freeing or economic exploitation of passive forces (reactive, frictional and inertial) are realized to the fullest and enhance the efficiency of active muscular force. Thus, *dof* are incorporated as functional units leading to enhancement through exploitation.

Constraints of action

While investigating the issues of *dof* problem, one must acknowledge the underpinning constraints of an action. Traditionally, there are two different approaches: (a) holonomic and non-holonomic constraints (Pattee, 1977) and (b) ecological constraints (Kugler et al., 1980; Newell, 1985). Non-holonomic constraints require physical representations that prescribe their action (e.g. biological DNA, computer algorithms). The traditional approach in motor control (central representations, schemas, motor programs, central pattern generators) adopted such a stance. However, there are certain drawbacks in this approach, especially while adding the number of *dof* in a dynamic system and also the origin of these constraints is still rather ambiguous. In contrast, holonomic constraints have no physical representations/embodiment and thus reduce *dof* without consuming additional *dof* (e.g. conservation laws of physics). In this viewpoint, a full-fledged account of the constraints are taken into consideration. On the other hand, the ecological approach underpinning motor skill acquisition ascertain constraints related to the task, organism, and environment. Hence, one needs to choose the framework pertaining to the constraint of actions while studying human movement system and investigate the overall effect it has on the reduction/increment of the *dof*.

Local and global coordination in moving support surface (Relative Phase)

The question ‘what is controlled during movement execution’ has evoked dual research strategies in movement science. Ultimately, it is the performance itself, the achievement of the task goal that has to be controlled. Or, to paraphrase Bizzi what has to be controlled is the movement behavior at the interface with the environment (Bizzi, Hogan, Mussa-Ivaldi & Giszter, 1992). The majority of the arising multi-joint investigations have not exceeded beyond the complexity of a two-component system (Bernstein, 1967). One focus is to investigate multi-limb coordination on a moving support surface such as a skiing apparatus, moving platform, and tilted platform that will help us understand the mechanism of how *dof* are organized to meet the demands of the task. Past research has investigated the changes over time observed in the movements of the platform, the changing interaction between the apparatus and subject regarding the relative phase between the platform and the center of mass. It also described the learning changes on the subject regarding changes in body configuration and changes in position of the center of mass (Vereijken, van Emmerik, Bongaardt, Beek, & Newell, 1997). It was demonstrated that platform movement increased with practice, and there was increased regularity in its phase cycles. The relative phase movements of the center of mass and platform converged towards a comparatively stable nearly anti-phase relation. With practice it was noticed that there was more the center of mass sway, the phase cycles became more regular. Thus, it was shown that the complexity of whole body skill was mapped onto a low-dimensional description of coordinative structures and hence it was interpreted that this low dimensional subject related description would potentially be extended to model neurological models to include complex movement behavior. Based on this low dimensional coordinative structure the concept of collective variable and control parameter was introduced in motor behavior literature that would be discussed in the next section (Kelso, 1995).

Collective variable and control parameter

The core thesis of a dynamical approach in motor skill acquisition is that human behavior from neurons to mind is governed by the generic processes of self-organization (Kelso, 1995). Self-organization refers to the spontaneous formation of patterns and pattern change in open, non-equilibrium systems. These systems can interact with the environment, exchanging energy, matter or information with their surrounds; and non-equilibrium in the sense that without such sources they cannot maintain their structure or function. According to Bénard, there is no reference state with which feedback can be compared and no place where the comparison operations are performed. Hence, non-equilibrium steady states emerge from non-linear interactions among the system's components, but there is no feedback-regulated set point or reference values as in a thermostat. This phase transition from one state to another state in a critical period where the system abruptly flips, i.e. order-disorder-order is an intriguing phenomenon in human behavior, which results in emerging pattern enslaving the cooperation and competition of collective variable constrained by the control parameter (Kelso, 1995).

The control parameter does not prescribe or contain the code for the emerging pattern. It simply channelizes the system through the variety of possible states or patterns (e.g. temperature gradient, frequency). Parameters that lead the system to different patterns, but typically are not dependent on the patterns themselves, are called control parameters. Such control parameters may be quite unspecific in nature, i.e. in no sense do they act as code or a prescription for the emerging patterns. Instabilities are created by control parameters that move the system through its collective states. You do not know you have a control parameter unless its variation causes qualitative change, which is necessary to identify collective variables (Kelso, 1984).

On the other hand, collective variables (order parameters) have origins in Mathematics (Linear stability analysis). Relevant *dof* characterizing emerging patterns in complex systems are called collective variables. In synergetics, the collective variable is created by the cooperation of the individual parts of the system. Conversely, it governs or constrains the behavior of the individual parts (circular causality). Collective variables are found near non-equilibrium phase transitions, where loss of stability gives rise to new or different patterns or switching between patterns. They may exist far from transitions as well, but it is difficult to identify them. In any situation, the individual will assemble a behavioral response that is the collective pattern of the current status of the ensemble- a preferred pattern that involves the cooperative interactions of all the components within particular situation. This cooperativity, the reduction in the dimensionality of the original components to a compact pattern can be captured in one or a few collective variables, i.e. variables that describe the collective variable of the ensemble.

According to the slaving principle of synergetics (Haken et al., 1985) selection mechanism from random initial conditions a specific motion is preferred. It is this coherent pattern that is described by the control variable, and it is the control variable dynamics that characterizes how patterns form and evolve in time. For example, for a given temperature gradient (control parameter), there would be several vibratory modes, which would eventually damp out. Hence, the mode or pattern with the biggest rate of increase will dominate. Firstly, this introduces the concept of synergy where individual variables are organized into larger groupings called linkages or synergies. During a movement, the internal *dof* are not controlled directly but are constrained to relate among them in a relatively fixed and autonomous fashion. Secondly, it is hypothesized to be a function or task-specific. For Bernstein (1967), the reflex did not contribute to the solution of the coordination problem. Instead, it was part of the problem. His hypothesis was not about hard-wired anatomical units; rather synergies were proposed to be functional units, flexible, and temporarily assembled in a task-specific fashion. Assimilating all these ideas, one can investigate the role of synergies that result in the formation of collective variables that emerges as a function of the control parameter.

In the non-redundant bimanual task, the relative phase of the motion of two index fingers has been identified to be the collective variable of the bimanual oscillation system whereas the oscillation frequency has been defined as the control parameter leading the system switch from the anti-phase to in-phase coupling (Haken et al., 1985). In suprapostural activities it was proposed that the ankle-hip coordination pattern is the collective variable describing the organization of the postural control system and the control parameter originated from multiple resources such as the oscillation frequency, amplitude of the tracking target, the height of the center of mass, the length of the foot and the surface of support (soft, firm, rolling) (Bardy et al., 2002). The phase relation discrepancy was due to the substantial differences of the mechanical properties of the upper and lower body such as the length, mass, moment of inertia and eigenfrequency of the trunk and lower extremity. It was concluded that the ankle and hip joint motion displayed an in-phase coordination pattern and coordination dynamics in the joint space level are not limited to pure 0° and 180° coupling.

In a study on the bi-pedalo task, it was suggested that there was a reduction in the number of collective variables (patterns of coordination) with practice (Haken, 1996), thereby implicating that modulation of the global dynamics results in restrictions to the changes occurring at the local level intra- and inter-limb dynamics. In a similar framework, the effect of practice on a skiing task showed that the principal components shifted their relative contributions but did not change the number of principal components (Hong & Newell, 2006a). It also highlighted the recruitment and suppression of the mechanical *dof* as a function of practice that were done within the same number of dynamical *dof* where more than a single mode of coordination was required to capture the richness of the collective behavior of all the available limb segments performing the task.

CHAPTER 3: MAINTENANCE OF POSTURAL STABILITY AS A FUNCTION OF TILTED BASE OF SUPPORT

Abstract

The experiment was set-up to investigate the mechanisms of postural control by manipulating the base of support angle, using tilted platform wedges. The primary focus was to analyze the coupling of the motion of the center of mass (CoM) and the center of pressure (CoP), and the motions of the leg joints considered as individual components and synergies. The CoM-CoP coupling (both mediolateral and anteroposterior) was preserved (~0°) across all tilted platform angles (35°, 30º, 20º, 10º Down, 0° Flat and 10º, 20°, 25° Up), reflecting an in-phase pattern. There was high coherence (~1) for CoM-CoP in the lower frequency range, whereas contrarily the hip, knee and ankle pair-wise couplings had values ranging between (0.4 to 0.7) across the different platform angle conditions. These findings are consistent with the view that the local pair-wise coupled variables of Hip, Knee and Ankle motions adaptively self-organized to preserve the CoM-CoP coupling at equilibrium over the baseline (0° Flat) platform condition and all other tilted platform angles. The findings support the hypothesis of CoM-CoP coupling acting as a collective variable that reflects the structural integrity of the system for quiet upright standing across the platform angle conditions.

Introduction

Stabilization of quiet upright posture involves multiple joints and muscles and reflects a continuous self-organized coordination process (Aruin, 2002; Hsu, Scholz, Schöner, Jeka, & Kiemel, 2007; Massion, 1992; Wang et al., 2014). The nature by which the large number of *dof* (*dof)* are organized in posture is of prime importance in motor control, both theoretically and experimentally (Bernstein, 1967; Horak, Shupert, & Mirka, 1989; Kelso, 1995; Winter, 1995). Several studies have investigated the role of the stabilization of the center of mass (CoM) to maintain postural equilibrium in upright stance (e.g. Corriveau, Hébert, Raîche, Dubois, & Prince, 2004; Peterka, 2002). It is recognized that upright posture is compromised when the projection of the line of gravity of the postural system falls outside the base of support; that is only a certain range of CoM spatial positions are feasible for the maintenance of balance (Winter, 1995). However, the stabilization of the CoM could be a consequence of the control of other variables, meaning its spatial position may not be directly controlled (Hsu et al., 2007).

Joint orientation, in particular of the lower limb, are relevant for the control of upright posture (Krishnamoorthy, Yang, & Scholz, 2005; Scholz, Schöner, Hsu, Jeka, Horak & Martin, 2007). Past studies have also investigated the synergies of body effectors that afford quiet standing stabilization (Massion, 1994; Nashner & McCollum, 1985). A long-standing hypothesis holds that the stabilization problem is addressed by active control of the ankle joint in combination with passive musculoskeletal properties that regulate the body as an inverted pendulum in quiet standing (Winter, 1995). Based on this ankle strategy, the position of the head, CoM and joints in space are inter-related, which would simplify the integration of sensory information from multiple sources. This postural control model has been the framework for many studies of balance and posture (Aramaki, Nozaki, Masani, Sato, Nakazawa & Yano, 2001; Horak, Dimitrova, & Nutt, 2005; Jeka, Oie, Schoner, Dijkstra, & Henson, 1998; Peterka, 2002).

A contrasting hypothesis holds that the inverted pendulum is an overly simplistic model for postural control, given that ankle, knee and hip joints are coordinated as different 'eigen modes', although there are independent combinations of all three joints as revealed by principal component analysis (Alexandrov, Frolov, Horak, Carlson-Kuhta, & Park, 2005). Ankle 'eigenmodes' predominantly involve ankle motion, yet knee and hip motion also make important contributions to the control of the upright stance, which reflects the importance of the distinction between mechanical and functional *dof* (Li, 2006; Newell & Vaillancourt, 2001). Similarly, head fixed patterns (Buchanan & Horak, 1999), buckled pendulum and ankle-knee-hip mode (Ko, Challis, & Newell, 2001) describe other postural coordination modes that emerge under different conditions. Collectively, these studies have revealed qualitative changes in the coordination of the joint space *dof* s by perturbing and manipulating the postural system of quiet stance.

Wang et al., (2014) investigated the coordination and control of *dof* s in quiet human standing, primarily identifying the changing time scale properties of the candidate collective variable (CoM-CoP) and component and synergy variables (hip, knee, ankle), as a function of different stances and postural sways. The stabilization of postural equilibrium with its multiple joint *dof* affords a distinction, unavailable with a bivariate bimanual coordination set-up, between the postulated collective variable and the neuromuscular synergies. It was shown that CoM-CoP had a high coherence (~1) for frequency < 1Hz whereas ankle, hip, and knee had a mid-range coherence (~.5) with tasks involving different ankle/hip compensatory cophase patterns. Similarly, two modes of coupling between variations of leg and trunk segment angles were revealed during quiet stance using spectral coherence and cophase analysis (Creath, Kiemel, Horak, Peterka, & Jeka, 2005).

The effect of floor slope on standing posture along the sagittal plane has revealed significant influences on lower back moment, knee and ankle angles across floor slope (Reiser & Dalton, 2005). Past studies have shown that the trunk and pelvis remain aligned on the earth's vertical axis at any surface inclination, and that postural adaptations are task-specific (Leroux, Fung, & Barbeau, 2002). Overall, the limited research on floor slope reveals that postural instability emerges due to the inability to maintain trunk orientation to vertical while standing on an inclined base of support.

Here we investigated whether the motions of the lower limb joint angles are differentially modulated to maintain the low dimensional variable (CoM-CoP coupling) that captures the structural integrity of the collective organization of the system behavior across the tilted platform conditions. We investigated how the postural system regulates the joint *dof*s under different surface angles of a tilted platform as a function of whether the participant faced up or down the slope. The time scales of the change in the motions of the individual joints (ankle, knee, hip), pair-wise synergies and candidate collective variables (CoM and CoP) were determined and contrasted as a function of platform angles.

We examined the hypotheses that: 1) CoM-CoP coupling would be in-phase in both mediolateral (ML) and anterio-posterior (AP) planes and would be conserved across all platform angles given the maintenance of balance; and 2) that the cophase and coherence measures for the individual joint and synergies would show intermediate values between in-phase (~0º) and anti-phase (~ ±180º) modes. Support for these hypotheses would reflect the self-organizing properties of the biological system to preserve the task demand of upright postural equilibrium across all platform angle conditions through differential modulation of the collective variable and local joint synergies of postural control.

Methods

Participants

Fifteen healthy male participants were recruited, according to an experimental protocol approved by the Pennsylvania State University Institutional Review Board. Their heights ranged from 163 cm to 182 cm (mean = 171.3 cm) and the masses ranged from 55 kg to 89 kg (mean = 71 kg). All participants self-reported no apparent neurological disorders and musculoskeletal injuries that could influence postural control.

Apparatus

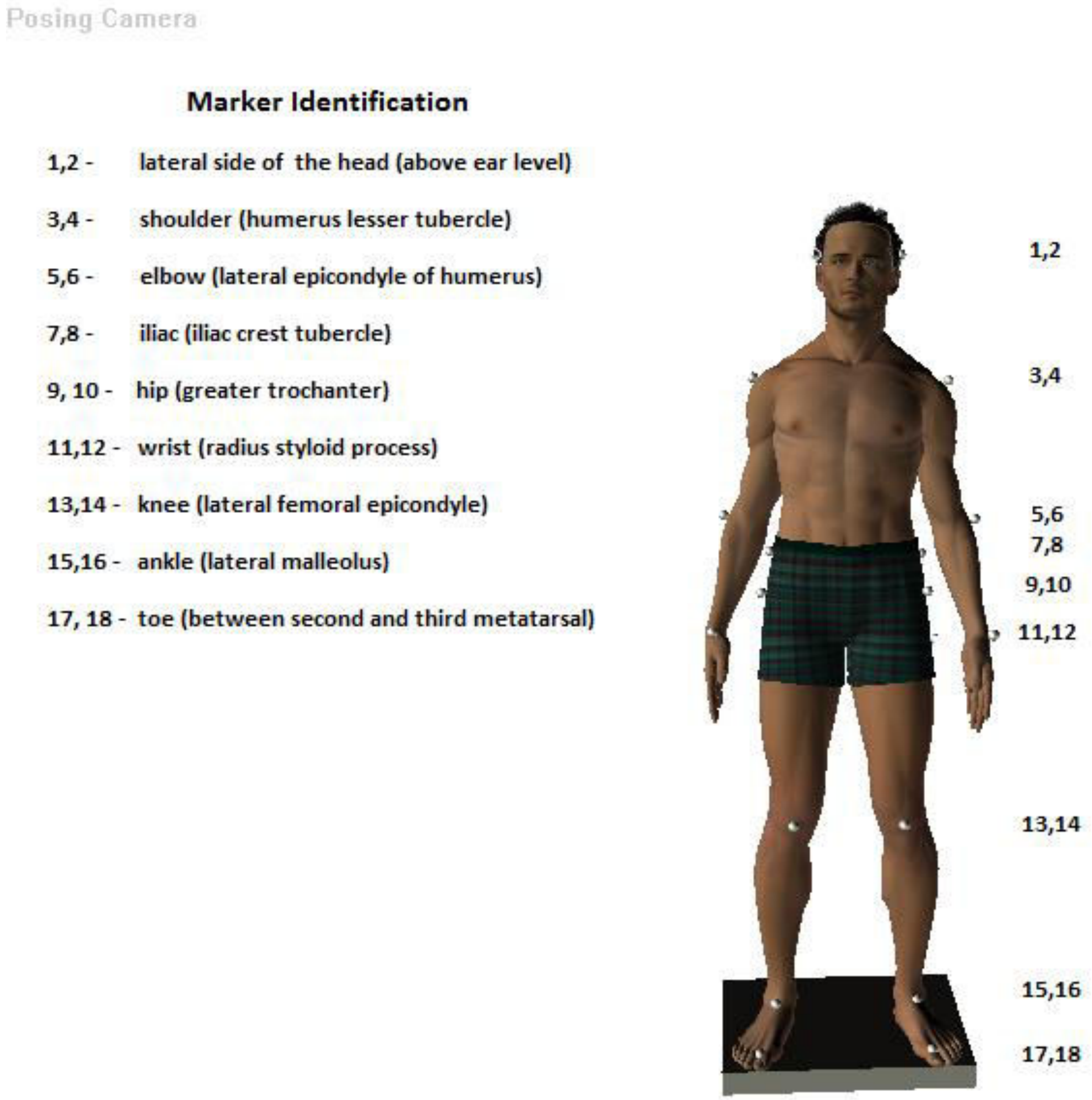
A 3-D motion analysis system (QTM, Sweden) was used to record the motion of passive markers attached over the anatomical joints of the experimental participants. A 13-segment model was reconstructed from an 18-marker system (Winter, 2009). A force platform (AMTI, OR 6-5-1000) was used to derive the displacement of the body's center of pressure (CoP), where pre-fabricated wooden platform wedges of different angles (25°, 20°, 10º Up, 0°Flat, 10º, 20°, 30°, 35°Down) were mounted on the force platform. The base of support of the platform wedges was covered with commercial sand paper of grain size 100 to standardize the coefficient of friction across all platform angle conditions. The motion analysis system and the force platform data capture were synchronized with the aid of an external trigger. Both systems used a 100 Hz sampling frequency. The recorded data were later filtered by a low-pass second order Butterworth filter with a cut-off frequency of 5 Hz.

Procedures

The participants were instructed to maintain their upright postural balance when they stood on the force platform with bare feet, eyes open and focused on a visual target placed 2 m away from the platform at the eye level. The participants placed their feet side-by-side (see Figure 3.1). The total duration of the trials for each platform condition was 45 s. The initial 5 s of data from a trial were removed so that any artifacts arising from adaptation and initial discomfort were removed from data analysis. The platform angles were assigned randomly, with the baseline (0° flat) as the first trial. For each platform condition subjects performed 2 trials, with 1 min of recovery between successive trials and 4 min between each platform condition.

Data Analysis

Kinetic and kinematic variables: The local variables consisted of hip, knee, and ankle relative angular joint motions that were defined based on passive markers that were attached to anatomical landmarks (see Figure 3.1).



Marker Identification

1,2 -	lateral side of the head (above ear level)
3,4 -	shoulder (humerus lesser tubercle)
5,6 -	elbow (lateral epicondyle of humerus)
7,8 -	iliac (iliac crest tubercle)
9, 10 -	hip (greater trochanter)
11,12 -	wrist (radius styloid process)
13,14 -	knee (lateral femoral epicondyle)
15,16 -	ankle (lateral malleolus)
17, 18 -	toe (between second and third metatarsal)

Figure 3.1. Marker model for the experimental setup (1-18).

The CoM was calculated from the 13 segment model according to the anthropometric data of Dempster (1955). Applying the weighting factors of the segmental masses, the whole body CoM position was estimated by the weighted summation of the individual segment CoM positions (Winter, 2009). Three force components (*Fx*, *Fy*, and *Fz*) and three moment components (*Mx*, *My*, and *Mz*) were simultaneously measured by the force platform. With these measures, the center of pressure (CoP) in both AP and ML plane was obtained (Winter, 2009).

Cophase: The global variable of CoM-CoP coupling was considered as a candidate for the collective variable of the whole body system. The component (local) coupled variables of ankle, knee and hip angular motions were also investigated by applying the cophase technique (Creath et al., 2005). To characterize the lead-lag relationship of the frequency components of two ascribing signals, cophase analysis was applied to compare the nature of the signals. Typically, 0º implies that the signals are coupled in-phase, whereas anti-phase mode would be reflected by +180° (signal *a* leads signal *b*) or -180° (signal *b* leads signal *a*).

$$Cophase(f) = atan2d[-imag(S_{ab}(f), real(S_{ab}(f))] \qquad (1)$$

where $S_{ab}(f)$ is the cross power spectral density of the two time-series (Bloomfield, 2004).

Coherence: The collective and component variables were also analyzed using the Chronux toolbox (Mitra & Bokil, 2008). Coherence measures the correlation of two signals in the frequency domain where multi-taper spectral tool reduces the spectrum estimation bias by obtaining multiple independent estimates from the time-series that is dependent on the sampling frequency and time-series bandwidth (Thompson, 1982). Typically, values range between 1 (perfect linear prediction between variables) to 0 (variables are linearly independent).

$$Coherence(f)^2 = \frac{|(S_{ab}(f)|^2}{S_a(f).S_b(f)} \qquad (2)$$

where $S_a(f)$ and $S_b(f)$ are the power spectral densities of signal *a* and *b,* respectively. An initial assessment to determine the frequency power of the dependent variables was carried out by running a FFT. It was found that signal power was constrained to <1 Hz for all analyzed signals which was consistent with earlier findings (Creath et al., 2005). We then examined the lowest frequency resolution of the data (0.0286 Hz) that gave us a basis to divide the data into 9 equal bins between 0 and 1 Hz. Circular statistics were used to calculate the mean, standard deviation and coefficient of variation of coherence across the 9 sequential bins (Mardia, 1975). *Statistics:* One way ANOVAs (8 levels) were run on the baseline platform condition (0° flat) and the 7 platform angle conditions. We employed the Watson-Williams test for main effect analysis and the Tukey post hoc test to determine the differences on all paired levels for the dependent variables.

Results

A representative participant's CoM and CoP motion (ML and AP) as a function platform angles (0º baseline flat, 35° extreme down and 25° extreme up) is shown in Figure 3.2.

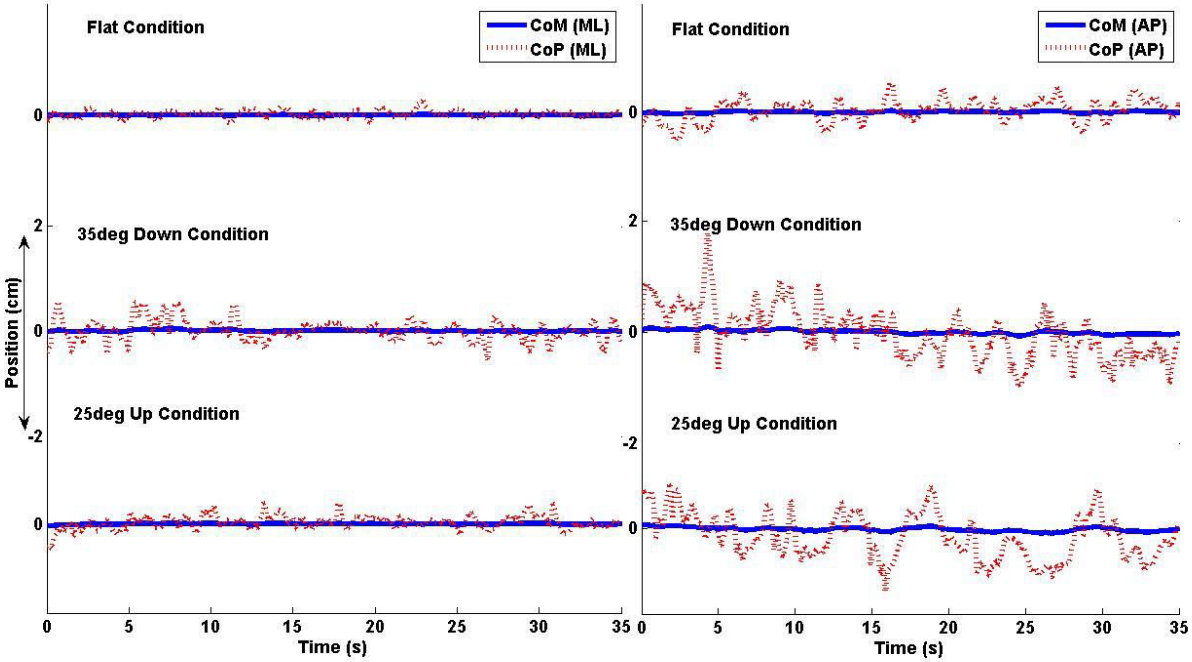


Figure 3.2. Representative single trial CoM and CoP motion along the ML and AP directions as a function of platform tilt.

As hypothesized the CoM motion was preserved in both ML and AP directions and across all tilted platform conditions, including the extreme platform angles (35° Down and 25° Up). In contrast, the CoP motion oscillates around the CoM motion and tended to oscillate with a greater non-periodic amplitude as a function of increasing platform angle. The amplitude of CoP motion is more prevalent in AP direction than ML (see Figure 3.3).

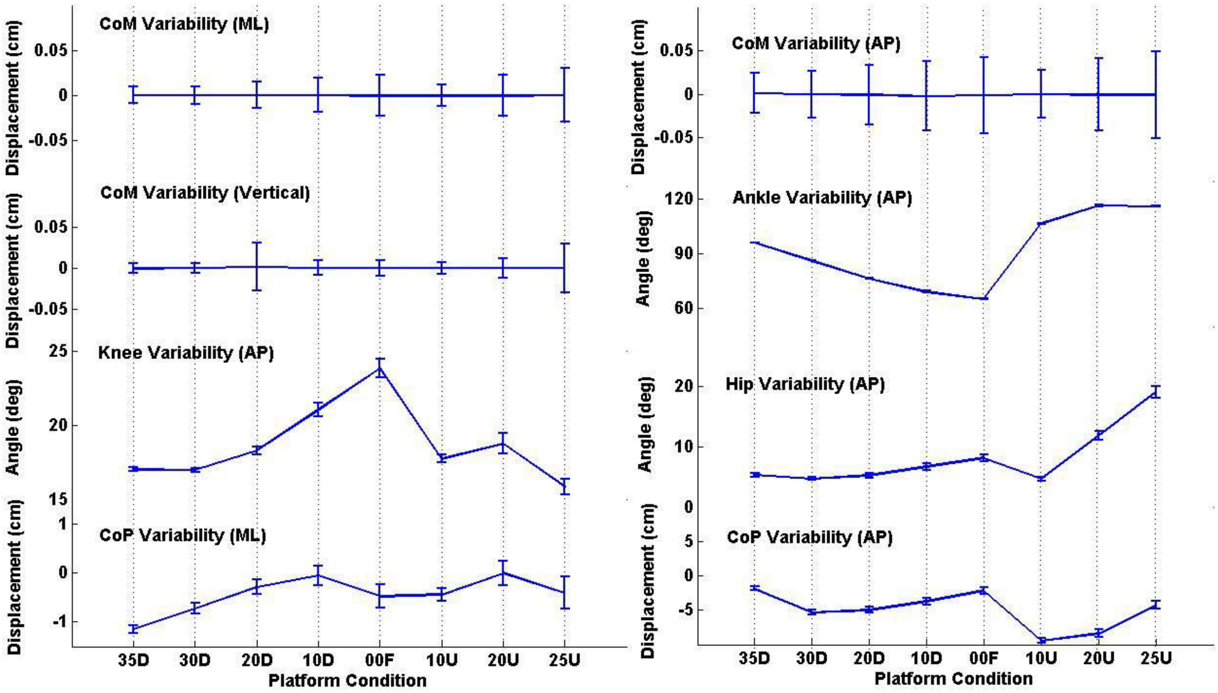


Figure 3.3. The Mean and SD of CoM, CoP displacement and Ankle, Knee, Hip Angular displacement as a function different platform conditions across all subjects.

Table 3.1 shows the variability of CoM, CoP displacement and joint angle as a function of tilted platform conditions across all subjects. The Watson-Williams test did not reveal any main effect for tilted platform conditions for the CoM or CoP. However, the joint angles differed significantly as a function of tilted platform conditions. Knee variability was highest, whereas ankle variability was low (restrictive) in the flat condition. Graphical interpretation of Table 3.1 (see Figure 3.3) suggests that at extreme tilted platform conditions, i.e. at 35°Down and

25ºUp, Knee variability shifts from lower to higher and Ankle variability shifts from higher to lower as they approach the baseline platform condition of 0º Flat.

Table 3.1. Mean and SD Cophase values of CoM, CoP displacement and joint angles as a function different platform conditions.

Variables	35° Down	30° Down	20° Down	10° Down	0° Flat	10° Up	20° Up	25° Up
CoM (ML)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
CoM (AP)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
CoM (Z)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
CoP (ML)	-1.2 ± 0.1	-0.7 ± 0.1	-0.3 ± 0.2	-0.1 ± 0.2	-0.5 ± 0.2	-0.4 ± 0.1	-0.0 ± 0.3	-0.4 ± 0.3
CoP (AP)	-1.9 ± 0.3	-5.3 ± 0.3	-5.0 ± 0.4	-3.7 ± 0.5	-2.2 ± 0.5	-9.5 ± 0.4	-8.4 ± 0.5	-4.3 ± 0.6
Ankle	96.0 ± 0.1	86.2 ± 0.2	76.3 ± 0.2	69.0 ± 0.4	65.0 ± 0.5	106.5 ± 0.2	116.5 ± 0.5	115.9 ± 0.4
Knee	17.0 ± 0.1	17.0 ± 0.1	18.3 ± 0.3	21.0 ± 0.5	23.8 ± 0.6	17.7 ± 0.3	18.7 ± 0.7	15.8 ± 0.5
Hip	5.3 ± 0.3	4.7 ± 0.3	5.2 ± 0.4	6.7 ± 0.4	8.2 ± 0.6	4.7 ± 0.4	11.9 ± 0.7	19.1 ± 1.0

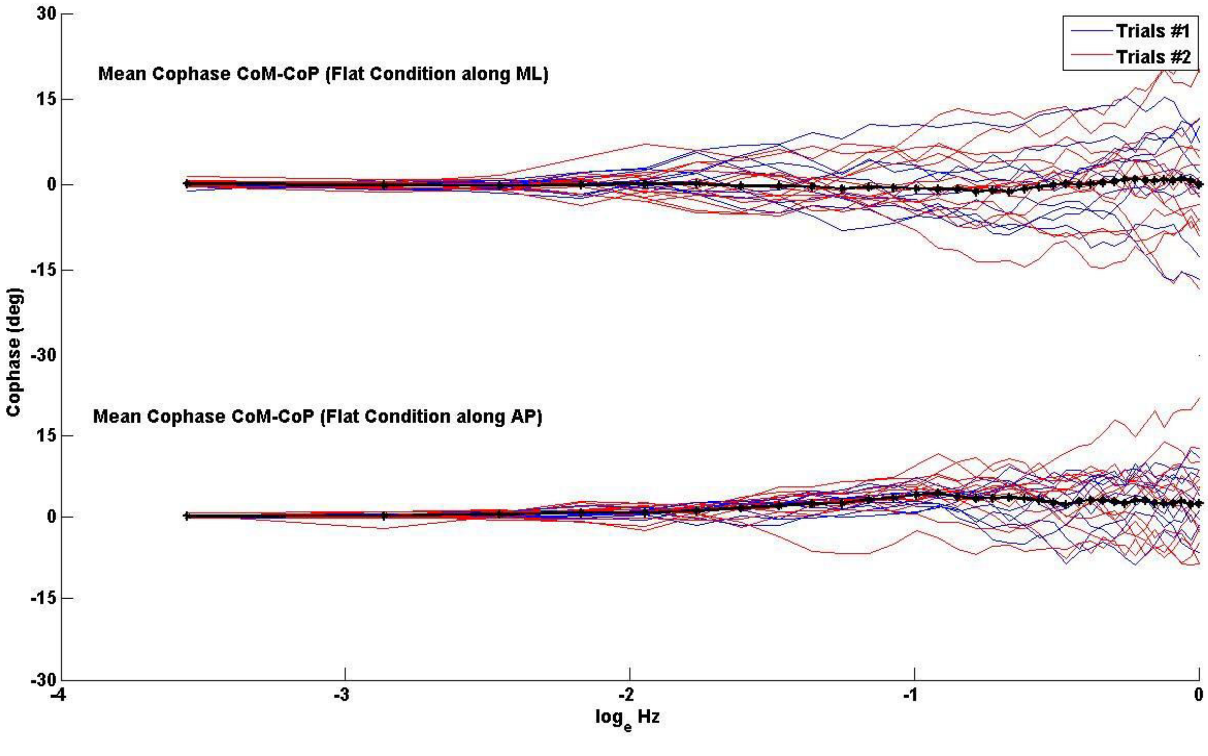


Figure 3.4. Mean CoM-CoP cophase with individual trials along ML and AP direction.

Figure 3.4 illustrates the CoM-CoP cophase of all the trials in the flat condition plotted along with the mean for CoM-CoP along ML and AP direction, respectively. Typically, the CoM-CoP signals are synchronized and have values close to 0° degree, which primarily shows that the coupled variables are in-phase.

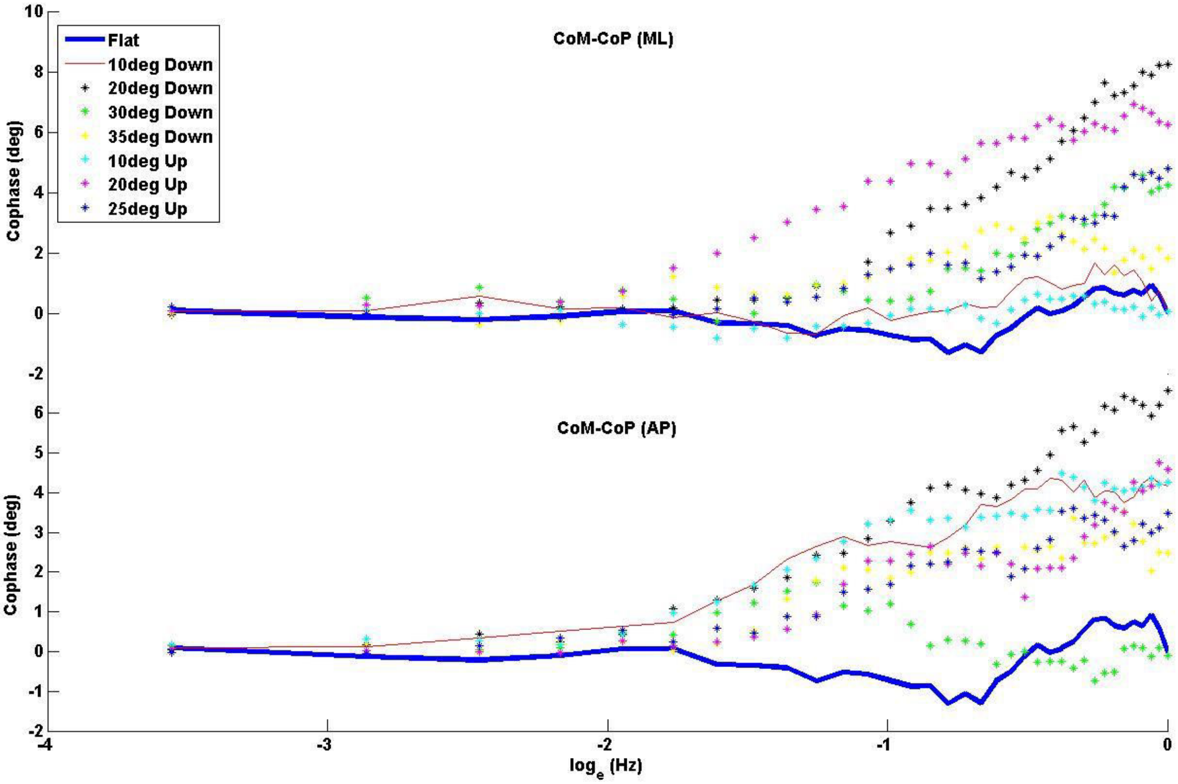


Figure 3.5. Mean cophase for CoM-CoP (ML and AP) for the tilted platform conditions.

Figure 3.5 illustrates the CoM-CoP coupling (both ML and AP) as a function of the 8 platform angle conditions. There is a gradual shift in the CoM-CoP coupling from 0º to 10º as a function of the higher natural logarithmic frequency components. This primarily reflects that CoM-CoP coupling is strongest in the flat condition and is gradually weakened as the platform is tilted to higher angles. Also, the range is smaller in the AP direction compared with the ML, which reflects that motion along the ML axis has larger variability in quiet standing.

A one-way ANOVA found that the main effect of CoM-CoP (ML) coupling was significant, *F*(7,280) = 37.87 (*p* <0.001) across all tilted platform conditions. Post hoc Tukey pairwise comparisons showed that the platform condition 20ºUp-20ºDown and 25ºUp-30ºDown cophase values were not significant with a 95% confidence interval. The CoM-CoP (AP) coupling was significant, *F*(7,280) = 18.90 (*p* <0.001). A posthoc Tukey pairwise comparison showed that the 10dºUp-10ºDown, 20°Up-25ºUp-35ºDown were not significantly different with a 95% confidence interval.

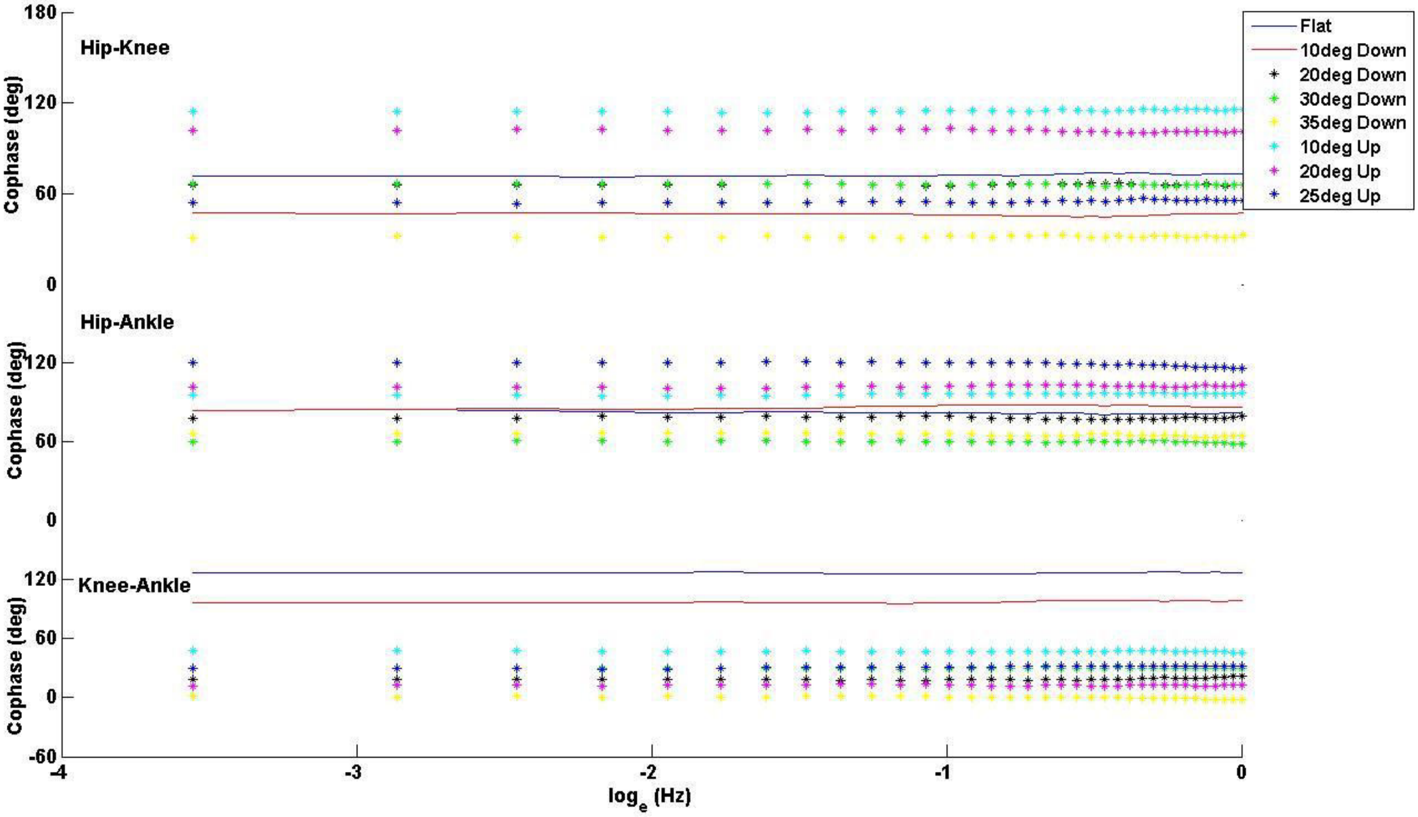


Figure 3.6. Mean cophase for Hip-Knee, Hip-Ankle and Knee-Ankle as a function of platform conditions.

Figure 3.6 depicts the cophase analysis of the angular coupled variables for the Hip, Knee, and Ankle. At baseline (0º Flat) Hip-Ankle coupling is ~90°. However, the coupling relations diverge as a function of platform inclination. For upward platform angle conditions (10°, 20° and 25º) the co-phase modes shift towards 120°, which reflects that the Hip-Ankle coupling gets weaker when standing at platform angles facing up. Contrarily, the Hip-Ankle coupling gets stronger and approaches ~60° when standing at platform angles facing downward. For Hip-Knee coupling the cophase gradually shifts from ~70º to ~15° at 35º Down platform condition, whereas the Hip-Ankle coupling is initially scaled up ~ 120° (across 10º, 20º Up) and then is scaled down to ~55° for 25º upward platform angle condition. This shows that the lower limb synergies and particularly Hip-Knee are tightly coupled at extreme upward conditions.

Knee-Ankle coupling shifted from a ~130º anti-phase mode at flat baseline condition to a more ~0º in-phase mode for the 35º Down tilted platform condition. On the other hand, it is evident that for the 25° Up platform condition, the cophase is closer to ~40º, which reflects that the task constraints require Knee-Ankle to be strongly coupled for that platform condition. For local couplings, again a one-way ANOVA revealed that the main effect of Hip-Ankle coupling was significant, $F(7,280) = 13697.49$ ($p < 0.001$) across all tilted platform conditions. Post hoc Tukey pairwise comparisons showed that cophase values across all tilted platform conditions differed significantly ($p < 0.05$). Hip-Knee coupling was significant, $F(7,280) = 56763.98$ ($p < 0.001$) across all tilted platform conditions. Tukey analysis revealed that 20ºDown-30ºDown was not significant with 95% confidence interval. On Knee-Ankle coupling, cophase values were significant, $F(7,280) = 106704.49$ ($p < 0.001$) across all tilted platform conditions with posthoc analysis revealing that cophase values for Knee-Ankle coupling across all tilted platform conditions differed significantly ($p < 0.05$).

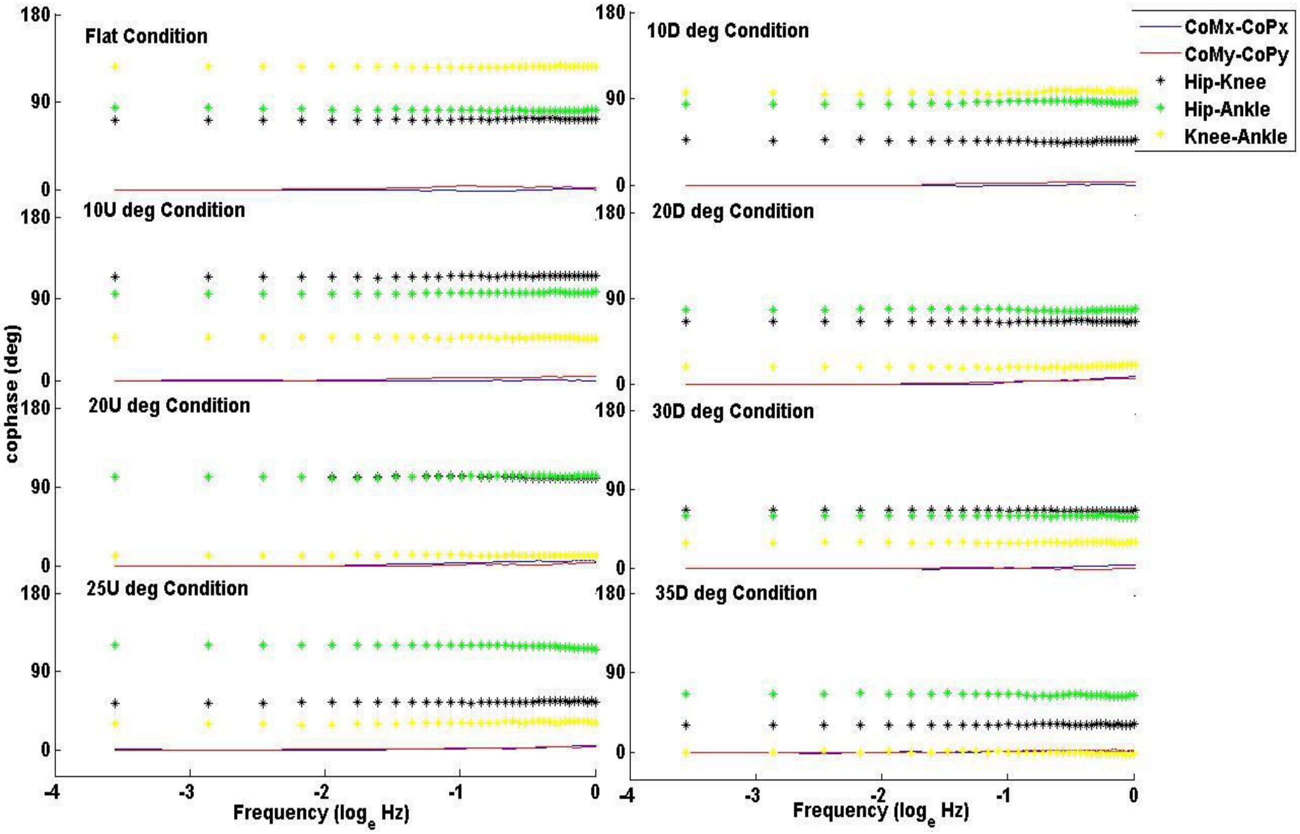


Figure 3.7. Mean cophase for CoM-CoP (AP and ML), Hip-Knee, Hip-Ankle and Knee-Ankle across all platform conditions.

Figure 3.7 shows the cophase for the dependent variables (CoM, CoP, Hip, Knee and Ankle) across all the tilted platform angle conditions. As expected (Creath et al., 2005; Wang et al., 2014), the CoM-CoP coupling for both AP and ML direction is in-phase across all platform conditions. At baseline (0º Flat), the Hip-Knee is at ~90° and approaches ~70 at 25° Up condition. On the other hand, the downwards platform condition (10º, 20°, 30º) has cophase values ~50° which shows that the downwards direction has Hip-Knee coupling that is relatively stronger at 35º downward platform angle and has a value ~30° and hence closer to an in-phase mode.

At baseline (0º flat), the Hip-Ankle coupling is ~80º. The coupling is relatively weaker ~120° as it approaches extreme upward platform conditions (25º Up). For downward conditions, the Hip-Ankle synergy gets stronger ~60° as the platform angle approaches (~35º Down). Knee-Ankle coupling is weakly coupled at baseline condition with 126° (cophase values closer to 180º), but approaches ~30º for 25ºupward condition and oscillates at ~0° (in-phase) at 35º Down condition.

One-way ANOVAs were conducted that revealed that the cophase coupling indexes for the CoM-CoP (AP and ML), Hip-Ankle, Hip-Knee and Knee-Ankle were significant at 0.005 level for all platform conditions. For Flat condition, $F(4,175) = 155223.41$ ($p < 0.001$), at 10degDown, $F(4,175) = 59744.97$ ($p < 0.001$), at 20degDown, $F(4,175) = 14653.23$ ($p < 0.001$), at 30degDown, $F(4,175) = 485.987$ ($p < 0.001$), at 35degDown, $F(4,175) = 31482.8$ ($p < 0.001$), at 10degUp, $F(4,175) = 143322.79$ ($p < 0.001$), at 20degUp, $F(4,175) = 55579.9$ ($p < 0.001$) and at 25degUp, $F(4,175) = 53956.94$ ($p < 0.001$). Tukey post hoc comparisons showed that all the 5 cophase variables differed significantly across the 8 platform conditions at ($p < 0.05$), baring the exceptions among CoM-CoP(AP) and CoM-CoP(ML) at 10ºDown & 25ºUp and lastly among Hip-Ankle and Hip-Knee at 20ºUp.

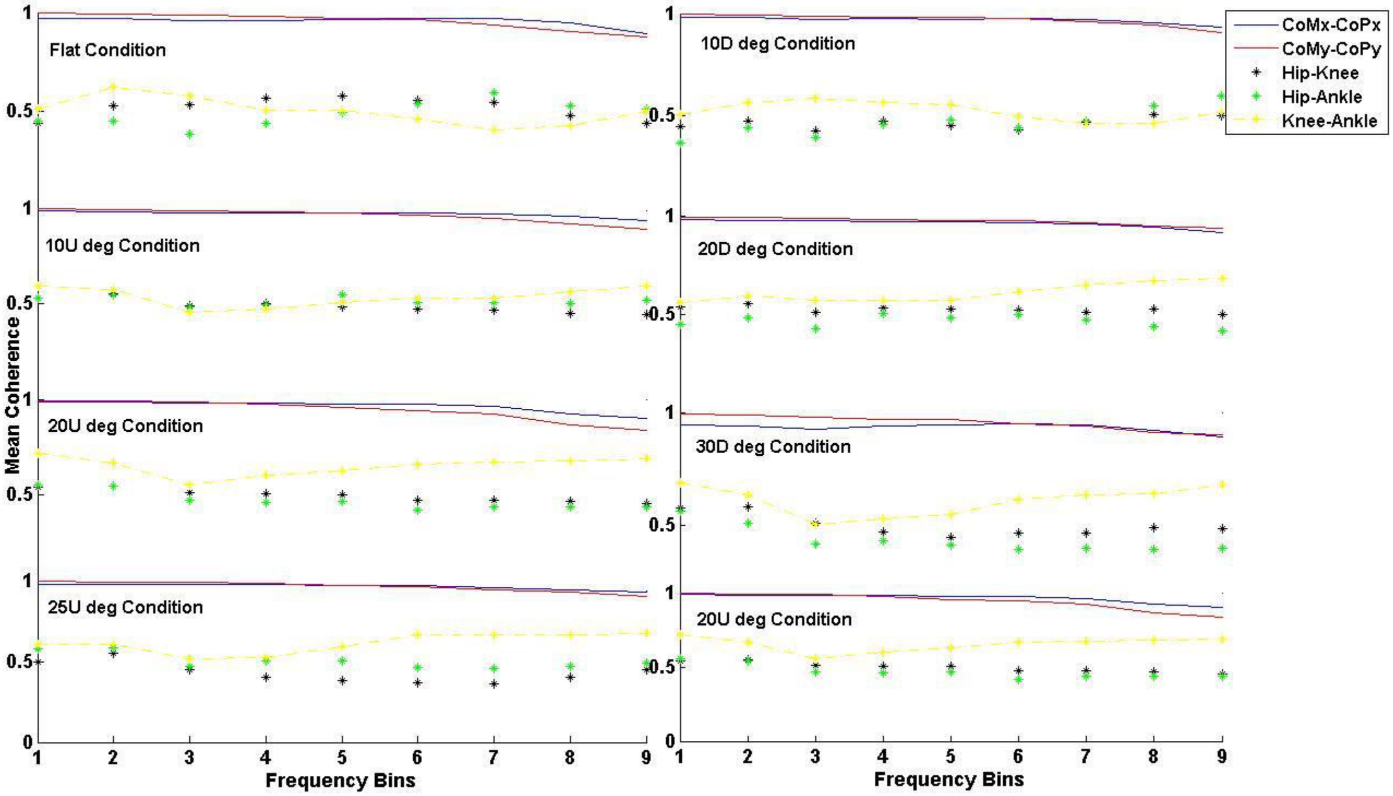


Figure 3.8. Mean coherence for CoM-CoP (AP and ML), Hip-Knee, Hip-Ankle and Knee-Ankle across all platform conditions.

Figure 3.8 depicts the coherence analysis for the dependent variables (CoM, CoP, Hip, Knee and Ankle) across all the tilted platform angle conditions. The CoM-CoP signals appear phase locked with values ~1, which reflects that the CoM-CoP coupling for both AP and ML maintain congruity across all platform conditions. Complementing the results of cophase, the local joint coordination of Hip-Knee, Hip-Ankle and Knee-Ankle have values ranging from 0.4 to 0.7. Typically, the Knee-Ankle, Hip-Knee and Hip-Ankle coherence gets stronger when compared with the baseline (0º platform condition) to extreme platform conditions (25° Up or 35º Down).

One-way ANOVAs were conducted to investigate the coherence coefficient of variation to show the extent to which the two variables are correlated in the frequency domain and revealed that CoM-CoP (AP and ML), Hip-Ankle, Hip-Knee and Knee-Ankle were significant at 0.005 level for all platform conditions. For the Flat condition, $F(4,40) = 55.12$, at 10ºDown, $F(4,40) = 75.52$, at 20ºDown, $F(4,40) = 77.60$, at 30°Down, $F(4,40) = 49.77$, at 35ºDown, $F(4,40) = 62.52$, at 10ºUp, $F(4,40) = 60.37$, at 20°Up, $F(4,40) = 63.37$ and at 25°Up, $F(4,40) = 96.8$. Post-hoc Tukey comparisons showed that the CoM-CoP differed from the joint angle coherence for the 0º Flat and the 10ºUp condition, the former had values closer to 1 and the later had values closer to 0.5. For the remaining platform conditions, the coupled variables of Hip-Knee, Hip-Ankle, Knee-Ankle and CoM-CoP differed significantly at $p < 0.05$.

Figure 3.9 and Table 3.2 illustrate the individual and cumulative cophase joint angles across all platform conditions. Although CoM-CoP coupling is conserved in an in-phase mode (~0º) and postural stability is sustained through the co-activation of the lower limb couplings (Hip-Knee-Ankle) across all platform conditions, it is shown that the cumulative cophase joint angles have a definite structure as a function of constrained inclined base of support. For 0º Flat condition, the cumulative joint angle is highest (280º) and illustrates reduced angles at extreme conditions of 35ºDown (97°) and 25°Up (206º) respectively.

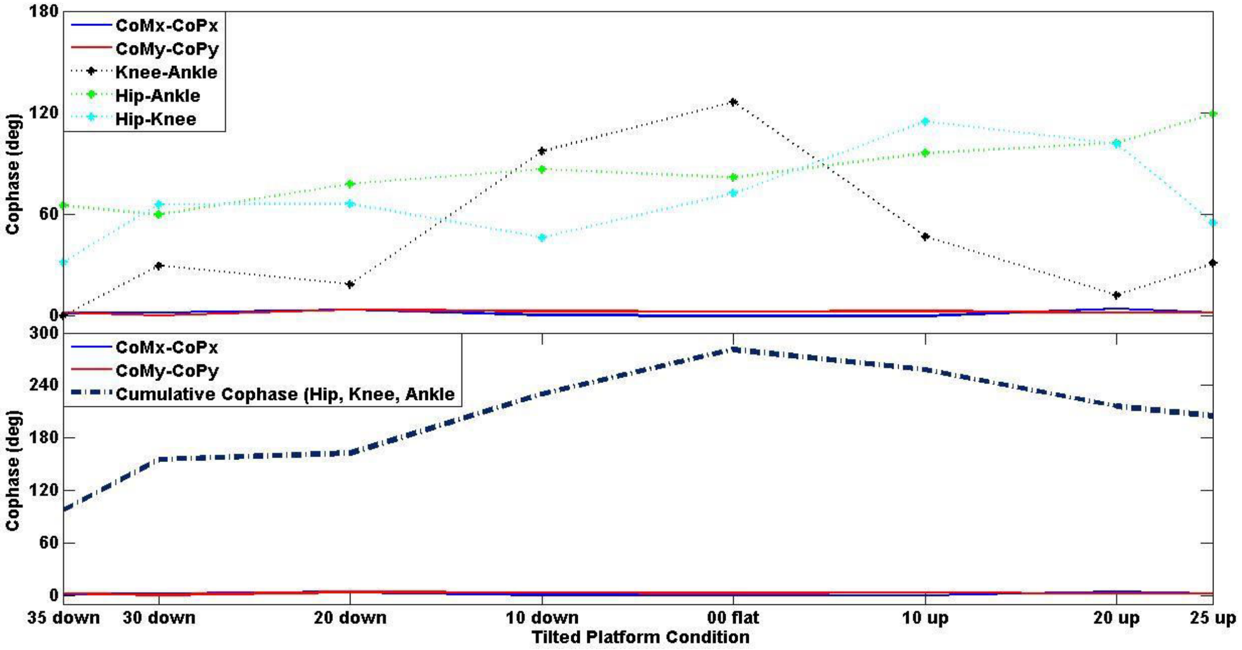


Figure 3.9. Cumulative and individual cophase values for CoM-CoP and joint angles across all platform conditions.

Table 3.2. Individual cophase joint angles and cumulative cophase joint angles across all platform conditions.

Platform Condition	Knee-Ankle	Hip-Knee	Hip-Ankle	Cumulative Angle
35 Down	0 ± 0.60	32 ± 0.41	65 ± 1.20	97
30 Down	30 ± 0.28	66 ± 0.52	60 ± 0.49	156
20 Down	19 ± 1.12	66 ± 0.53	78 ± 0.59	163
10 Down	97 ± 1.05	46 ± 0.89	87 ± 1.30	230
00 Flat	**126 ± 0.51**	**72 ± 0.74**	**82 ± 0.96**	**280**
10 Up	47 ± 0.49	115 ± 0.59	96 ± 0.68	258
20 Up	12 ± 0.49	102 ± 0.51	102 ± 0.81	216
25 Up	31 ± 1.03	55 ± 0.52	120 ± 1.51	206

Discussion

Theorizing on upright postural control has been strongly influenced by the traditional inverted pendulum hypothesis that has active control of the ankle joint in combination with passive musculoskeletal properties to maintain alignment of the other joints (Jeka et al., 1998; Nashner & McCollum, 1985; Winter, 1995). The inverted pendulum model holds a direct correspondence between ankle joint angle and the body's position in space as the postural control mechanism in upright stance. However, this hypothesis has been challenged given evidence that there are individual contributions of ankle, knee and hip joints for a range of postural control tasks (e.g., Alexandrov et al., 2005; Hsu et al., 2007), and signatures of in-phase and anti-phase coupling of legs and trunk during quiet standing (Creath et al., 2005).

Given that postural control is a multivariate problem with active contributions across multiple *dof* s, system-oriented approaches in human motor control have proposed the idea of collective variables that capture the structural organization of the system (Federolf & Nigg, 2013; Haken et al., 1985; Hsu et al., 2007; Mitra et al., 1998). Previous studies have shown that controlling the CoM is an important aspect of upright postural control where sensory feedback (Jeka et al., 2004; Scholz et al., 2007) and an ankle-hip strategy (Horak & Nashner, 1986; Ko et al., 2014) contribute to maintaining balance. It has also been shown that there are two co-existing modes that integrate spatial and temporal movement parameters according to the task and environmental demands of upright standing (Creath et al., 2005).

The aim of the present study was to examine the coordination of the functional joint *dof* s in the framework of quiet upright standing under different slopes of the surface of support. The focus was to investigate whether a low dimensional quantity captures the structural integrity of the collective organization of the system behavior across slope conditions. Participants were instructed to stand quietly on several platform wedges of different surface angles, assigned randomly with both feet planted side-by-side. A central finding was that the CoM-CoP dynamics (both ML and AP) showed a high coherence (~1) in the low-frequency range and hence maintained postural integrity of the pattern of coordination across all tilted platform conditions. In contrast, the coherence of Hip-Knee, Hip-Ankle and Knee-Ankle had values ranging between 0.4 to 0.7 and typically the pairs of joint motion shifted to upper mid-range (0.7) when compared with the 0° Flat condition to extreme platform conditions i.e. 25° Up or 35° Down.

That the coherence between pairs of joint angles was quite low, underscores the fact that the fluctuating motions of the leg joints were not strongly coupled. Hence, this pattern of findings is counter to a strict ankle, or ankle-hip control strategy for postural control. Against the background of modest coupling of the individual joint motions (Hip, Knee, Ankle) the CoM-CoP coupling by contrast remained strongly in-phase for both ML and AP planes for the postural task. The contrasting patterns of change of these emergent and synergistic variables provide supporting evidence to the idea of CoM-CoP as the candidate collective variable in the modulation of CoM in the state space (Ko et al., 2014; Wang et al., 2014).

The Hip angle was highly constrained in the upward facing platform conditions compared with flat and downward platform conditions. The Knee angle showed highest variability for the flat condition compared with the other platform conditions, whereas the Ankle angle variability was lower for the flat condition (see Figure 3.3). The lower limb joint angle variability reflects the organization of the individual *dof* s motion and supports the proposition that postural control involves active control of the multiple individual joint components to maintain body coordination and balance (Aramaki et al., 2001; Morasso & Schieppati, 1999; Pinter, van Swigchem, van Soest, & Rozendaal, 2008).

The cophase analysis revealed that CoM-CoP coupling was in-phase, especially at the lower frequencies (< 1 Hz), both along the ML (3.13º±3.09º) and AP (2.88º±2.10º) directions across all platform conditions. It also revealed that CoM-CoP coupling was strongest for the flat platform condition and was gradually weakened as the platform was tilted to higher angles. Cophase analysis on the lower limb joint angles of the Hip, Knee and Ankle also showed statistical significance across all platform conditions. Typically for Hip-Ankle coupling the mean cophase value was 86º±20º, Hip-Knee 69º±27º, and Knee-Ankle 45°±43° (see Table 2).

These results show that lower limb cophase values were not in an in-phase mode unlike the CoM-CoP coupling, yet the multiple *dof* arising from the lower limb were largely modulated to preserve the CoM-CoP coupling across all tilted platform conditions. These findings provide further evidence that CoM-CoP coupling is more consistent across all platform conditions than the individual joint motions and paired joint couplings and this differential modulation supports the notion of CoM-CoP as the collective variable for this task. In-phase preservation of CoM-CoP coupling with lower variability across all platform condition in comparison with the Hip, Knee and Ankle paired phase relations at the musculoarticular level with higher variability shows that CoM-CoP (candidate collective variable) coupling evolves at a slower time scale than the local joint synergies (see Figure 3.7) (Kelso, 1995; Mitra et al., 1998).

The postulation of CoM-CoP coupling as a collective variable is further supported by the evidence arising from the coherence analysis, which showed a high and systematic correlated pattern in the frequency domain. Figure 3.8 depicts that the coherence patterns across all the platform conditions were essentially identical in which the CoM-CoP are highly correlated (~0.9) for the sequential frequency bins, whereas the synergies at the musculoarticular level showed the coherence values were mid-ranged (~0.3 – 0.7) across the platform conditions. Such a modest level of coupling is one of the significant features at the musculoarticular level, in which synergies are adaptive in both cooperative and compensatory ways (Bernstein, 1967; Kelso, 1995). This is also consistent with the idea that the collective variable (CoM-CoP) is a higher-order parameter that emerges from the interaction of the neuro-muscular components in the context of the environment and task constraints.

Figure 3.9 shows an interesting phenomenon where the fluctuating mean cophase values at the musculoarticular level were summed to investigate if there was any significant collective pattern as a function of the platform conditions. Indeed, it was found that the cumulative cophase angles were highest (280º) for the flat condition and tapered to lower values (97º and 206º) for the extreme tilted platform condition of 35º Down and 25º Up, respectively. This finding provides evidence of the characteristics regarding the mechanism of the larger joint space exploration for the flat condition in comparison with the constrained tilted platform conditions.

To conclude, this experiment has provided further evidence that CoM-CoP coordination could be a candidate for a collective variable for quiet standing across different tilted platform conditions (Ko et al., 2014; Wang et al., 2014). Although, these previous studies have shown that such relation holds for other postural tasks, and have examined muscular and somatosensory perception while quiet standing coordination on inclined planes (Mezzarane & Kohn, 2007; Paquette, Franzén, & Horak, 2015; Simeonov, Hsiao, & Hendricks, 2009) this study is the first to generalize the concept of a collective variable to the tilted platform surface of support – a postural control task that occurs in everyday life. We have shown that the principles of coordination dynamics that hold that the collective variable is an emergent property as result of the compensatory and cooperativity of the individual components at the musculoarticular level map well to the organization of postural control. In this view (Kelso, 1995), the collective variable constrains the behavior of these individual components and reflects the construct of circular causality – a reciprocal constraint that is observable in the multi-joint *dof* of postural coordination under the demands of task and environmental constraints. Subsequent studies need to address the weighting of each joint angle (upper and lower body) and analyze how the weightings co-vary across the different platform conditions to explicitly examine the role of collective variables on each functional *dof* in postural control.

CHAPTER 4: TRANSITIONS OF POSTURAL COORDINATION AS A FUNCTION OF OSCILLATORY PLATFORM DYNAMICS

Abstract

This study was set-up to investigate the multi-segmental organization of human postural control. The focus was on the coupling between the center of mass (CoM) and center of pressure (CoP) as a candidate for a collective variable in a dynamic balance task that required the participant to maintain balance on a sinusoidally translated platform in the medial-lateral plane that 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 of the support surface dynamics, 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 a collective variable that is supported by the faster time scale motions of the joints and their synergies.

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 et al., 2005; Federolf et al., 2013; Hsu et al., 2007; Wang et al., 2014) and not motion at the ankle joint only as has been postulated by the standard inverted pendulum model (Winter, 2009). However, the nature of the organization of these multiple joint space *dof* in postural control 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 across the multiple *dof*s defined over multiple scales of space and time (Bernstein, 1967; Gelfand & Tsetlin, 1962; Kelso, 1995).

Several studies have investigated the coordination of the body effectors that afford stability in the act of quiet standing posture (Massion, 1994; Nashner & McCollum, 1985) under both discrete (Gu, Schultz, Shepard, & Alexander, 1996; Hughes, Schenkman, Chandler, & Studenski, 1995) and continuous (Buchanan & Horak, 1999; Ko, Challis, & Newell, 2013; Ko, Challis, & Newell, 2003) motion of the base of support. Two primary postural coordination modes have been identified through these experimental strategies. One mode is that of an ankle strategy where the postural system is viewed as an inverted pendulum (Winter, 2009). The second mode is a hip strategy where the hip motion maintains the postural stability (Nashner & McCollum, 1985). Other investigators have used different terms for these postural coordination modes such as ride pattern (Buchanan & Horak, 1999), inverted pendulum pattern (Horak & Nashner, 1986) and rigid mode (Ko, Challis & Newell, 2001) which all represent the same coordinative behavior. Similarly, head fixed pattern (Buchanan & Horak, 1999), buckled pendulum and ankle-knee-hip mode (Ko et al., 2001) describe related coordinative phenomena.

Collectively, these studies have revealed qualitative change in the coordination of the joint space *dof*s by perturbing the postural system of quiet stance.

Ko et al., (2013) conducted an investigation to determine if the relative phase of CoM-CoP could be considered a collective variable for the task of upright postural stance (Bardy, Marin, Stoffregen, & Bootsma, 1999; Kelso, 1995; Mitra et al., 1998). The postural balancing 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. A moving platform that sinusoidally oscillated in the anterior-posterior plane provided an experimental manipulation as a control parameter to scale the postural coordination patterns under different parameter regions of the state space. 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 were also shorter than that of the CoM-CoP couple.

In this present study, we investigated how the postural system regulates the *dof* when the surface of support is subjected to a medial-lateral (ML) oscillating perturbation. The ML motion in dynamic balance postural tasks is organized differently 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). Here we investigated the relative phase between coupled variables of CoM, CoP, Head, Hip, Knee and Ankle joint trajectories to determine the time scales of the change in the motions of the individual joints, synergies and candidate collective variables as a function of platform frequency.

We examined the hypothesis that CoM-CoP, CoM-Platform and Head-CoP couplings would abruptly shift from in-phase (at both quiet standing and low platform frequencies) to anti-phase at higher frequencies and that practice would be reveal the independence of head motion from that of CoM, particularly at the higher platform frequencies (Ko et al., 2013; Ko & Newell, 2015). Given the adaptation of a preferred postural coordination as a function of increasing platform frequency (Ko et al., 2001), we also investigated whether the critical fluctuations arising from the CoM-CoP transition were a function of body scale properties (Kugler & Turvey, 1987), with emphasis on the BMI or Quetelet index derived from body mass and height. To determine the critical fluctuations of the postural mode in the transition from in-phase to anti-phase for the couplings of CoM-CoP and Head-CoP, we analysed point estimate relative phase and phase portraits of the *dof*s across quiet standing together with low and high oscillating frequencies of the moving platform (Hamill, McDermott, Haddad, 2000; Jeka & Kelso, 1989; Schöner, Haken, & Kelso, 1986). Phase plane techniques represent the motions geometrically, the critical phase angles-relating one articulator's position-velocity state to another, and can reveal the coordination among effectors (Kelso, 1984).

Methods

Participants

Eleven healthy male participants (age: 20-28 years) free from neurological disorders and musculoskeletal injuries were recruited, according to the experimental protocol approved by Pennsylvania State University Institutional Review Board. The participants self-reported that they had no previous exposure to dynamic balancing tasks such as skiing, surfing and rollerblading.

Instrumentation

A 3-D motion analysis system (QTM, Sweden) was used to record the motion of passive markers attached over the joints of the experimental subjects. A 13-segment model was reconstructed from a 20-marker system (Winter, 2009). A force platform (AMTI, OR 6-5-1000) was used to derive the displacement of the body's center of pressure (CoP) and was mounted on a moving platform. The motion analysis system and the moving platform device were synchronized with the aid of an external trigger. Both systems were set at 100 Hz as the sampling frequency to record the data that were later filtered by a low-pass second order Butterworth filter with a cut-off frequency at 4 Hz.

Tasks and procedures

The participants were instructed to maintain their postural balance when they stood on the moving platform with bare feet, eyes open and focused at a distant visual target placed 2 m away from the platform at the eye level. The participants placed their feet side-by-side comfortably and kept their arms folded across their chest (see Figure 4.1). The moving platform was controlled by a motor that generated sinusoidal lateral translations along the ML direction. There were six frequencies of 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 Hz at a platform motion amplitude of 20 cm. The initial 15 s consisted of quiet standing with no motion of the platform, followed by 6 oscillation cycles of each frequency in ascending step-wise order and then again descending order followed by another 15 s of quiet standing. The total duration of each trial was about 170 s. Each day had a trial block of 6 trials, with 1 min of recovery time between each trial to reduce fatigue. Subjects were asked to maintain their postural balance irrespective of the scaling of the platform frequency.

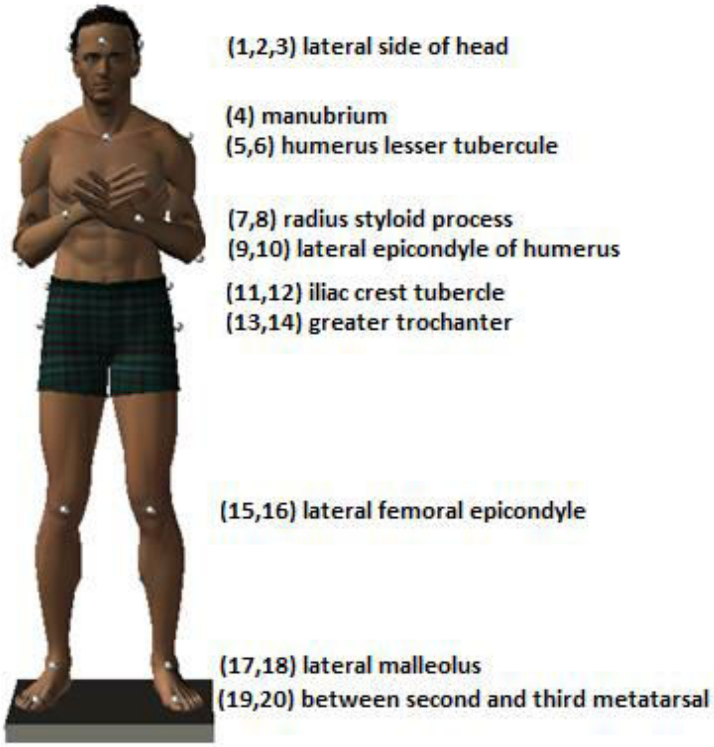


Figure 4.1: Marker model for the experimental setup (1-20)

The local variables consisted of hip, knee and ankle angular joint motions that were defined based on passive markers that were attached to the anatomical landmarks (see Figure 5.1). The CoM was calculated from the 13 segment model according to the anthropometric model data of Dempster (1955). Applying the weighting factors of the segmental masses, the total body CoM position was estimated by the weighted summation of the individual segment CoM positions (Dempster, 1955). Three force components (*Fx*, *Fy*, and, *Fz*) and 3 moment components (*Mx*, *My*, and, *Mz*) were simultaneously measured by the force platform that had 4 strain gauges embedded. With these measures, the CoP in the ML plane was obtained (Dempster, 1955).

Data Analysis

Relative Phase: The global variables of CoM-CoP and Head-CoP relative phase were considered as candidates for the collective variable of the whole body system (Ko et al., 2014). The local variables of ankle, knee and hip joint motions were also investigated by applying relative phase techniques (van Emmerik & Wagenaar, 1996). Typically continuous relative phase (CRP) (Kelso, 1995) or point estimate relative phase (PRP) (Hamill, Bates, & Holt, 1992) have been applied to investigate the coordination relation of two variables. In this study we used PRP, since the moving platform induces rhythmical postural movement of variables such as CoM-CoP and thereby resulting in distinct peaks and valleys of the signal. PRP is also not dependent on the signal having a stationary quasi-sinusoidal structure (Diedrich & Warren, 1995).

Applying the first derivative test we determined the local maxima and local minima of two signals (reference and target) for a given platform frequency condition. The lead/lag relationship of two signals was divided by the period between two successive peaks of the reference signal and was further multiplied by 360º to map the indices to degrees. PRP angle was calculated as follows:

$$PRP = \frac{t_1 - t_2}{T} * (360^{\circ}) \qquad (1)$$

where, t_1 = time to local maximum of reference signal (CoM or Head), t_2 = time to local maximum of target signal (CoP) and T = time period between two consecutive peaks of the reference signal.

The design of the experiment ensured 6 distinct pairs of peaks and valleys reflecting the 6 platform cycles for each frequency condition. The relative phase time series for each platform frequency condition had 10 PRP events since T could not be computed for the last cycle. Absolute PRP values were used to investigate the temporal relation between two variables rather than lead/lag dynamics. Hence, the *mean* value reflected the temporal relation of two signals and the standard deviation indicated the variability of that temporal relation that was computed using circular mean and standard deviation (Mardia, 1975). In this study, in-phase mode (~0º) indicates that two stationary signals move in the same direction (medial-medial or lateral-lateral whereas anti-phase mode (~180º) indicates that the signals are moving in opposite direction (medial-lateral or vice-versa).

Non-equilibrium phase transition: Preliminary superimposed plots of two signals illustrated that a phase transition occurred somewhere between 0.4 Hz and 0.6 Hz. Given the fact that the coupled variables had a phase transition within the range of (0.4 to 0.6) Hz for the increasing condition and vice-versa for the decreasing condition, we divided the initial broader range from (0.2 to 0.8) Hz into 14 segments that included 4 cycles of platform oscillations and two cycles overlapping the successive segment (Bardy et al., 2002; Kelso et al., 1986). Once the phase transition segment was detected it was clamped and 3 segments were defined prior and after the clamped segment. The *mean* and standard deviation were computed for the above-mentioned ensemble of 7 segments for each subject and then averaged over subjects using circular statistics (Berens, 2009). The transition was indicated by the *mean* and standard deviation value out of range from the preceding segment for the increasing condition and subsequent segment for the decreasing condition. A similar approach was used for Hip-Ankle coordination.

To investigate hysteresis effects for the 2 platform conditions, the platform oscillation frequency that was consistent with the clamped segment for each subject was determined. A paired *t-test* and ANOVA were used to analyze the variance across platform conditions and frequencies for CoM-CoP, Head-CoP and Ankle-Hip couplings. We employed the Bonferroni post hoc test to determine the differences on all paired levels for the dependent variables.

Results

Candidate Collective variables

Figure 4.2 illustrates the phase transition of CoM-CoP and Head-CoP at both increasing and decreasing platform conditions for a representative subject trial. Both CoM-CoP and Head-CoP coordination transitioned from in-phase to anti-phase or vice-versa depending on the platform condition (increasing and decreasing, respectively). This was the signature pattern across the 11 subjects that occurred within the first two oscillations of the moving platform at the critical frequency. There were critical fluctuations at 0.6 Hz for CoM-CoP and Head-CoP couplings for the increasing platform frequency condition and at 0.4 Hz for the decreasing condition.

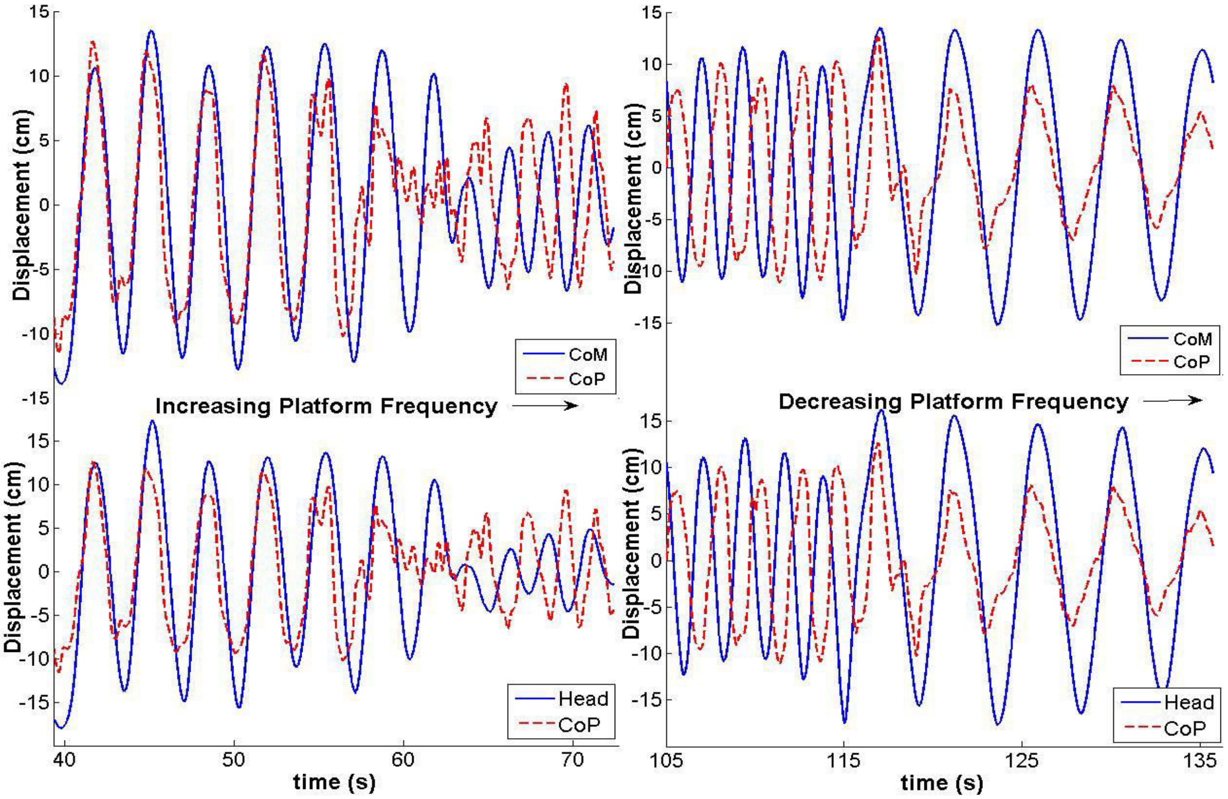


Figure 4.2: Single trial example of phase transition of CoM-CoP and Head-CoP at both increasing and decreasing platform frequencies

Figure 4.3 illustrates the coordination of CoM-CoP, Head-CoP and Hip-Ankle across all platform frequencies (increasing and decreasing). The *mean* point relative phase relation is plotted by the error bars and the standard deviation is marked by the line graphs. The *mean* point relative phase relation increased from (45º - 55º) at 0.4 Hz to (155º - 165º) for both the CoM-CoP and Head-CoP couplings with their corresponding standard deviation ranging between (35º - 40º) at 0.4 Hz and (145º - 150º) at 0.6 Hz. Similar trends were also present in the decreasing condition. For the Hip-Ankle coupling, a phase transition occurred at approximately 0.4 Hz at both the increasing and decreasing conditions before peaking at the 1.2 Hz platform frequency. The *means* fluctuated from (5º - 10º) at 0.2 Hz to (80º - 90º) at 0.4 Hz and (140º - 150º) at 0.6 Hz with their corresponding standard deviations as 6º, 55º and 85º respectively. An abrupt elevation of standard deviation at the critical frequency (0.6 Hz) from the preceding platform frequency (0.4 Hz) reflects the phase transition for the global variables. A similar change in the standard deviation occurred at the decreasing platform conditions.

A 2-way repeated ANOVA of 5 (frequency) x 2 (condition – increasing/decreasing) was conducted for the coupling of CoM-CoP. There was a significant main effect of frequency, $F(4,90) = 21863.26$, $p < .05$, for CoM-CoP coupling. The main effect of condition (increasing and decreasing), $F(1, 90) = 3.712$, $p = .057$, was also significant. The interaction of frequency and condition was significant, $F(4,90) = 14.594$ at $p < .05$. The Bonferroni post hoc test showed that the interaction was due to only the following comparisons (0.2 Hz-0.4 Hz), (0.2 Hz-0.6 Hz), (0.2 Hz-0.8 Hz), (0.4 Hz-0.6 Hz) and (0.4 Hz-0.8 Hz) being significant at the 0.05 level for platform frequency.

Similarly for Head-CoP, there was significant main effect of frequency, $F(4,103640.23) = 17827.377$ at $p < .05$, and increasing/decreasing condition, $F(1, 44.864) = 7.717$ at $p = .007$. The interaction of frequency and condition was also significant, $F(4,47.631) = 8.931$ at $p < .05$. Bonferroni post-hoc revealed that the following comparisons were significant at the 0.05 level for the interaction between (0.2 Hz-0.4 Hz), (0.2 Hz-0.6 Hz), (0.2 Hz-0.8 Hz), (0.4 Hz-0.6 Hz) and (0.4 Hz-0.8Hz).

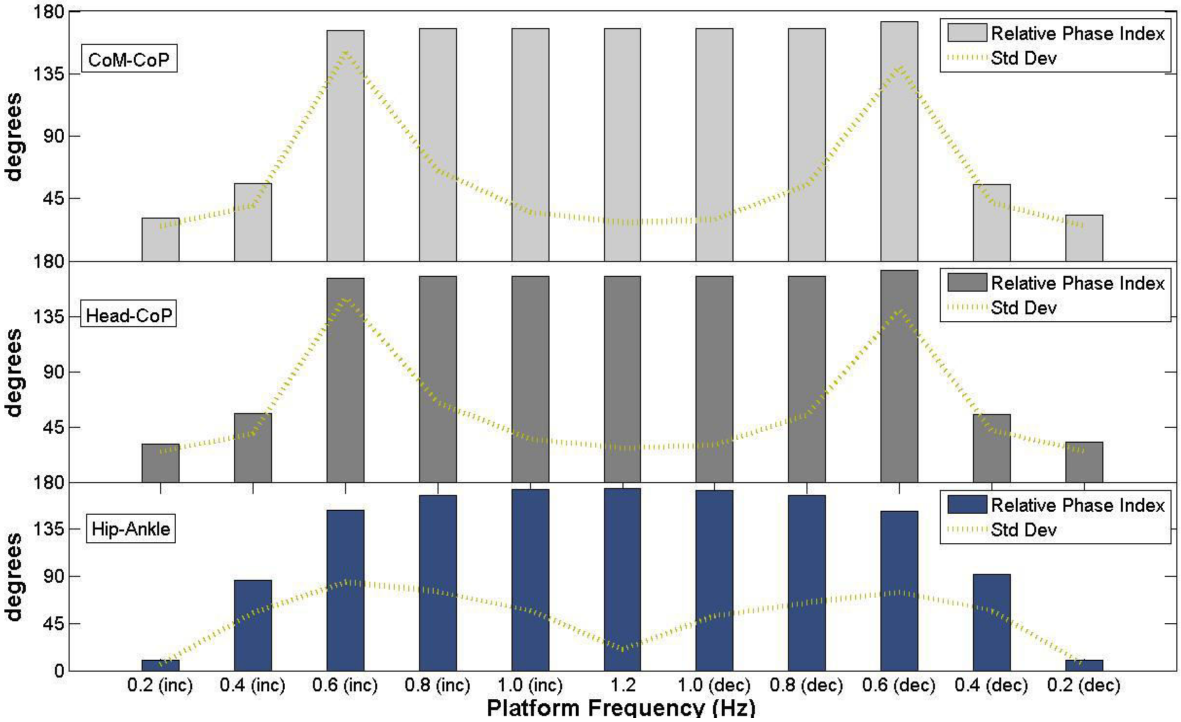


Figure 4.3: Mean Point Relative Phase and SD as a function of platform frequency as a function of coupling relations

Independence of CoM and Head motion

Figure 4.4 illustrates the phase portraits of CoM, Head and CoP motion as a function of platform frequency. The CoM motion is that of a limit cycle oscillator with a large amplitude and overlapping trajectories, whereas the Head motion oscillates at a higher frequency but with a smaller amplitude. Figure 4.5 depicts the mean correlation coefficient for CoM and Head as a function of increasing platform frequency. *Mean* and standard deviation of the *r* values were as follows, 0.74, 0.10 (0 Hz); 0.98, 0.01 (0.4 Hz); 0.84, 0.05 (0.8 Hz) and 0.52, 0.14 (1.2 Hz). The line plot correlation coefficient clearly reveals that scaling of the platform frequency alters the dynamics of the CoM and Head and reflects their independent motions at the higher platform frequencies.

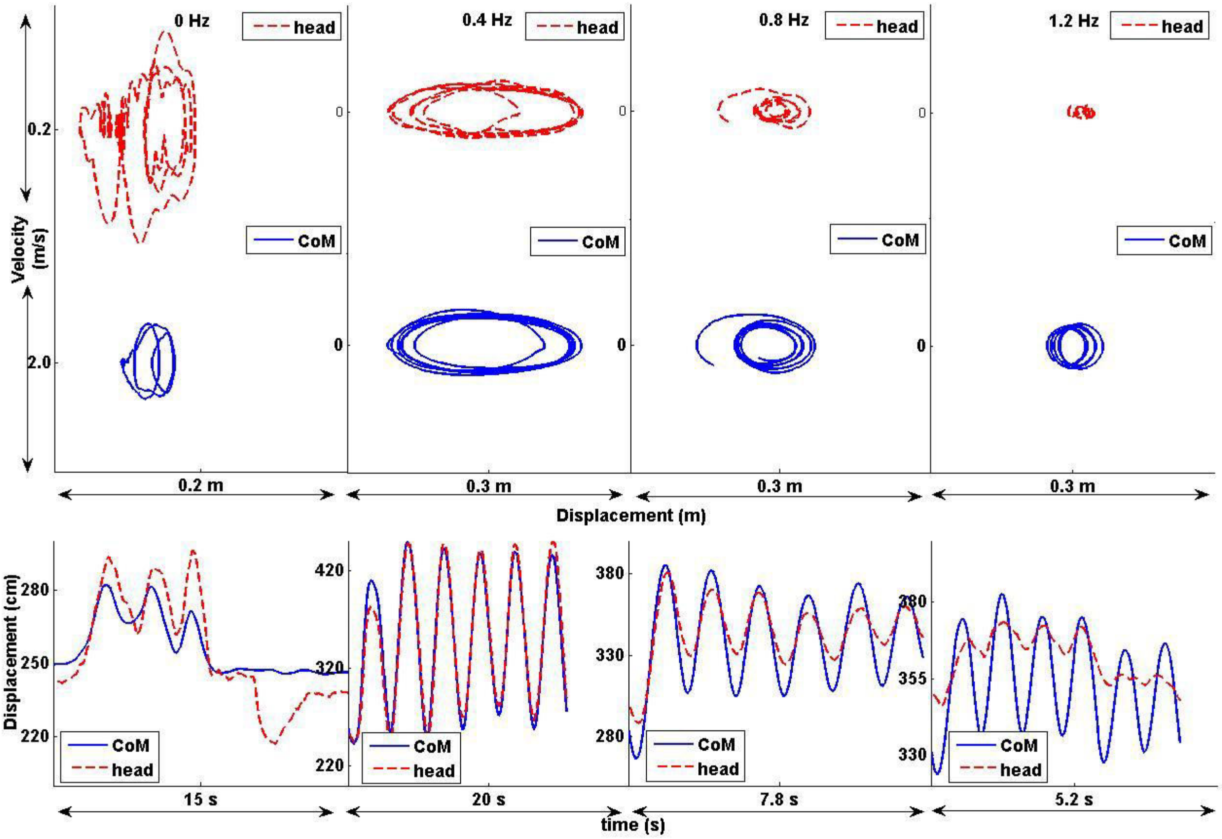


Figure 4.4: Representative phase plane analysis of CoM and Head motion as a function of platform frequency

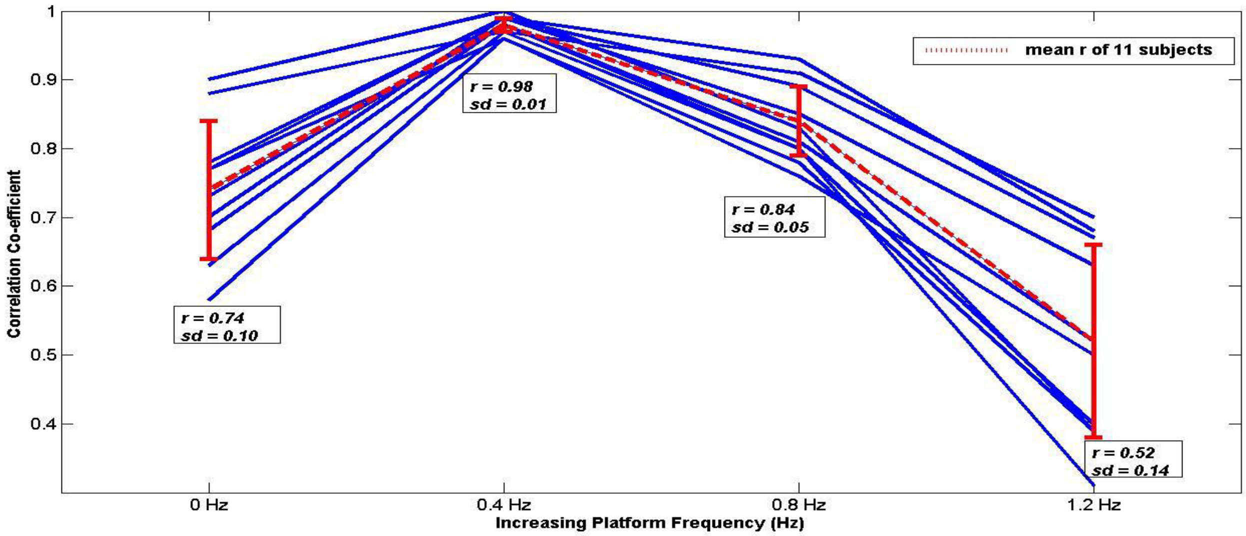


Figure 4.5: Correlation Coefficient of CoM and Head motion as a function of platform frequency.

Hysteresis

Figure 4.6 exhibits the hysteresis effect at the phase transition frequency from in-phase mode to anti-phase mode and vice versa for both CoM-CoP and Head-CoP couplings. The *mean* relative phase of the decreasing platform frequency condition is higher (174º) than that of the increasing platform frequency condition (162º) at 0.6 Hz. However, the standard deviation was larger in the increasing condition when compared with the decreasing condition. A paired sample t-test at 0.6 Hz showed that the relative phase index of CoM-CoP and Head-CoP differed significantly ($p < 0.05$) for both increasing and decreasing platform frequency conditions.

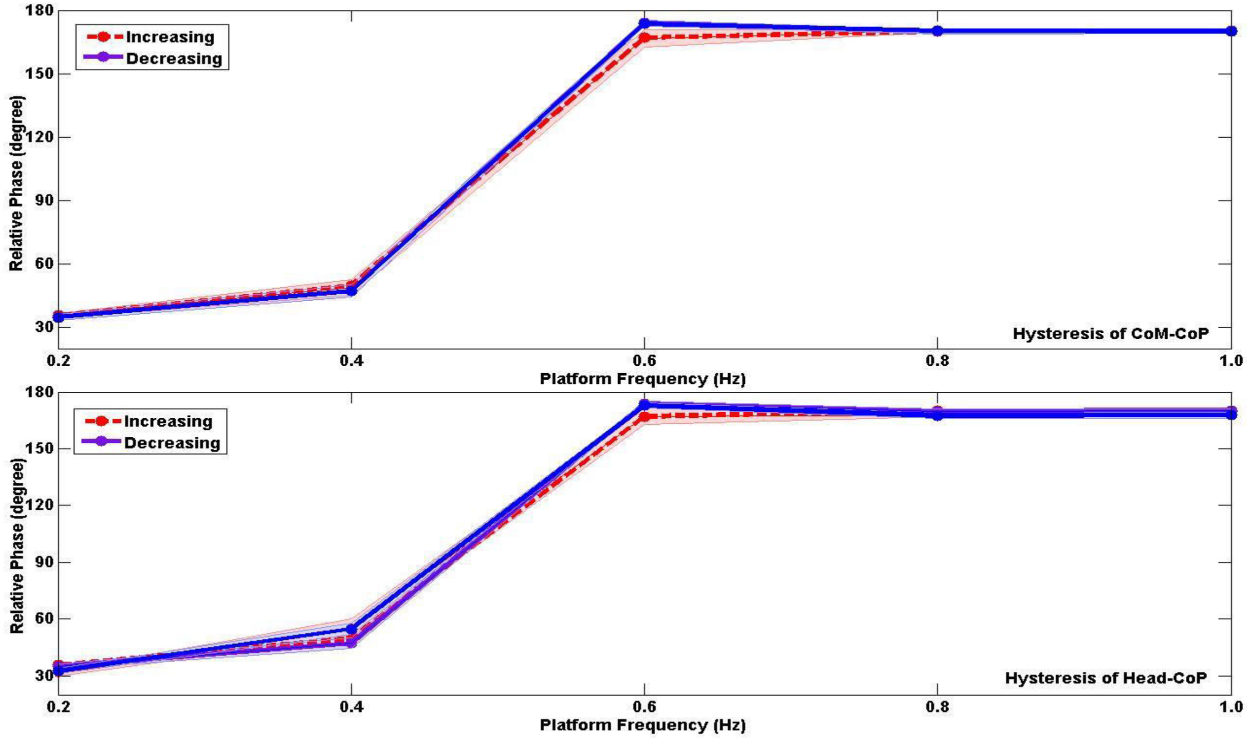


Figure 4.6: Hysteresis effect of CoM-CoP and Head-CoP relative phases (mean of 11 subjects) across both platform frequencies

Practice and Learning

Figure 4.7 depicts the effects of practice and learning across trials and days for the relative phase of CoM-CoP and Head-CoP couplings. We calculated the ratio of the *mean* relative phase value at 0.6 Hz with that of 0.4 Hz. Progression of lower to higher ratio indices reflects that subjects had a larger change from in-phase mode to anti-phase mode. This clearly signifies that as a function of practice, stability was attained with more significant phase transition difference that equates from values closer to 0º at 0.4 Hz to values closer to 180º at 0.6 Hz. A paired sample t-test across day1 and day2 showed that CoM-CoP coupling differed significantly from Head-CoP coupling at 0.05 level. Thus, comparing the dynamics of CoM-CoP with Head-CoP coupling shows that CoM-CoP is potentially a stronger candidate to be a collective variable as it demonstrates enhanced stability across practice days when compared with Head-CoP coupling.

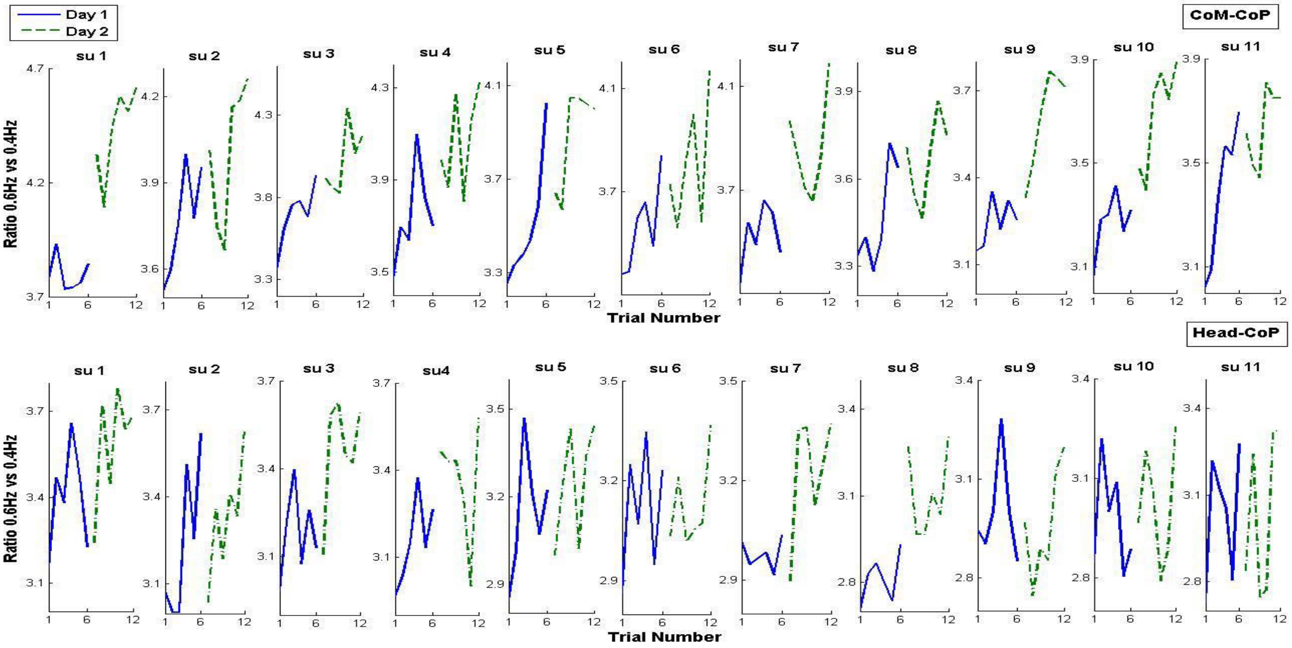


Figure 4.7: Practice effect of CoM-CoP and Head-CoP ratio at 0.4 and 0.6 Hz across trials and days

BMI Transition Relation

To investigate whether body scale (Kugler & Turvey, 1987) affects the CoM-CoP transition a general regression analysis was performed between BMI (x-axis) against the *mean* values of CoM-CoP relative phase (y-axis), where their natural logarithmic ratio values between 0.6 Hz and 0.4 Hz were plotted to investigate if BMI had any relation to the larger variation of the critical fluctuations (see Figure 4.8). The natural logarithmic was considered as the ratio values were often skewed. The following quadratic polynomial equation best fit the data,

$$f(x) = p_1(x^2) + p_2(x) + p_3 \qquad (2)$$

where p_1 = 0.002105 (-0.00021, 0.00442), p_2 = -0.1226 (-0.2344, -0.01081), p_3 = 3.026 (1.688, 4.363) and coefficients were set with 95% confidence bounds. The goodness of fit had SSE: 0.001624, R-square: 0.9473 and RMSE: 0.01425

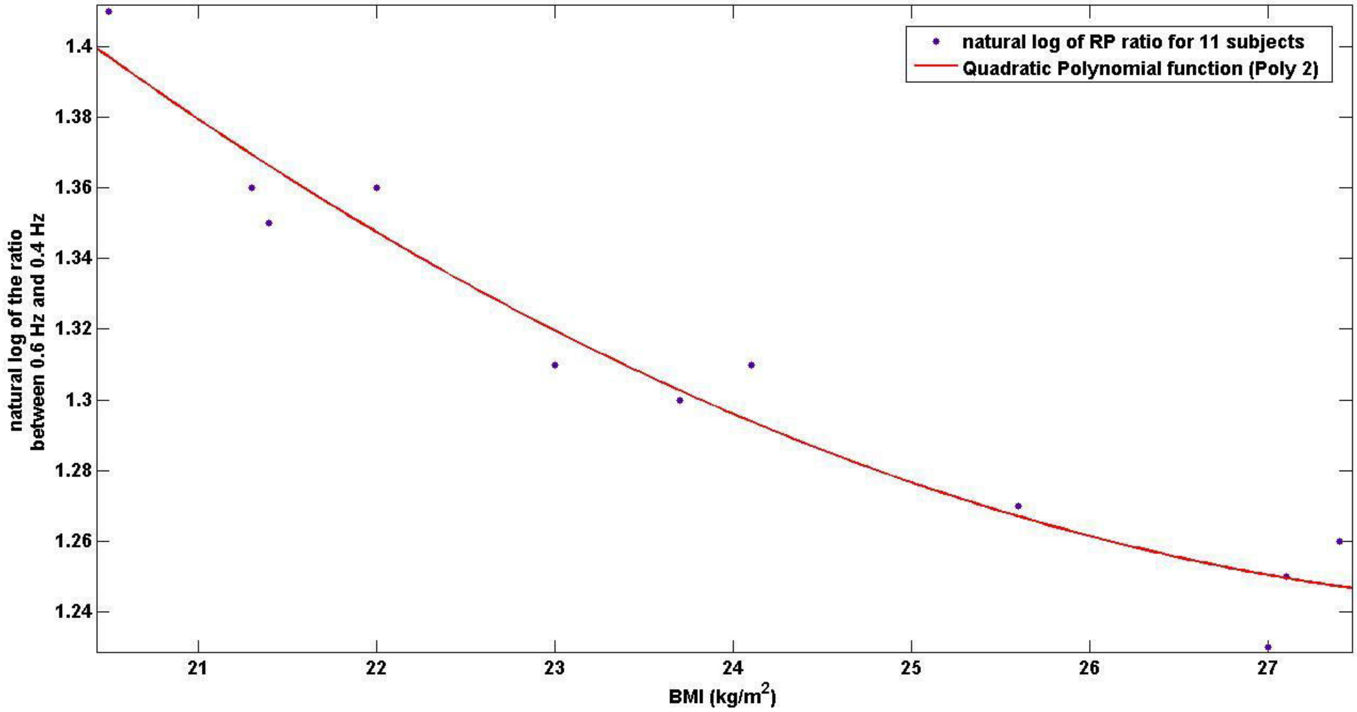


Figure 4.8: Regression Analysis of natural log of the ratio vs. BMI

Discussion

Postural control is a multivariate problem with active contributions from many joint and torso *dof* (Alexandrov et al., 2005; Federolf et al., 2013; Hsu et al., 2007; Wang et al., 2014). The relative roles of the particular joint *dof* are, however, not well understood in part because of the traditional emphasis on the simplifying single-link inverted pendulum model that has dominated the study of postural control (Winter, 2009). There have been several system-oriented approaches to motor control that have postulated the role of macroscopic global variables that capture the structural organisation of the system and labelled variously as essential variables (Gelfand & Tsetlin, 1962), order parameters (Haken et al., 1985) and as investigated here as collective variables (Mitra et al., 1998).

Determining a low dimensional quantity that captures the structural integrity of the collective organization of the individual *dof*s that govern the system's behavior would aid in understanding how multiple *dof* are organized in motor skill acquisition such as in maintaining dynamic stability on a moving platform. Previous studies have shown that controlling CoM is an important aspect of stabilizing posture, a finding that supports the interpretation that the nervous system can estimate the CoM position based on information from the many sensory channels available to it (Bottaro, Casadio, Morasso, & Sanguineti, 2005; Jeka et al., 2004; Scholz et al., 2007). In contrast, but more directly to the experimental context here (Bardy et al., 1999; Bardy et al., 2002) proposed that the ankle–hip synergy was the collective variable for posture tasks whereas Ko et al., (2014) provided evidence for CoM-CoP coupling to be a candidate collective variable in a dynamic balance task.

The findings of the current study reveal a distinction in the qualitative dynamics of the candidate global variables of CoM-CoP and Head-CoP coupling and the local variable coupling

Hip-Ankle for multi-segmental coordination in a dynamic balance task. The findings also show that the differences in these variable categories of movement organization are influenced by practice across trials and days. As illustrated in Figure 4.2, the CoM-CoP and Head-CoP couplings revealed dynamics consistent with a self-organized non-equilibrium phase transition as a function of the scaling of platform frequency while maintaining stability in the dynamic balancing task. CoM-CoP and Head-CoP couplings were found to shift abruptly from in-phase (~0º) to anti-phase (~180º) as the frequency of the moving platform increased. The reverse transition behavior (anti-phase to in-phase) occurred when the scaling of platform frequency decreased.

The construct of synergetics provides a theoretical framework to quantify and predict the qualitative macroscopic changes in movement coordination dynamics (Haken, 1983; Kelso, 1995). To determine whether CoM-CoP and Head-CoP coupling reflected the salient signatures of a collective variable, we investigated the dynamic phenomena of phase transitions, hysteresis and critical fluctuations. CoM-CoP and Head-CoP both demonstrated large variability (high standard deviation) at the phase transition region (0.6 Hz), which shows the dynamic phenomena of critical fluctuations that are typically associated with a non-equilibrium phase transition due to loss of stability (Kelso, 1995). The standard deviation was larger by almost 90º and peaked at the phase transition frequency of 0.6 Hz than preceding platform frequency (0.4 Hz) and subsequent platform frequency (0.8 Hz). A similar trend in the coupling standard deviation was found for the decreasing platform frequency condition. Thus, the phase transition of CoM-CoP was clearly associated with the scaling of platform dynamics and showed the properties consistent with this being a collective variable for this task.

The differences in the scaling of the platform dynamics as a function of increasing and decreasing platform frequency illustrate the hysteresis effect for the coordination of global variables. The findings also showed that the collective variable coordination was stronger and more stable when moving from anti-phase to in-phase pattern (decreasing condition), than in-phase to anti-phase pattern (increasing condition). Although, the transition frequency remained the same (0.6 Hz) for both conditions (increment of 0.2 Hz), the coordination of the CoM-CoP was higher and more stable in the decreasing condition, with less variability thereby illustrating that the initial critical fluctuation imparts larger instability and weaker coordination. This may imply that the pseudo attractor basins are different (deeper potential valley landscapes for decreasing condition) for the two platform conditions, even though they may coexist for the same collective variable depending on the direction of the control parameter (platform frequency) (Haken et al., 1985).

The analysis of hip-ankle (local) synergetic coordination also showed critical fluctuations from in-phase to anti-phase in the increasing condition and vice-versa. However, the shift in these two coordination modes occurred earlier (0.4 Hz) and later (across 0.4 – 0.8) Hz in the increasing and decreasing scaling of the platform frequency than the critical fluctuations of the candidate collective variable (CoM-CoP or Head-CoP) which occurred abruptly/sharply at (0.6 Hz). This contrast in the frequency of the transition reflects that the coordination of collective/global variables occurs on a slower time scale as a function of the scaling of the control parameter (platform frequency) (see Figure 4.3).

Ko et al. (2014) proposed CoM-CoP as the candidate collective variable for postural coordination while maintaining dynamic stability on a moving platform. The findings here show that CoM-CoP and Head-CoP coupling both show the necessary dynamic properties of potential candidates for collective variables (see Figure 4.2 and Figure 4.3). However, Figure 4.8 reveals that CoM-CoP coordination develops stronger coupling across trials and days when compared with Head-CoP coordination, which also becomes more independent from CoM-CoP at the higher platform frequencies. The instabilities of CoM-CoP coordination are mastered progressively when subjected to similar perturbations. This pattern of findings suggests that the individual assembles a behavioral response that is the collective pattern of the current status of the ensemble, a preferred postural pattern that involves the cooperative interactions of all the components within particular situation. This cooperativity, which reflects the reduction in the dimensionality of the original components to a compact pattern, can be captured in one or a few collective variables, in this case, CoM-CoP coordination (Haken, 1983; Kelso, 1995).

The principles of coordination dynamics (Kelso, 1995) hold that the collective variable is an emergent property of the cooperation of the individual elements of the system. Conversely, the collective variable governs or constrains the behavior of the individual elements. This reciprocal constraint is an example of the construct of circular causality that is more readily observable in a whole body many degree of freedom postural coordination task than the bimanual movement task. In our dynamic balance task the individual joint space variables influence the local synergy of ankle and hip that in turn affect and is affected by the candidate collective (global) variables CoM-CoP.

Finally, the experiment provided preliminary evidence for the role of body scale in mediating the dynamic properties of the postural transitions (Kugler & Turvey, 1987). Previous studies have revealed that new coordination modes and transitions are a function of body scale parameters in running and grasping (Cesari & Newell, 2002; Fallahi & Jadidian, 2011; Hreljac, 1995). The regression analysis of BMI vs. natural logarithmic value of CoM-CoP coordination between 0.4 Hz and 0.6 Hz ratio values of relative phase suggests that subjects with lower BMI, i.e. lower moment of inertia, tend to have a larger difference between relative phase of CoM-CoP coupling in order to meet the demands of the task, i.e. maintain upright stance during the scaling of platform dynamics. The findings show that body scale properties mediate the dynamics of postural control and reveal the importance of analyzing the transitions and variability of individual postural movement patterns.

CHAPTER 5: PRIOR PRACTICE EXPERIENCE AND ACQUSITION OF DYNAMIC POSTURAL STABILITY

Abstract

The investigation examined the influence of skill level and practice in learning a dynamic cyclical postural stability task (ski-simulator) and investigated the dynamic pathways of change in two groups – experienced and novice skiers. Practice was carried out over 140 trials across 7 consecutive days. The goal of the task was to maximize simultaneously the amplitude and frequency of sideways movement and maintain dynamic postural stability. The findings showed that some participants in the novice group revealed in the first few trials of day 1 a transition in the coordination pattern of in-phase to anti-phase coupling of CoM-platform motion whereas all the experienced group and the remaining novices produced on the first trial of practice an anti-phase coupling. The novice group also progressively increased their joint angle range and higher angular deviation as a function of practice in comparison to the experienced group. The study revealed a range of pathways of change was used to attain the new coordination pattern and scale platform motion to the task demands. Overall, the findings provide qualitative and quantitative evidence to support the role of CoM-platform coupling as a collective variable for this ski-simulator task that constrains the freezing and freeing of the individual joint space degrees of freedom (*dof*s).

Introduction

The acquisition of dynamic motor skills requires spatiotemporal coordination of multiple individual degrees of freedom (*dof*) (Bernstein, 1967). Early theories in motor learning conceived skill acquisition as a progressive and continuous refining process, where an individual builds internal representations that are progressively refined over practice (Schmidt, 1975). Such a view was supported by the power law (Lacquaniti, Terzuolo, & Viviani, 1983; Snoddy, 1926), that has described the evolution of performance as a power function on the duration of practice (Crossman, 1959; Newell & Rosenbloom, 1981). The power law was usually supported by averaging learning curves which contributes to masking the evidence of exponential and discontinuous change in motor learning (Heathcote, Brown, & Mewhort, 2000; Newell, Liu, & Mayer-Kress, 2001; Newell, Mayer-Kress, & Liu, 2006).

The traditional concept of learning as continuous has been challenged as non-linear, discontinuous, and marked by qualitative behavioral self-organization across multiple *dof*s to improve movement efficiency and task outcome (Newell, 1985, 1991). Early learning theories were typically confined to the paradigm of single *dof* movement coordination that required execution of simple tasks (Adams, 1971; Schmidt, 1975), and often resulted in methodological artifacts resulting in special cases of continuous performance trajectories. Furthermore, the studies that advocated the idea of continuous learning were typically carried out over a short period of practice time encompassing the early adaptation phase.

Dynamical systems theory is a robust framework that relates to properties such as phase transition, hysteresis, self-organization, entropy, instabilities and can be applied to investigate the discontinuities in learning (Kelso, 1995; Liu & Newell, 2015; Newell, Mayer-Kress & Liu, 2006; Zanone & Kelso, 1992) among skilled and non-skilled groups. The framework provides a spatiotemporal profile of developmental processes that can explain nonlinear change in movement behavior and the qualitative properties of learning and development (Muchisky, Gershkoff-Stowe, Cole, Thelen, 1996; Newell et al., 2001; Zanone & Kelso, 1992). The application of a dynamical systems theory perspective can be further justified in its widespread applications across various branches of general science spanning physical, life science, and their associated fields.

According to the propositions of dynamical systems theory in motor learning (Kelso, 1995; Zanone & Kelso, 1992) the coordination modes are spontaneously adopted by participants in a given task. The emerging coordination patterns are the expression of the intrinsic dynamics of the system, where certain coordination patterns appear more stable and easier to control and thereby are interpreted as attractors of the intrinsic dynamics (Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). The principles of dynamical systems theory hold promise to understanding high-dimensional datasets arising from whole body movement coordination and thereby addressing the problem of mastering *dof* as formulated by Bernstein (1967).

Bernstein (1967) postulated the notion of exploring the mechanisms involved in joint coordination dynamics as a function of practice. He conceptualized that a novice learner would have to coordinate and control large number of mechanical *dof* while attempting to learn a novel motor task. He proposed that novices would partially freeze out the *dof* (joint angles) at the initial learning stage a finding that has been experimentally supported (Vereijken, van Emmerik, Whiting, & Newell, 1992). Typically, freezing the joint angles would vertically project the CoM over the platform, thereby resulting in an in-phase coupling between the two variables. Bernstein (1967) reflected that such a preliminary strategy by novices would aid in reducing the *dof* to a tractable problem. His hypothesis was not about hard-wired anatomical units; rather synergies were proposed to be functional units, that are flexible and temporarily assembled in a task-specific configuration (Kelso, 1995).

The solutions in subsequent stages of learning can involve strong couplings between the multiple *dof* – adjoining phase relations in joint space (Hong & Newell, 2006; Jeka & Kelso, 1989; Vereijken, van Emmerik, Bongardt, Beek & Newell, 1997). Indeed, Bernstein (1967) proposed that the three stages of learning a novel skill involve – freezing out mechanical *dof* of joints, releasing the constrained *dof*s and exploiting the *dof*s to produce economical and efficient movement as a function of practice. This produces fluent alternative movement in skiing (Whiting, Bijlard, & den Brinker, 1987), that is, an anti-phase coupling of CoM and platform motion that is required (albeit implicitly) to realize the task demands.

Hong and Newell (2006b) investigated the coordination and control of *dof*s in a ski-simulator task, primarily identifying the changing time scale properties of global variables such as CoM (ML and AP), platform and local variables such as knee joint. The study revealed that the coupling of CoM and platform was significantly different from knee joint angle movement. It was shown that the global variables had higher peak coherence values across all block of trials in comparison to the local variables that had a coherence value of 0.92 in the first block of trials and improved to 0.98 for the fourth block of trials. Similarly, the local variable had an intermediate phase relationship 128.4°-107.7° when compared to CoM and platform that had a relatively higher phase relationship < 171.2°. However, the study addressed the practice effect in coupling only among novice skiers and the investigation was largely restricted to knee joint as a local variable. Nevertheless, the findings provided support for the proposal that CoM-platform coupling may be the collective variable in this whole body task as has also been supported in a dynamic platform balance protocol (Ko et al., 2014).

The question that we address in this study is the mechanisms that are involved in learning a novel task (dynamic cyclical postural stability in a sideways skiing movement). We compare the pathways of change in novice and experienced prior practice individuals in the course of learning as a function of practice. There were two major hypotheses in this study.

Firstly, we investigated the relation of the candidate collective variable (CoM-platform) and synergy variables (head-platform, hip-ankle, hip-knee and knee-ankle) for two pools of participants (experienced and novice) as a function of practice days. We hypothesized that the pathways of forming the respective couplings would be different where the collective variable would reveal slower stable time scales than the synergy variables as a function of the control parameter that is, increasing platform velocity with practice. The collective variable would move to a stronger anti-phase pattern whereas the synergy variables would be self-organized in a non-linear mechanism and reflect more transient relative phase values between the in-phase and anti-phase pattern. It was also hypothesized that the experienced participants would illustrate an earlier and more distinct collective variable of anti-phase coupling than the novice participants. It was expected that the experienced group would maintain an anti-phase pattern for CoM-platform and head-platform due to their attunement in such motor tasks while contrarily the novice would show at different rates the transitioning of the coupling index for the collective variable as a function of practice days.

Secondly, we predicted that the pathway of freeing *dof*s across practice days would be different between the two participant groups. The novice group was expected to demonstrate a progressive increment of lower limb joint angle range (freeing *dof*s) than the experienced group and illustrate higher standard deviation of lower limb joint angles as a function of practice (exploiting *dof*s). Collectively, this pattern of findings would reflect the different pathways of achieving dynamic postural stability as a function of skill level across practice days.

Methods

Participants

Twelve healthy female participants were recruited, according to an experimental protocol approved by The Pennsylvania State University Institutional Review Board. The participants consisted of two groups – novice and experienced. The novice group had no previous experience of dynamic balancing tasks such as surfing, skiing, rollerblading and snowboarding, whereas the experienced group consisted of experienced alpine skiers from a local club team. Their average height was 164.4 ± 6.2 cm and their average weight was 53.2 ± 4.3 kg. All participants self-reported no apparent neurological disorders and musculoskeletal injuries that could influence postural control.

Apparatus

The ski-simulator (Skier's Edge, Utah) was the experimental apparatus, which is a movable wheeled platform comprising of two co-dependent footplates. The elastic band fitted underneath the footplates facilitates lateral oscillations (see Figure 5.1). A 3-D motion analysis system (QTM, Sweden) was used to record the motion of passive markers attached over the anatomical joints of the experimental participants. The data were sampled at 100 Hz and were digitally low-pass filtered with a second order Butterworth filter and a cutoff frequency of 5 Hz.

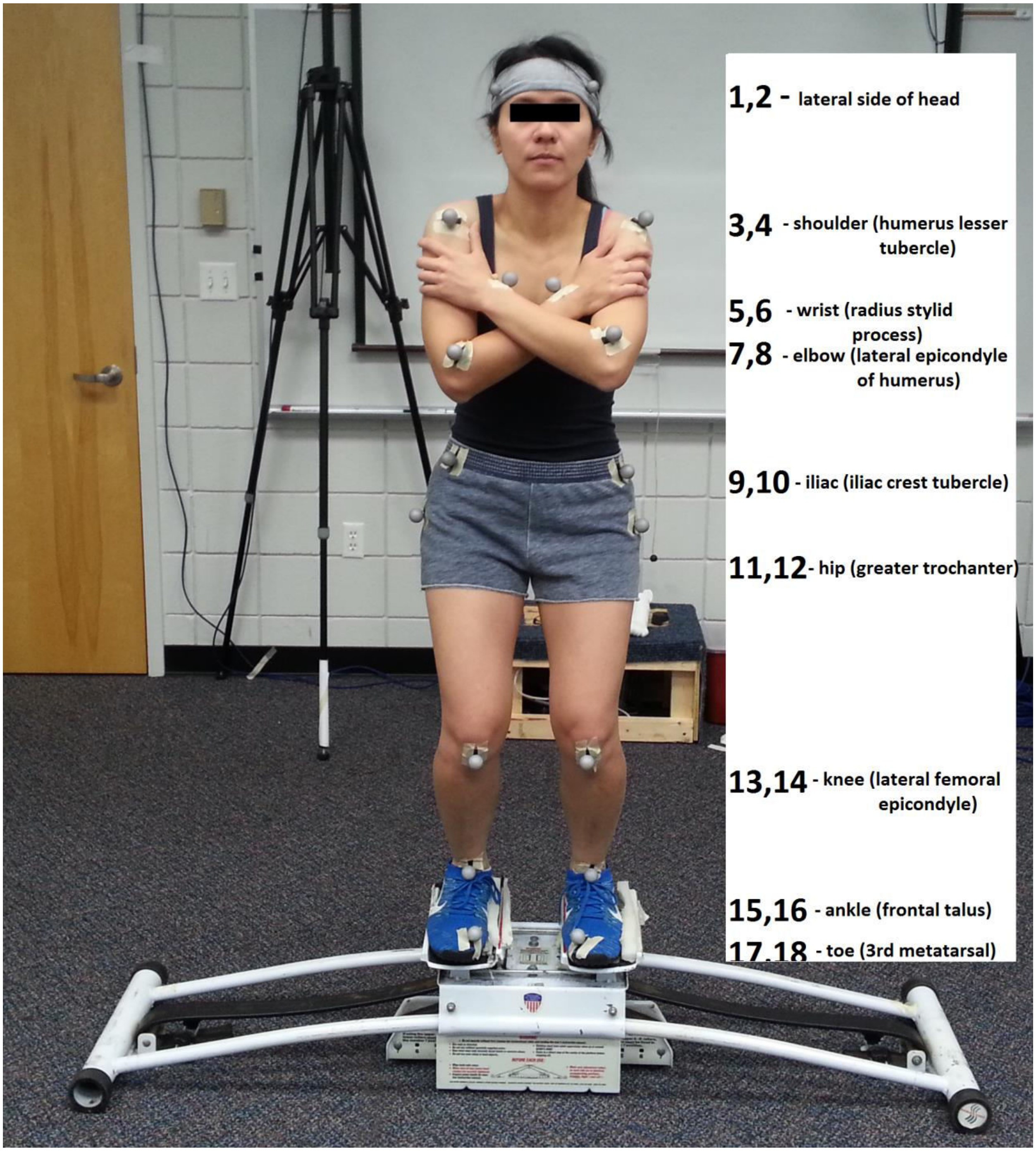


Figure 5.1. The ski-simulator apparatus (Skiers's Edge, Utah).

Task and Procedures

The participants were instructed to make large amplitude and high frequency side-to-side movements on the ski-simulator with their hands folded on the front of their torso (see Figure

5.1). No additional information was provided. Each participant practiced for a total of 140 trials spanning over 7 consecutive days. Every trial consisted of 45 s of practice followed by 1 min of rest.

Data Analysis

Kinematic variables: The kinematic variables were compromised of individual joint angles (hip, knee and ankle) calculated on the mediolateral plane that were defined based on passive markers attached to anatomical landmarks. The CoM was calculated from the 13 segment model, reconstructed from an 18-marker system according to the anthropometric data of Dempster (1955) (see Figure 5.1). Applying the weighting factors of the segmental masses, the whole body CoM position was estimated by the weighted summation of the individual segment CoM positions (Winter, 2009).

Cophase: The coupled variables of CoM-platform, head-platform, hip-ankle, hip-knee and knee-ankle were investigated by applying the cophase technique (Creath et al., 2005). Typically, 0º implies that the signals are coupled in-phase, whereas anti-phase mode would be reflected by +180°.

$$Cophase(f) = atan2d[-imag(S_{ab}(f), real(S_{ab}(f)] \qquad (1)$$

where $S_{ab}(f)$ is the cross power spectral density of the two time-series (Bloomfield, 2004).

Coherence: The coupled variables were also analyzed using the Chronux toolbox (Mitra & Bokil, 2008). Coherence measures the correlation of two signals in the frequency domain where multitaper spectral tool reduces the spectrum estimation bias by obtaining multiple independent estimates from the time-series that is dependent on the sampling frequency and time-series bandwidth (Thompson, 1982). Typically, values range between 1 (perfect linear prediction between variables) to 0 (variables are linearly independent).

$$Coherence(f)^2 = \frac{|(S_{ab}(f)|^2}{S_a(f).S_b(f)} \tag{2}$$

where $S_a(f)$ and $S_b(f)$ are the power spectral densities of signal *a* and *b,* respectively. An initial assessment to determine the frequency power of the dependent variables was carried out by running a FFT. It was found that the signal power was constrained to <2 Hz for all analyzed signals which was consistent with earlier findings (Hong & Newell, 2006b). Circular statistics were used to calculate the mean and standard deviation of coherence across the trial period (Mardia, 1975).

Statistics: Two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) was carried out across the cophase and coherence values of CoM-platform, head-platform, hip-ankle, hip-knee, and knee-ankle), the asymmetry correlation coefficients, joint angle variables and platform kinematics. We employed the Tukey post hoc test to determine the differences on all paired levels for the dependent variables where Mauchly's test indicated violation of sphericity, the Greenhouse-Geisser estimate was used to provide a conservative test of ANOVA main and interaction effects.

Results

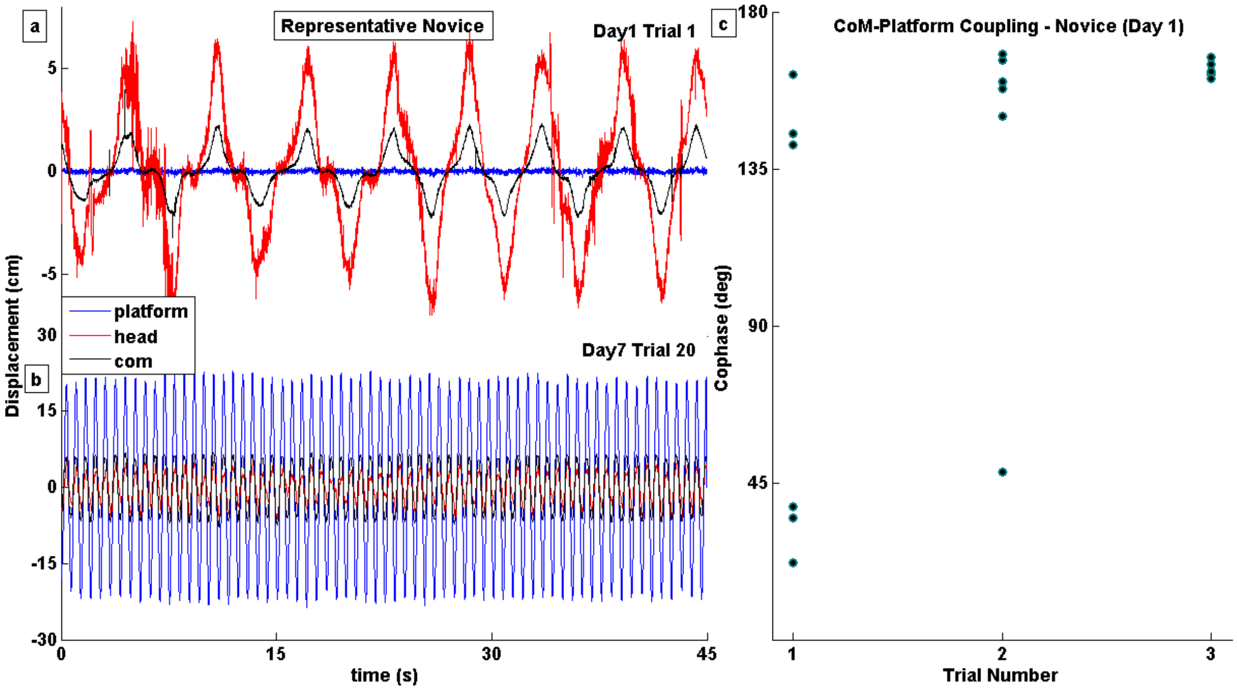


Figure 5.2. Representative novice subject - day1, trial 1 (upper left panel), day7, trial 20 (lower left panel), cophase values of CoM-platform (ML) all novices – day 1, trials 1-3.

Figure 5.2a and Figure 5.2b illustrate the kinematic ML motion of CoM, Head and Platform of a representative novice participant on day 1, trial 1 and day 7, trial 20, respectively. On day 1, trial 1, the amplitude of the platform motion is highly constrained (~ 1 cm) with a low CoM oscillating amplitude (~2 cm) and a large head oscillating amplitude (~7 cm), reflecting an inverted pendulum phenomenon, i.e. larger amplitude in the distal end (e.g., head) and constrained amplitude at the pivoted end (e.g., platform). On the contrary, for the same participant on day 7, trial 20, the oscillating amplitude of the platform is higher (~ 17 cm), whereas the amplitude of CoM oscillates intermediately (~ 5 cm) and the amplitude of head oscillation is highly conserved (~ 3 cm), reflecting a hanging pendulum anti-phase mode.

Figure 5.2c illustrates the cophase values of the CoM-platform coupling for the novice group on day 1 across trials 1 to 3. Two novice individuals in the study, transitioned from in-phase coupling (~0º) to anti-phase coupling (~180°) between trial 1 and trial 2. One novice individual transitioned from in-phase to anti-phase coupling between trial 1 and trial 3, whereas the remaining novices and all the experienced participants showed anti-phase coupling on the initial trial of day 1.

Platform Kinematics

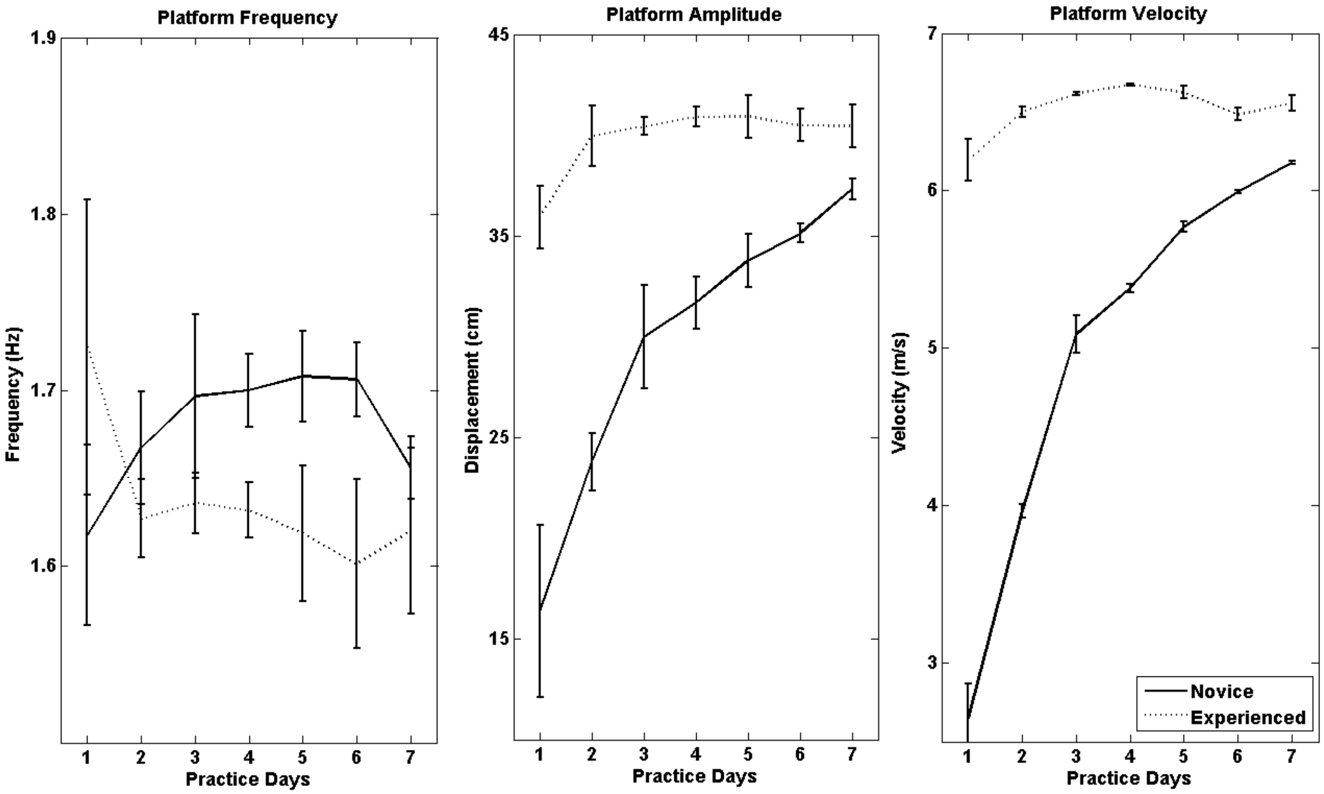


Figure 5.3. Platform frequency, amplitude and velocity of sideways skiing movement of two groups across practice days.

The amplitude of the sideways skiing movement for the novice group increased significantly as a function of practice days when compared to the experienced group (see Figure

5.3). The amplitude of the novice group was 16.36 ± 4.26 cm ($n = 6$) on day 1 which progressed to 37.32 ± 1.56 cm on day 7. In contrast, the experienced group had a group mean of 35.91 ± 1.51 cm on day 1 which progressed to 40.45 ± 1.05 cm on day 7. A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) was carried out across the platform frequency and showed statistical significance for the main effect of group, $F(1, 82) = 36.02$ at $p < 0.01$. Similarly, for platform amplitude and platform velocity there was statistical significance for the main effect of group, $F(1, 82) = 87.00$ at $p < 0.01$, and $F(1, 82) = 66.78$ at $p < 0.01$, respectively.

Cophase

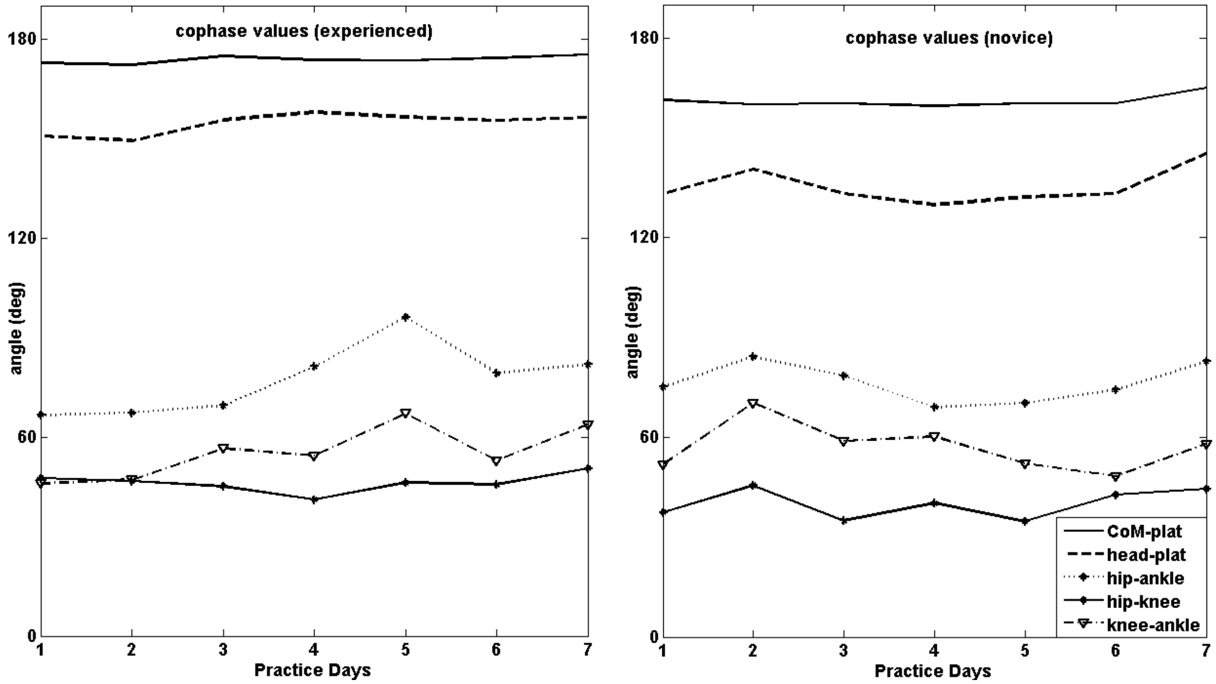


Figure 5.4. Group mean of experienced and novice groups and their cophase values across practice days.

Figure 5.4 illustrates the cophase on the different couplings (CoM-platform, head-platform, hip-ankle, hip-knee, and knee-ankle) across practice days for the two groups – experienced (left panel) and novice (right panel). The CoM-platform cophase values are around 174° for experienced (ex) and 161° for novice (no). Similarly, the two groups showed a difference in head-platform coupling, 155º (ex) and 135° (no), respectively. Regarding the local variables the mean cophase values are 77° (ex) and 76º (no) for hip-ankle, 46° (ex) and 40º (no) for hip-knee and 55º (ex) and 57° (no) for knee-ankle.

A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) was carried out across the cophase values of CoM-platform and showed a statistically significant main effect of group, $F(1, 70) = 231.24$, $p < 0.01$. Similarly, for head-platform cophase values, there was statistical significance for the main effect of group, $F(1, 70) = 43.69$, $p < 0.05$. The interaction of group and days was significant, $F(6, 70) = 2.19$, $p < 0.05$, for hip-ankle cophase values. For hip-knee cophase values, there was statistical significance for the main effect of group, $F(1, 70) = 43.60$ at $p < 0.05$, whereas knee-ankle cophase values were not statistically significant.

Coherence

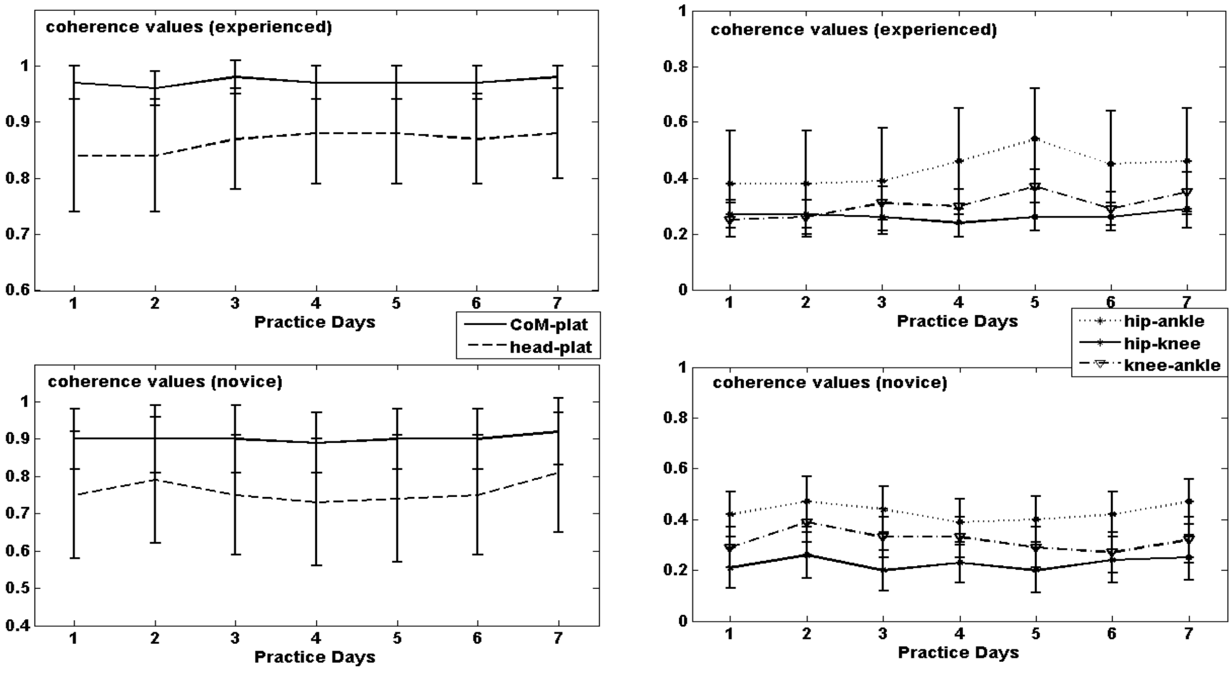


Figure 5.5. Group mean of experienced and novice groups and their coherence values with standard deviation across practice days.

Figure 5.5 illustrates the coherence with standard deviation of the different couplings of CoM-platform, head-platform for experienced (upper left panel), hip-ankle, hip-knee and knee-ankle for experienced (upper right panel), CoM-platform, head-platform for novice (lower left panel) and hip-ankle, hip-knee and knee-ankle for novice (lower right panel). A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) on the coherence values of CoM-platform showed a significant main effect of group, $F(1, 70) = 239.57$, $p < 0.01$. Similarly, for head-platform coherence values, there was statistical significance for the main effect of group, $F(1, 70) = 44.37$, $p < 0.01$. The interaction of group and days, $F(6, 70) = 2.23$, $p < 0.05$ was significant for hip-ankle cophase values. For hip-knee and knee-ankle, the coherence values were not statistically significant.

Asymmetry

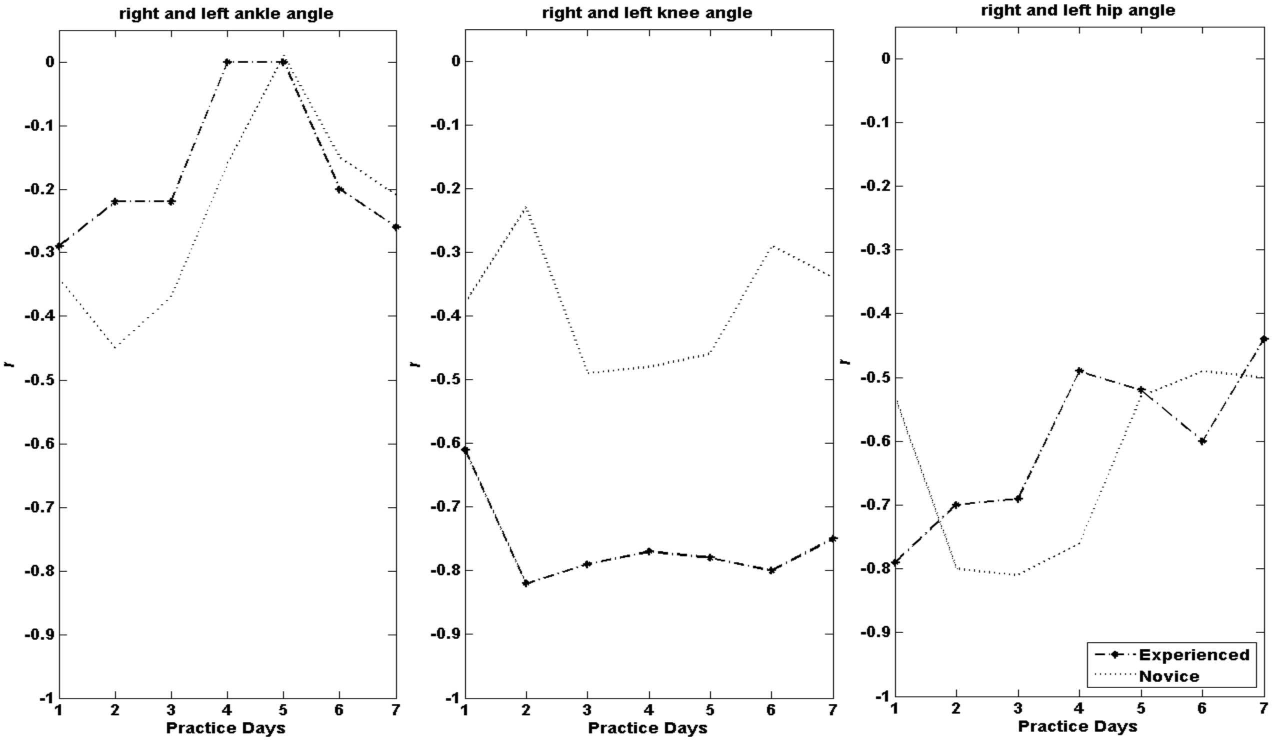


Figure 5.6. Group mean of experienced and novice groups and correlation coefficient of right and left joint angles (ankle, knee, and hip) across practice days.

A correlation coefficient was performed for the left and right angular joints – ankle (left panel), knee (middle panel) and hip (right panel) to determine any asymmetric differences between the two groups across practice days (see Figure 5.6). A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) was carried out across the correlation coefficient values of right and leg ankle angle and showed a statistical significance in main effect of day, $F(6, 70) = 2.16$. $p < 0.05$. For right and leg knee angle, there was a statistical significance in main effect of group, $F(1, 70) = 25.05$, $p < 0.05$. The asymmetry of ankle and hip joint angles was closer to 0 as a function of practice days.

Joint Angle Properties

Table 5.1. Coefficient of variation of experienced and novice groups for ankle, knee and hip angles across practice days.

Practice Day	Ankle		Knee		Hip	
	Experienced	**Novice**	**Experienced**	**Novice**	**Experienced**	**Novice**
1	**0.07**	**0.30**	**0.05**	**0.16**	**0.04**	**0.10**
2	**0.08**	**0.34**	**0.06**	**0.19**	**0.05**	**0.13**
3	**0.07**	**0.37**	**0.06**	**0.22**	**0.05**	**0.15**
4	**0.07**	**0.45**	**0.06**	**0.22**	**0.05**	**0.16**
5	**0.06**	**0.43**	**0.06**	**0.25**	**0.05**	**0.17**
6	**0.07**	**0.51**	**0.06**	**0.23**	**0.05**	**0.17**
7	**0.07**	**0.53**	**0.06**	**0.24**	**0.05**	**0.17**

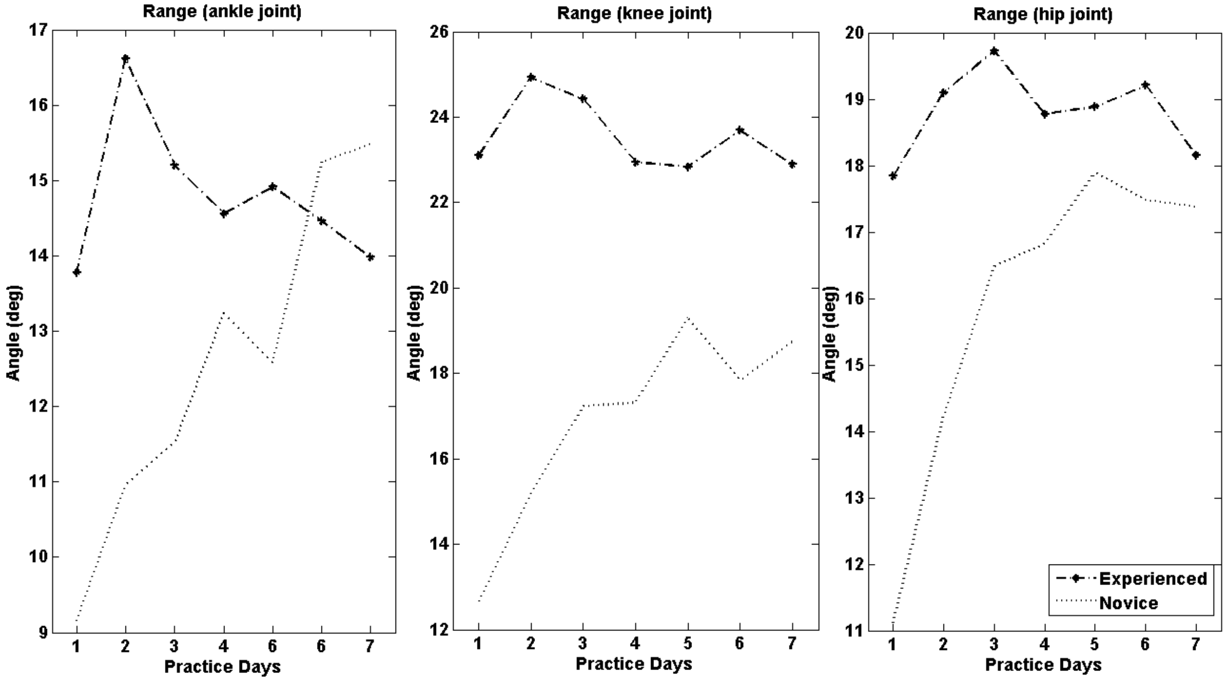


Figure 5.7. Group mean of experienced and novice groups and their joint angle range (ankle, knee and hip) across practice days.

Figure 5.7 and Table 5.1 depict the kinematic variables of angular joints – ankle (left panel), knee (middle panel) and hip (right panel) for the two groups, summed over the contralateral sides across practice days. Clearly, the novices enhanced their joint angle range across practice days (see Figure 5.7). As a function of practice days, the novice increased their angular standard deviation for all their lower joint angles (see Table 5.1) and showed the effect of exploiting the *dof* as a function of practice (Vereijken et al., 1992). The experienced group maintained their angular standard deviation across practice days. A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) was carried out across the knee joint angle, which showed statistical significance in the main effect of group, $F(1, 70) = 50.16$, $p < 0.05$. Similar analysis on hip joint angle showed statistical significance for the main effect of group, $F(1, 70) = 6.06$, $p < 0.05$.

A two-way repeated ANOVA of 7 (days) x 2 (groups – novice and experienced) on the standard deviation of ankle joint angle showed a significant main effect of group, $F(1, 70) = 234.84$, $p < 0.05$. For knee joint angle and hip joint angle standard deviation, the main effect of group was statistically significant, $F(1, 70) = 102.71$, $p < 0.05$ and $F(1, 70) = 236.57$, $p < 0.05$, respectively.

Discussion

The study investigated the acquisition of dynamic cyclical postural stability as a function of prior experience and practice in related whole body motor tasks. The theoretical focus was to analyze the dynamic mechanisms used to maximize the amplitude of the sideways skiing movement and simultaneously maintain dynamic postural stability. The study also compared the pathways of change of novice and experienced skiers in the course of learning the task.

The focus was an examination of Bernstein's (1967) *dof* problem in the early stage of skill acquisition (freezing the redundant *dof*) and subsequent stage of skill execution (freeing the redundant *dof*). In an earlier study, evidence was shown for the phenomenon of freezing and freeing redundant *dof* as a function of practice in the ski-simulator task (Vereijken et al., 1992). However, studies have not compared the pathways of change of joint couplings with that of a collective variable and how prior skill level influences such motor learning (Hong & Newell, 2006a; Nourrit et al., 2003; Vereijken et al., 1997; Wulf & Weigelt, 2013).

The findings showed that there was both a qualitative (see Figure 5.2c) and quantitative (see Figure 5.4 & Figure 5.5) pattern of change over time in learning the dynamic cyclical task (sideways skiing movement) as a function of practice. There was large variability in the novice group when compared with the experienced group and a distinct learning curve was not reflected by the traditional power law (Newell & Rosenbloom, 1981; Schmidt & Lee, 2013). Overall, the findings reveal a large repertoire of individual dynamic pathways that emerge from forming a new coordination pattern (anti-phase coupling of CoM-platform) adopted to maintain dynamic postural stability.

Figure 5.2c illustrates the cophase values of CoM-platform of the 6 novice individuals on day 1 across the first 3 trials. Three novice individuals showed a phase transition from an in-phase to anti-phase coordination mode between trial 1 and trial 3 on day 1. A phase transition was not shown by all the novice individuals as they attempted to execute the alternative sideways movement with identifiable lower platform amplitude in the early phases of practice. The finding of different pathways of change in the novice group in order to maintain dynamic postural stability highlight the principle of degeneracy in coordination dynamics (Bernstein, 1967; Edelman & Gally, 2001), which when viewed from the uncontrolled manifold hypothesis framework is considered occurring in the ‘null space’ where the task variable is preserved by self-organizing the elemental variables (Scholz, Schöner, & Latash, 2000).

The CoM and head motions appear to be independent kinematic variables when compared with the first phase of practice days (day 1, trial 1) to the last phase of practice days (day 7, trial 20) (see Figure 5.3a and Figure 5.3b). A subset of the novice participants adopted initially in practice an inverted pendulum mode with large amplitude in the distal end (head) and constrained amplitude at the pivoted end (platform) that was essentially in-phase. As a function of practice the inverted pendulum mode switched to a hanging pendulum mode with large amplitude in the distal end (platform) and constrained amplitude at the pivoted end (head) to reflect the learning of a new anti-phase coordination pattern (Newell et al., 2001, 2006; Vereijken et al., 1992, 1997).

Cophase and coherence analysis of the coupled variables illustrated that CoM-platform cophase value was higher (~ 174º) in the experienced group than the novice group (~ 161º). On the contrary, the head-platform coupling had weaker cophase values of ~150° for the experienced group and ~145º for the novice group, thereby highlighting distinct coupling when compared to the CoM-platform coupling pattern (see Figure 5.4). The couplings of the synergy variables (hip, knee and ankle) showed different coordination dynamics than the couplings of CoM-platform and head-platform (see Figure 5.4), which highlights that the self-organization of the synergy variables are occurring within the relative preservation of the coupling of the CoM-platform motion along ML plane (Haken, Kelso, Fuchs, & Pandya, 1990; Kelso, 1995; Ko et al., 2014). Intermediate coherence values of synergy variables (hip-knee-ankle) reveal that the coupling is weak when compared to the candidate collective variable. Hence, the time scales of the synergy variable couplings are faster and relatively unstable compared to the collective variable (Kelso, 1995).

The coherence values of the coupling of CoM, head, platform, hip, knee and ankle motion along ML direction were analyzed and revealed that the experienced group is already attuned to the demands of the novel task and hence can execute in-phase coupling of CoM-platform from trial 1, day 1 unlike the collective novice group. The coherence analysis showed that the coordination dynamics of the candidate collective variable (CoM-platform) reveals distinct coherence values (~1) when compared to the coupled synergy variables (~ <0.5) across practice days (see Figure 5.5) for both groups. By definition, a collective variable changes more slowly than the subsystems, i.e. the time constants are much longer than the time constants of the component motions. The property of CoM motion in comparison to head motion as a function of increasing platform velocity, reveals that CoM has a slower rate of change as a function of the control parameter (platform velocity) (Kelso, 1995).

The issue of asymmetry among the two functional groups was addressed by performing correlation analysis for the contralateral joint angles over practice days. The findings clearly show that the two body sides are not strictly coupled in their respective actions, since the cross-correlation coefficients did not approach ±1 (Vereijken et al., 1992). The negative signs of the cross-correlations of the hip, knee and ankle, are likely to be inherent of the task constraints imposed. Also, high negative cross-correlation coefficient values for hip and knee than the ankle reflect that the knee and hip had more alternate motions than the ankle for both the groups. The negative cross-correlation coefficient result of ankle is different from an earlier study (Vereijken et al., 1992) which showed that cross correlation coefficient of ankle was positive.

Table 5.1 and Figure 5.7 cumulatively illustrate the joint properties of the two groups and their pattern of change across practice days. As hypothesized the experienced and novice group revealed distinct joint angle motions. The novice group had larger angular standard deviation across practice days, thereby reflecting the freeing *dof*s (Bernstein, 1967) and is consistent with the previous findings in the ski-simulator task (Vereijken et al., 1992). The hip joint angle reduced considerably as a function of practice in both groups reflecting that the joint angle closer to CoM location was stabilized to attain dynamic postural stability.

The platform kinematics of platform frequency, amplitude and velocity were investigated to capture the nature of change across practice (den Brinker & van Hekken, 1982; Wulf, Höß, & Prinz, 1998) and showed statistical significance in the performance variable between the two skill groups. The instruction was to simultaneously increase the platform frequency and the amplitude of the sideways movement. The two groups had different pathways of change over practice to realize the task goal and is shown in the platform velocity. Typically, the novices had higher platform frequency due to smaller sideways amplitude in the early periods of practice. However, as the amplitude grew larger over practice, the frequency of the platform decreased, which highlights that simultaneous improvement in both platform amplitude and frequency is challenging for the novice. The experienced group had a platform velocity of 6 m/s that improved marginally by 0.5 m/s, yet the novice group showed a non-linear improvement of platform velocity over practice and had values closer to the day 1 values of the experienced group.

In summary, this study investigated how the influence of skill level and practice affect the different pathways of change involved in learning a novel task. The findings revealed that the novice group adopted a large repertoire of dynamic pathways consistent with the principles of degeneracy that emerge from solving a new coordination pattern. A subset of novice participants showed a transition of in-phase coupling of CoM-platform to anti-phase coordination pattern as they searched the variable space to realize the task goal – simultaneously producing maximum amplitude and higher frequency of the skiing movement. The slow time scale properties of CoM-platform motion when compared with head-platform and other synergy variables provide further evidence of CoM-platform as a candidate collective variable for this dynamic postural balance task.

CHAPTER 6: GENERAL DISCUSSION

This dissertation investigated the candidate collective variables of dynamic postural coordination patterns that emerge from the self-organization of sub-elements involving individual joint motions as a function of the nature of base of support. Investigation of such collective variables is critical to understanding the organization of multiple *dof* in dynamic postural control in a macroscopic dynamical systems paradigm. Three experiments were conducted based on the dynamic support surface paradigm – tilted platform (Paquette, Franzén & Horak, 2015; Simeonov, Hsiao, Dotson, & Ammons, 2003), moving surface (Buchanan & Horak, 1999; Ko, Challis & Newell., 2001) and ski-simulator (den Brinker & Van Hekken, 1982; Vereijken, van Emmerik, Whiting, & Newell, 1992). The general instruction required the participants to maintain their postural balance while standing upright on a base of support that was rotated up or down (tilted platform), moved sinusoidally with an external motor (moving platform) and continuous self-generated sideways movement (ski-simulator).

Primarily, there were four questions addressed in this dissertation: (1) How do the candidate collective variable and the synergy variables reveal a distinction in the qualitative dynamics for multi-segmental coordination in a dynamic postural balance task? (2) Does the nature of collective variable change as a function of practice? (3) How does prior skill level effect the acquisition of the collective variable? (4) What is nature of the coordination of the functional joint *dof*s in the framework of quiet upright standing under the different slopes of the surface of support? In Experiment 1 and 3, cophase and coherence analysis techniques were applied to investigate the nature of coupling of global (CoM-CoP) and synergy (hip-knee-ankle) variables across sloped surfaces. In Experiment 2, a point estimate relative phase analysis was applied to investigate the non-equilibrium phase transitions of CoM-CoP, Head-CoP along with synergy coupling consisting of hip, knee and ankle across continuous scaling of moving platform sinusoidally.

Theme 1: Candidate collective variable

In coordination dynamics, a major feature of the experimental agenda is to find the variable(s) that is used to coordinate and control the multiple *dof*s while attempting to realize a postural task, that is, Bernstein's *dof* problem (Bernstein, 1967). Nascent theories in postural coordination have deemed that posture is a behavioral expression of centrally programmed neural strategies (Alexandrov, Frolov, & Massion, 1998; Nashner & McCollum, 1985). However, under the constructs of dynamical systems theory, postural coordination is viewed as a self-organization of relevant individual *dof*s that exhibits hallmarks of non-equilibrium phase transitions between attractors (Kelso, Scholz, & Schöner, 1986; Kelso, 1995). Such a construct accommodates the aspects of biomechanical and neurophysiological holonomic and non-holonomic constraints (Pattee, 2012) including neural signals, sensory impulses and internal/external forces (Riccio, 1993; Thelen & Spencer, 1998) in postural control. Furthermore, coordination of relevant individual *dof*s to maintain upright dynamic posture under the given constraints could be associated with the concept of candidate collective variable of the postural control system that remains unresolved in the *dof* problem (Bernstein, 1967).

In synergetics, the order parameter or collective variable is created by the cooperation of the individual *dof*s of the system. Conversely, it governs or constrains the behavior of the individual *dof*s as hypothesized in the construct of circular causality (Frank, Michelbrink, Beckmann, & Schöllhorn, 2008; Kelso, 1995). In any situation, the individual will assemble a behavioral response, that is, the collective coordination pattern of the current status of the ensemble - a preferred coordination pattern that involves the cooperative interactions of all the individual components (*dof*s) within a particular situation. This cooperativity - the reduction in the dimensionality of the original components (*dof*s) to a compact pattern - can be captured in one or a few collective variables, that is, variables that describe the collective organization of the ensemble.

Past studies have provided preliminary evidence of collective variables in different movement tasks such as bimanual finger coordination (Kelso, 1984), posture (Ko, Challis, Newell, 2014), rhythmic movement (Beek & Beek, 1988) and locomotion (Schöner, Jiang, & Kelso, 1990). However, the question is whether a movement coordination can be represented by a single collective variable or could there be a cohort of candidate collective variables that describe the system? Typically, under the constructs of dynamical systems theory, a candidate collective variable should show the coordination among the individual *dof*s, and are typically slower changing variable compared to the motions of the individual *dof*s. Other criteria associated with collective variable include non-equilibrium phase transitions, critical fluctuations and hysteresis (Bardy, Oullier, Bootsma, & Stoffregen, 2002; Kelso, Scholz & Schöner, 1986; Schmidt, Carello, & Turvey, 1990).

In Experiment 2 and 3 we found preliminary evidence that CoM-CoP and CoM-Platform couplings are consistent with the criteria of a collective variable and have slower time scale motions than the synergy joint variable motions. We employed point estimate relative phase technique (Clark & Phillips, 1993) for Experiment 2 and cophase technique (Creath, Kiemel, Horak, Petreka & Jeka, 2005) for Experiment 1 and Experiment 3 . The point estimate relative phase technique is well suited to analyze coupled data that show distinct peaks and troughs, whereas cophase technique is appropriate when two-time series are measured simultaneously by computing the spectrum of one or more time series.

In Experiment 2, the candidate collective variable (CoM-CoP) showed that there was a distinct qualitative and quantitative coordination pattern linked to the continuous scaling of the control parameter (platform motion) which leads to a new emergent stable pattern (anti-phase) from an existing stable pattern (in-phase). At lower platform frequencies (< 0.6 Hz), CoM-CoP remains in an in-phase pattern, whereas at higher frequencies (≥ 0.6 Hz), CoM-CoP transitions to an anti-phase pattern. The phase transition frequency band (0.4 Hz to 0.6 Hz) between the two stable coordination patterns is marked by statistically significant variability (increased standard deviation) and hysteresis (see Figure 4.6). It exemplifies the characteristics of non-equilibrium phase transition and shows the qualitative and quantitative differences in the two postural coordination patterns to compensate the scaling of the control parameter (Ko, Challis & Newell, 2014). Although, this experiment extended the analysis to the mediolateral plane, it also investigated another potential candidate collective variable namely Head-CoP coupling that showed similar characteristics of CoM-CoP coupling (see Figure 4.2 and Figure 4.3). Further analysis of CoM and Head motion revealed that the two kinematic variables are independent (see Figure 4.4 and Figure 4.5). Also, as a function of practice trials, CoM-CoP showed a non-linear learning pattern when compared to Head-CoP (see Figure 4.7) and thereby highlighting that CoM-CoP can be potentially termed as a collective variable in maintaining postural stability across the paradigm of the sinusoidal oscillating platform.

In Experiment 3, the candidate collective variable (CoM-Platform) showed that there were distinct features in the coordination patterns such as phase transition and slower time scale motions than the synergy joint variable motions (hip-knee-ankle). The findings revealed that CoM and head motions appear to be independent kinematic variables compared with the first phase of practice days (day 1, trial1) to the last phase of practice days (day 7, trial 20), (see

Figure 5.3a and Figure 5.3b). Clearly, three novice individuals showed a phase transition from an in-phase to anti-phase pattern between trial 1 and trial 3 on day 1 (see Figure 5.3c), which highlights the associative principle of degeneracy in dynamical system coordination dynamics (Bernstein, 1967; Edelman & Gally, 2001).

In Experiment 1, the candidate collective variable of CoM-CoP showed a high coherence (~1) in the low-frequency range and hence maintained the postural integrity of coordination pattern across all tilted platform conditions. In contrast, the coherence of synergy variables (hip-knee-ankle) ranged between 0.4 to 0.7 Hz. Similarly, cophase analysis revealed in-phase coupling of CoM-CoP, especially at the lower frequencies (<1 Hz). On the other hand, the results showed that the lower limb cophase values were not in an in-phase pattern unlike CoM-CoP coupling, yet the multiple *dof*s arising from the lower limb were largely modulated to preserve the CoM-CoP across all tilted platform conditions. In-phase preservation of CoM-CoP coupling with lower variability across all platform condition in comparison with the hip, knee, and ankle paired phase relations with higher variability shows that CoM-CoP (collective variable) coupling evolves on a slower time scale than the joint synergy variable (see Figure 5.7) (Kelso, 1995; Mitra, Amazeen, & Turvey, 1998).

Theme 2: Functional changes in coordination pattern as an effect of practice

In Experiment 2 we showed that with practice trials and days, the collective candidate variable of CoM-CoP for postural coordination develops stronger coupling (see Figure 4.7). The instabilities of CoM-CoP coordination are mastered when subjected to similar perturbations throughout practice. This cooperativity, which reflects the reduction in the dimensionality of the original components to a compact pattern, can be captured in one or few collective variables, in this case, CoM-CoP coordination (Haken, 1983; Kelso, 1995).

In Experiment 3 under an effect of practice, we found that there was both a qualitative (see Figure 5.2c) and quantitative (see Figure 5.4 & Figure 5.5) pattern of change over time in learning the dynamic cyclical task (sideways skiing movement). There was larger variability in the novice group when compared with the experienced group, and a distinct learning curve was not reflected by the traditional power law (Newell & Rosenbloom, 1981; Schmidt & Lee, 2013). Overall, the findings reveal a large repertoire of dynamic pathways that emerge from forming a new coordination pattern (anti-phase coupling of CoM-platform) adopted to maintain dynamic postural stability. A subset of the novice participants adopted initially in practice an inverted pendulum mode with large amplitude at the distal end (head) and constrained amplitude at the pivoted end (platform) that was essentially in-phase. As a function of practice the inverted pendulum mode switched to a hanging pendulum mode with large amplitude in the distal end (platform) and constrained amplitude at the pivoted end (head) to reflect the learning of a new anti-phase coordination pattern (Newell et al., 2001, 2006; Vereijken et al., 1992, 1997).

Theme 3: Functional changes in coordination patterns as an influence of prior skill level

Experiment 3 examined the influence of skill level in learning a dynamic postural stability task (ski-simulator). Bernstein (1967) conceptualized that a novice learner would have to coordinate and control a large number of mechanical *dof* while attempting to learn a novel motor task. He argued that novices would partially freeze out the *dof* (joint angles) at the initial learning stage a finding that has been experimentally supported by (Vereijken, van Emmerik, Whiting & Newell, 1992). He reflected that such a preliminary strategy by novices would aid in reducing the *dof* to a tractable problem. Overall, the findings reveal a large repertoire of dynamic pathways that emerge from forming a new coordination pattern (anti-phase coupling of CoM-platform) adopted to maintain dynamic postural stability.

Three novice individuals showed a phase transition from an in-phase to anti-phase between trial 1 and trial 3 on day 1. Phase transition was not shown to all the novice individuals where the individuals attempt to execute alternative sideways movement with identifiable lower platform amplitude in the early phases of practice. Such different pathways of the novice group to maintain dynamic postural stability highlight the principle of degeneracy in coordination dynamics (Bernstein, 1967; Edelman & Gally, 2001). In comparison, all the experienced skiers maintained anti-phase CoM-Platform coupling across all practice days as a function of the control parameter (marginal improvement in the platform velocity). Cophase and coherence analysis of the coupled variables illustrated that CoM-platform cophase value was higher (~ 174º) in the experienced group than the novice group (~ 161º). On the contrary, the head-platform coupling had weaker cophase values of ~150° for the experienced group and ~145º for the novice group, thereby highlighting distinct coupling when compared to the CoM-platform coupling pattern.

Table 5.1 and Figure 5.7 cumulatively illustrate the joint properties of the two groups and their pattern of change across practice days. As hypothesized, the experienced and novice group revealed distinct joint angle motions. The novice group had larger angular standard deviation across practice days, thereby reflecting the freeing *dof*s (Bernstein, 1967) and is consistent with the previous findings in the ski-simulator task (Vereijken et al., 1992). The hip joint angle reduced considerably as a function of practice in both groups reflecting that the joint angle closer to CoM location was stabilized to attain dynamic postural stability. The two groups had different pathways of change over practice to address the task goal that was shown in the platform velocity. Typically, the novices had higher platform frequency due to lower sideways amplitude in the early periods of practice. However, as the amplitude grew higher over practice, the frequency of the platform decreased, which highlight that simultaneous improvement in both the factors of platform amplitude and frequency was arduous for the novice group. The experienced group had a platform velocity of 6 m/s that improved marginally by 0.5 m/s, yet the novice group showed a non-linear improvement of platform velocity over practice and had values closer to the day 1 values of the experienced group.

Theme 4: Functional changes in coordination pattern as an effect of dynamic support surface

In Experiment 1 we examined the nature of coordination of the functional joint *dof*s under the different tilted support surface. We investigated how the postural system regulated the joint *dof*s under different surface angles of a tilted platform as a function of whether the participant faced up or down the slope. The time scales of the change in the motions of the individual joints (ankle, knee, hip), pair-wise synergies and candidate collective variables (CoM and CoP) were determined and contrasted as a function of platform angles. A central finding was that the CoM-CoP dynamics (both ML and AP) showed a high coherence (~1) in the low-frequency range and hence maintained the postural integrity of the pattern of coordination across all tilted platform conditions. In contrast, the coherence of Hip-Knee, Hip-Ankle and Knee-Ankle had values ranging between 0.4 to 0.7, and typically the pairs of joint motion shifted to upper mid-range (0.7) when compared with the 0° Flat condition to extreme platform conditions i.e. 25° Up or 35° Down.

That the coherence between pairs of joint angles was quite low, underscores the fact that the fluctuating leg joint motions were not strongly coupled. Hence, this pattern of findings is counter to a constrained ankle, or ankle-hip control strategy for postural control. Against the background of modest coupling of the individual joint motions (hip, knee, ankle) the CoM-CoP coupling by contrast remained strongly in-phase for both ML and AP planes for the postural task. The contrasting patterns of change of these global and local variables provide supporting evidence to the idea of CoM-CoP as the candidate collective variable in the modulation of CoM in the state space (Ko et al., 2014; Wang et al., 2014).

The results show that lower limb cophase values were not in an in-phase mode unlike the CoM-CoP coupling, yet the multiple *dof* arising from the lower limb was modulated to preserve the CoM-CoP coupling across all tilted platform conditions. These findings provide further evidence that CoM-CoP coupling is more consistent across all platform conditions than the individual joint motions and paired joint couplings, and this differential modulation supports the notion of CoM-CoP as the collective variable for this task.

The postulation of CoM-CoP coupling as a collective variable is further supported by the evidence arising from the coherence analysis that showed a high and systematic correlated pattern in the frequency domain. Figure 3.8 depicts that the coherence patterns across all the platform conditions were essentially identical in which the CoM-CoP are highly correlated (~0.9) for the sequential frequency bins, whereas the synergies at the musculoarticular level showed the coherence values were mid-ranged (~0.3 – 0.7) across the platform conditions. Such a modest level of coupling is one of the significant features at the musculoarticular level, in which synergies are adaptive in both cooperative and compensatory ways (Bernstein, 1967; Kelso, 1995). The idea is consistent that the collective variable (CoM-CoP) is a higher-order parameter that emerges from the interaction of the neuro-muscular components in the context of the environment and task constraints.

Experiment 1 has provided further evidence that CoM-CoP coordination could be a candidate for a collective variable for quiet standing across different tilted platform conditions (Ko et al., 2014; Wang et al., 2014). Although, these previous studies have shown that such relation holds for other postural tasks, and have examined muscular and somatosensory perception while quiet standing coordination on inclined planes (Mezzarane & Kohn, 2007; Paquette et al., 2015; Simeonov et al. 2009), this study is the first to generalize the concept of a collective variable to the tilted platform surface of support – a postural control task that occurs in everyday life. We have shown that the principles of coordination dynamics that hold that the collective variable is an emergent property because of the compensatory and cooperativity of the individual components at the musculoarticular level map well to the organization of postural control. Subsequent studies need to address the weighting of each joint angle (upper and lower body) and analyze how the weightings co-vary across the different platform conditions to explicitly examine the role of collective variables to each functional *dof* in postural control.

To conclude, these cohort of studies provide a strong evidence for CoM-CoP coupling as a collective variable for various dynamic postural tasks but it could be speculated whether such a concept of collective variable can be generalized to other multifaceted tasks such as reaching while maintaining postural equilibrium or investigating postural stability among physically challenged participants.

Limitations

There were some limitations in the current experiments.

In Experiment 1 the pre-fabricated wooden wedges were laid on the force platform and zeroed after being mounted to get the center of pressure, which is based on the *x*, *y* and *z* components of force and moments. Although, the wedges were custom fit for the force platform, there is always a possibility while stepping on the wooden wedge that the side edges of the force platform might be touched which might affect the moment components of the center of pressure calculations.

In Experiment 2, the participants were to fold their arms in front of their chest during the trials. This measure was considered to simplify the center of mass calculations and also ensure that the sampling frequency (100 Hz) was consistent across the kinematic and kinetic measures. Typically rapid arm movements on a moving platform would require higher sampling rates. However, it is necessary to consider arms motions and then investigate how the organizational properties of postural stability were changed as a function of dynamic support surfaces.

Experiment 3 consisted of twenty trials for seven consecutive days. However, the effect of fatigue was not considered which might hinder overall performance as a function of practice trials. Lastly, CoP is an emergent variable that meets the criteria for qualifying as a collective variable, however due to technological constraints we were not able to apply the CoP variable in the third experiment. However, the platform kinematics is a commensurate variable that identifies the motion of the lower limb and that drives the postural stability in sideways skiing movement. Also, Experiment 1 and Experiment 2 analysis were based on the calculation of the CoP. Typical errors associated with such measures consists of parameters and variables that are combined which can lead to operational inaccuracies, the conditional changes from calibration to actual measurement time and also the derivatives of the CoP signal are less precise than original data.

General conclusions

In summary, the dissertation showed the following main outcomes:

(1) The concept of collective variable is generalized across multiple dynamic postural stability tasks involving tilted platform, moving platform and ski-simulator. In this view (Kelso, 1995), the collective variable of these individual synergy variables and reflects the constructs of circular causality – a reciprocal constraint that is observable in the multi-joint *dof* of postural coordination under the demands of the task and environmental constraints.

(2) The pattern of findings suggests that the individual assembles a behavioral response that is the collective pattern of the current status of the ensemble, a preferred postural pattern that involves the cooperative interactions of all the components of a particular situation. This cooperativity, which reflects the reduction in the dimensionality of the original components to a compact pattern, can be captured in one or few collective variables, in this case, CoM-CoP for tilted and moving platform and CoM-Platform for the ski-simulator task. The CoM and head reveal independent motions.

(3) The influence of skill level (Experiment 3) and practice (Experiment 2 and Experiment 3) affect the different pathways of change involved in learning a novel task. These findings revealed that the novice group adopts an extensive repertoire of dynamic pathways consistent with the principles of degeneracy that emerge from solving a new coordination pattern.

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VITA

Aviroop Dutt-Mazumder

Education

The Pennsylvania State University, University Park, PA

PhD Candidate, Kinesiology	*May, 2016 (expected)*
Graduate Online Teaching Certificate	*2015*

University of Otago, Dunedin, New Zealand

Postgraduate Diploma, Sports Science	*2011*

Jadavpur University, Kolkata, India

BSc, Physics; minor, Math	*2008*

Honors

Marie Skłodowska-Curie Actions, European Commission

Post-doctoral fellowship	*2016*

Annual Graduate Exhibition, The Pennsylvania State University

1st Prize (Health Science Division)	*2015*

Peer-Reviewed Publications

1. **Dutt-Mazumder, A.,** & Newell, K. (under preparation). Transitions of postural coordination as a function of oscillatory platform dynamics. *Royal Society Open Science*.
2. **Dutt-Mazumder, A.,** Challis, J., & Newell, K. (under preparation). Maintenance of postural stability as a function of tilted base of support. *Human Movement Science*.
3. **Dutt-Mazumder, A.,** Slobounov, S., Challis, J., & Newell, K. (under preparation). Postural stability margins as a function of support surface slopes. *Gait & Posture*.
4. **Dutt-Mazumder, A.,** & Newell, K. (under preparation). Influence of skill level on acquisition of dynamic cyclical postural stability as a function of practice. *Journal of Experimental Psychology: Human Perception & Performance*.