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Postural Instabilities and the Maintenance of Bi-manual Rhythmic Movement

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POSTURAL INSTABILITIES AND THE MAINTENANCE OF BI-MANUAL RHYTHMIC MOVEMENTS

A Thesis Presented

by

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DEDICATION

I would like to dedicate this project to all of my drum instructors. In our quest for perfection, they helped me develop the work ethic that allowed me to persevere through this degree. Thank you for always asking me to demand more of myself, more importantly, thank you for being my inspiration.

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ABSTRACT

POSTURAL INSTABILITIES AND THE MAINTENANCE OF BI-MANUAL RHYTHMIC MOVEMENTS

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Most research on bimanual rhythmic coordination has occurred with the participants in a seated posture. Many activities of daily living, however, require the interaction of standing postural and manual tasks. A population of individuals that are ideal for studying the integration of a manual task into the ongoing control of posture are expert marching percussionists; they have learned to produce rhythmic movements accurately under a variety of temporal and postural constraints. The purpose of the current study was to investigate the integration of bimanual rhythmic movements and posture in expert marching percussionists. Participants (N=11) were recruited from the University of Massachusetts Drumline, and were asked to perform three rhythmic tasks [1:1, 2:3, and 2:3-F (2:3 rhythm played faster at a self-selected tempo)] in one of three postures: sitting, standing on one foot, and standing on two feet. Discrete relative phase, postural time-to-contact, and coherence analysis, were used to analyze the performance of the manual task, postural control, and the integration between postural and manual performance. Across all three rhythms, discrete relative phase mean and variability (SD) results showed no effects of posture on rhythmic performance. The complexity of the manual task (1:1 vs 2:3) had no effect on postural time-to-contact. However, increasing the tempo of the manual task (2:3 vs. 2:3=F) did result in a decreased postural time-to-contact in the two-footed posture). Coherence analysis revealed that the coupling between the postural and manual task significantly decreased as a function of posture (going from a two footed to a one footed posture) and rhythmic complexity (1:1 vs. 2:3). Taken together, these results demonstrate that expert marching percussionists systematically decouple postural and manual fluctuations in order to preserve the performance of the rhythmic movement task.

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CHAPTER 1

INTRODUCTION

The ability to stand and perform multiple tasks (e.g. standing and reaching for an object on a shelf) requires complex neurological control. To simply rise from a chair, reach for an object on the top shelf, or stand at a concert tapping along to your favorite band requires the nervous system to coordinate its 10^3 muscles and 10^2 joints into one cohesive unit (Kelso, I995). Most activities of daily living do not necessarily carry adverse consequences if they are not performed in a specific manner; but activities such as marksmanship, dancing, or marching band require highly accurate and reproducible movements. For example, how does the nervous system of an expert marching percussionist maintain an internal sense of time, while playing isochronously with his/her peers, and maintain upright posture? Does the nervous system control the multiple tasks as one motor function, or do the individual subtasks work cooperatively to form a complex movement?

Some of the answers to the questions posed above have come from the study of rhythmic movements. Research on these movements has shown the nervous system functions as a self-organizing system whose subcomponents work cooperatively.

Movement is not controlled as one hierarchical top-down process, but by the interactions of multiple degrees of freedom working in concert (Kugler & Turvey, 1987). How this cooperation and integration is accomplished is still largely unknown. The sections that follow will provide a brief review of each of the subtasks and how they may interact.

Postural Control

The goal of the postural system is to maintain systemic balance as the body's segments change their geometrical configuration throughout a movement; this requires full body coordination. Balance is only achieved when the body's center of mass (CoM) is aligned with the gravitoinertial force vector (Riccio & Stroffregen, 1988). The relatively constant position of the COM during quiet stance (resting between the feet if standing shoulder width apart) is regulated by the more variable center of pressure (CoP). The CoP is the position of the ground reaction force vector reflecting all of the pressures being applied to the support surface (Winter, 1995). Movements along the kinematic chain are reflected in the CoP fluctuation pattern (Collins & De Luca 1993).

Measures of postural stability traditionally have used stabilogram (a 2D plot of anterior-posterior vs medio-lateral postural sway) variability and total postural excursion as means of gauging systemic stability (i.e. larger variability and path length is indicative of an unstable system). These spatial measures do not take into account the rate of change of the CoP relative to the boundary of the base of support (BoS) formed by the feet. In the control of stance the geometry of the base of support plays an important role in decision making of whether a compensatory action, stepping, will occur. Stepping is a means of increasing the area of the BoS in the plane of the perturbation and allows the CoP enough room to distance itself from the CoM (Blaszczyk, 2008; Slobounov & Newell, 1994; Winter, 1995). Stepping is often considered compensatory strategy of 'last resort', but when left unconstrained it is more likely to occur then other strategies such at the ankle and hip strategy, in which there is no change in the base of support (McIlroy & Maki, 1993). Rather than using the CoP excursion as a measure of instability, Riccio (1993) proposed the time to contact of the CoP with the base of support as a more viable means of quantifying instabilities. The time to contact (TtC) variable, is thought to be a directly perceivable and dynamically controlled variable; it considers the rate at which the CoP moves toward a functionally specific boundary (Haddad et al., 2006). It is thought that the system is able to perceive the gap between the CoM and the base of support, and when this gap closes is when a compensatory step is taken. Due to its dynamic nature, the TtC variable is a better suited variable to understand postural control.

Rhythmic Movements

The study of oscillatory movements has provided insights into the organizational properties of the nervous system (Turvey, 1990; Turvey & Carello, 1996). For example when two index fingers are oscillated 180° anti-phase (i.e. one moves up while the other is moving down) their relative motion or phase relationship shifts to in-phase (i.e. moving in the same direction together) as frequency reaches a critical point (Kelso, 1984). Regardless of the limb couplings (wrists, fingers, pendulums), the anti-phase pattern consistently gives way to in-phase movement as frequency of oscillation increases, but the opposite does not occur (Haken et al., 1985; Kelso, 1984; Kugler & Turvey, 1987). Changes from one mode of coordination to another are accompanied by increased variability in the signal, followed by an abrupt non-linear transition (i.e. a behavioral transition that resembles a step on a stair case) of the collective variable (a variable whose pattern of behavior can distinguish between different states of the system), relative phase, to a new behavioral pattern. The ability to switch pattern demonstrates the flexibility of the system and its ability to form new phase relationships to maintain systemic stability in light of perturbations.

Multi-frequency, polyrhythmic, behavior is a result of the nervous system coordinating oscillators of different natural frequencies into a temporarily constructed unit of action. These types of couplings exist at all levels of the body (i.e. from the most microscopic to the viewable macroscopic level), but understanding the principles which underlie their formation can be difficult. Rhythmic movements performed by untrained and trained musicians have shown that the nervous system uses principles of resonance to couple limbs of unlike frequencies (e.g. a coupling in which one oscillator is moving at 2 Hz while the other oscillator moves at 3 Hz) (DeGuzman & Kelso, 1993; Treffner & Turvey, 1993; Peper et al., 1995). Understanding the frequency ratios which the nervous system is biased toward can be explained by the sine circle map. Iterating the sine circle map through its parameter space produces a series of mode locking regions known as the Arnol'd tongues. Each resonance region or tongue represents a stable frequency ratio (Ω) of the two coupled oscillators. These regions increase in width as the coupling strength, K, increases (e.g. the oscillators above would form a 2:3 ratio). When comparing lower frequency ratios (1:1, 2:1, 3:2) to the higher frequency ratios (4:3, 3:5), the lower frequency ratios are wider compared to higher frequency ratios making them more stable and robust against perturbations. In tasks where the participant was asked to maintain the motion of a drum stick in mid air in accordance with the metronome, such that the metronome and hand formed a particular coupling frequency, participants tended to shift from high order frequencies (2:5,3:5,3:4) to lower order frequencies (1:1,2:1). Similarly when participants tapped a 2:3 rhythm, the frequency spectrum demonstrated that the faster rhythm influenced the behavior of the slower rhythm by increasing the power at higher frequency levels, suggesting that coupling strength is inversely proportional to movement frequency (DeGuzman & Kelso, 1993; Peper, 1995).

Postural-Focal Dynamics

The main goal of the postural system is to remain upright, but this task is often complicated by other concurrent tasks. In laboratory settings, dual task paradigms have been used in a variety of ways to understand how the nervous system integrates two concurrent tasks. Postural stability is influenced by tasks being performed concurrently (Bardy et al., 1999). These scenarios require the system to embed the supra-postural (focal) task into the ongoing control of posture. Von Holst suggested the nervous system accomplishes this through the superimposition, or the summation, of different rhythmic wave forms. For example in a reaching task there are two functional synergies that must be controlled (i.e. the reaching synergy and trunk synergy). Regardless of whether or not the trunk is involved in the reaching task, velocity profiles and spatial trajectory of the arm remain constant (Ma & Feldman, 1995). Postural response can also be affected by manipulating sensory information. For example during a visual tracking task the relative phase between the ankle and hips reflects the speed by which the object being tracked is moving at. As frequency increases the relative phase between the ankle and hips goes from an in-phase (30°) to an anti-phase (170°) mode of coordination; the opposite occurred when the frequency of oscillation decreased (Bardy et al., 2002). Unlike the stable phase relationships realized in bi-manual rhythmic performance, in postural control in-phase movements give way to anti-phase as a function of the oscillatory frequency of the object being tracked (Bardy et al.,2002; Faugloire et al. 2005).

In the previously mentioned studies the visual task influenced the postural responses, suggesting that postural control is modulated by task constraints. For example in block fitting tasks, when greater precision is needed the time to contact of the COP to the base of support is increased as the block approaches the hole. The rate of contact of the COP is not as tightly regulated in tasks which do not require as much precision (Haddad et al 2010. Postural control is a key pre-requisite in the control of rhythm. In one of the few (if not the only) studies that have incorporated postural control into the production of rhythm, Welsh and colleagues demonstrated a decrease in rhythmic variability (in a 1:1 rhythmic task) as the movement of the trunk was reduced by a support surface (Welsh et al., 2010). Taken together with the previously reported studies, these results speak to the importance of controlling the degrees of freedom during postural-focal tasks.

Specific Aims

The marching percussion activity poses challenges to the nervous system requiring simultaneous control of end-effectors (sticks) and the postural system. Given that inter-segmental coordination is a result of superimposition of rhythms, marching percussionists are ideal for studying rhythm as a suprapostural task. The objective of the current work is to quantitatively describe how bimanual coordination is affected when the stability of the postural system is changed. The central hypothesis is that postural fluctuations will be increasingly reflected in the bi-manual rhythmic task as postural demands increase.

The testing of the central hypothesis and completion of the current proposal's objective will be realized through the following specific aims:

Aim 1: To quantify the changes in bimanual coordination dynamics as a function of postural and rhythmic constraints. Hypothesis: Decreases in postural stability (i.e. standing on one foot versus sitting down), and increases in rhythmic task difficulty will result in an increase of relative phase variability in a manual drumming task. To test this hypothesis, markers will placed on the stick and their trajectories will be recorded during the performance of two different rhythms (2:3 and 4:6). The primary means of analysis will be Discrete Relative Phase (DRP) between several points in the rhythmic cycle.

Aim 2: To quantify the changes in postural control as a function of postural and rhythmic constraints. Hypothesis: As rhythmic and postural demands increase, postural stability will decrease. Postural measures will be derived from ground reaction force time series obtained from a single force plate (600 x 1800, AMTI). The primary analysis of postural control will be the time to contact (TtC) variable of the COP. A decrease in mean TtC and an increase in TtC variability will be indicative of decreased postural stability.

Aim 3: To quantify the changes in postural-focal interaction dynamics as a function of postural and rhythmic constraints. Hypothesis: Drum stick movement patterns and CoP will become more tightly coupled as postural stability decreases. To test this hypothesis, CoP and stick time series will be analyzed using cross mutual information (CMI). Large CMI values will be indicative of increased coupling between the two signals.

CHAPTER 2

LITERATURE REVIEW

Degrees of Freedom problem

The question that has long plagued motor control theorists is: How does the nervous system control its large number of degrees of freedom? Degrees of freedom (DoF) are defined as the minimal number of independent coordinates needed to define the position of an element in a system (Turvey et al., 1982). The Human body is a complex system with a number of scales of magnitude, thus it has a large number of variables which can be consider individual (10^3 muscles and 10^2 joints, 10^{10} neurons) (Kelso, 1995). Vital to control of movement are constraints. Constraints work to place elements of the system into relations, thus reducing the number of DoF that must be accounted for. For example a tricycle would be difficult to control if each wheel) had its own individual control mechanism. By constraining two of the tires by using an axle, the system's degrees of freedom changes from 6 to 5 (eq. l) (N is the number of elements, D is the number of dimensions, and C is the number of constraints) (Turvey et al., 1982).

Equation 1: Degrees of Freedom

Degrees of Freedom= ND-C

In order to constrain its degrees of freedom, the nervous system temporarily groups muscles into functional units of movement, muscle synergies or coordinative structures (Turvey et al., 1982, Kugler & Turvey, 1987). This strategy, although similar to the tricycle example above, differs in the sense that mechanical degrees of freedom do not form the only source of variation in human movement; there are a number of other biological processes (e.g. conduction rate, disease status, etc.) that contribute to the final motor output (Mayer-Kress et al., 2006). For example the elbow joint has a limited number of degrees of freedom, but it has wide array of behavioral functions as well as force producing capabilities which it can perform given its biomechanical constraints. Creating system wide linkages, via the nervous system, allows the body's numerous subsystems to cooperate, so that coordination then becomes the control of relations between the components or elements rather than controlling each individually. For example, if the jaw receives a perturbation during speech, adjustments by the tongue and lips are automatically made to produce the selected utterance (Kelso et al., 1984). This example is meant to highlight the nervous system's ability to rapidly adjust the relationship of the elements within a coordinative structure so that a task (in this case speaking a particular word) may be completed. If coordinative structures are self-adjusting, then what are the principles which guide their formation and annihilation?

The principles which guide the assembly and disassembly of coordinative structures are derived from the study of physical nonlinear self-organizing systems. Russian physiologist Nikolai Bernstein recognized the challenge faced by the motor system (i.e. excessive DoF) and proposed the motor apparatus is controlled as a mass-spring system whose equilibrium point is the intended limb position. A mass-spring is a physical oscillatory system that is impervious to initial conditions; after it's perturbed it eventually settles back down on its equilibrium point. Although human movement may abide by some of the same principles, (i.e. regardless of initial conditions a limb can return to a desired position), a mass-spring requires an external source of energy for it to begin moving, making it an unsuitable model to describe an animate system. Humans, unlike mass-springs, have the ability to internally produce energy to counterbalance the loss of energy during movement. A more appropriate oscillatory system to model the behavior of coordinative structures is the limit cycle (Turvey et al., 1982; Tuller et al., 1982; Turvey, 1990).

Homeokinetic theory predicts that complex systems are composed of numerous limit cycles. A limit cycle oscillator is a self-sustaining oscillatory system that maintains a relatively constant frequency and amplitude regardless of any disturbances to the system (Kelso. et al., 1981; Kugler & Turvey, 1986). For example when two fingers are oscillating opposite of each other (i.e. one moves up while the other moves down}, and one of the fingers receives a sudden perturbation, its relationship to the other finger returns immediately (Kelso et al., 1981). Limit cycles are stable because their force producing and timing mechanisms are independent of each other when one is disturbed, the other is left relatively unaffected. Their ability to keep energy flux at a relatively stable level makes this class of physical systems robust to parametric changes. When perturbations begin to reach critical levels, and the amount of energy being input to the system is larger than the amount of energy it is able to dissipate, the system undergoes a pattern change, or a change in elemental relationships (Kelso, 1995). The concept of changes in elemental relationships is a key property of the limit cycle which makes it an ideal candidate for understanding movement and its control. In the sections that follow we will review a variety of examples of how the nervous system uses the principles of self-sustaining oscillators to control posture, focal tasks, and ultimately how it is able to integrate two subtasks into one controllable unit of action.

Postural Control

The control of human posture is a dynamic task that must take into account a variety of internal as well as external variables (Riccio & Stroffregen, 1988). Posture is defined here as any configuration of limb segments within their mechanical limits. In most movements the goal of the postural system is to maintain the center of mass (CoM) within the limits or the boundaries of stability (BoS) defined by the geometry of the feet (Riccio et al., 1993). The CoM is a point that represents the sum of all limb segments in which all torques acting on the body are balanced.

Some authors argue it is the CoM that is at the heart of posture control while others focus on the dynamics of the center of pressure (CoP) (Winter, 1995). The CoP vector is the position of the vertical ground reaction force, which represents the sum of all internal and external forces (Winter, 1995). Because the CoP does not inherently have mass, its movement about the BoS is instantaneous and there are no adverse effects on balance as a result of its quick movements; this is not true for the CoM. There are clear consequences for the CoM crossing the boundaries defined by the feet (i.e. you fall). Thus the large fluctuations of the CoP, as seen in Figure 1, serve to "corral" the CoM, thereby maintain stability (Van Emmerik & Van Wegen, 2002; Winter, 1995).

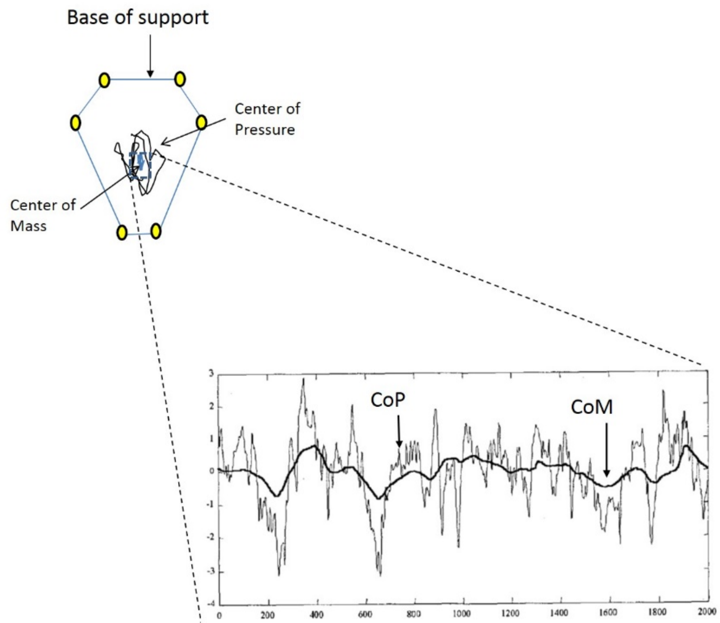

Figure 1: CoP-CoM relationship. The blown out time series recording of the CoP and CoM depicts how highly variable large CoP amplitude fluctuations work to maintain the relatively stable CoM position. (Time series adapted from Van Emmerik & Van Wegen (2002)

Like all other voluntary movements, when the postural system is met with a disturbance it must make corrective movements to maintain upright. The postural system is able to dissipate the added energy due to the perturbation in a variety of ways (e.g. extending your arms, reaching for a stable surface, squatting, etc.) (Riccio & Stroffregen, 1988; McIlroy & Maki, 1995). The most commonly studied response strategies have been the ankle, hip, and stepping strategies (Nashner & McCollum, 1985). In quiet stance, or any activity where the BoS is not in motion, the ankle and hip strategy are considered static balance recovery methods. In a traditional definition of the ankle and hip strategy, the ankles are responsible for dissipating smaller perturbations by plantar flexing, while the hips are used to dissipate larger perturbations in both medial-lateral (M-L) and anterior-posterior (A-P) directions (Shumway-Cook & Woolacott, 2002). Much of the literature in postural control regards the A-P and M-L mechanisms as independent, but in reality these two mechanisms work cooperatively to maintain upright stance (Oullier et al., 2002). Work done by Bardy and colleagues has shown that postural control is understandable through the principles of oscillatory attractors. In a series of experiments, which will be reviewed in greater detail later, they were able to demonstrate that the hips and ankles are able to assume stable in- and out-of phase relationships (29° and 171°) during a dynamic balance task (Nashner & McCollum 1985; Bardy et al., 1999).

When the functional postural synergy between the hips and ankles can no longer dissipate the energy, a step is used in balance recovery (Shumway-Cook & Woolacott, 2002). Traditionally stepping has been viewed as the final compensatory mechanism to prevent falling, but much like the ankle and hip strategy, this idea was born from laboratory based constraints. When subjects are left unconstrained, they prefer to step at light perturbation levels, suggesting that stepping is not a last resort strategy, but more preventative (McIlroy & Maki, 1993). These results may be potentially reflected in the fluctuations of the CoP.

Postural instabilities have traditionally been studied through the variability observed in postural sway. A system displaying a high degree of variability is often considered to be unstable. Traditional measures such as path length or area are static and spatially oriented measures that do not take into consideration the functional boundaries (i.e. the base of support) that are important in controlling the task. Furthermore they fail to capture the underlying dynamics involved in postural control. A more appropriate measure to understand dynamic stability is the time-to-contact variable (TtC). Time-to-contact is defined as the time before a surface or boundary is contacted by an object; in the case of postural control the "object" is center of pressure or center of mass (Riccio, 1993; Van Emmerik, 2002). Time-to-contact is thought to be a perceivable variable that encompasses the position as well as the rate of change of the CoP (Riccio, 1993).

In a series of three experiments Slobounov and colleagues (1997) presented compelling evidence for the direct perception of TtC. Using the same six participants throughout the course of the experiment, subjects voluntarily swayed at 75%, 50%, and 25% of their maximum CoP sway speed in two different postural conditions (i.e. free and frozen). The postural conditions were classified according to the number of degrees of freedom involved in the movement. In the "free" condition participants were allowed to sway in the A-P direction (Experiment 1) and in a circulatory motion (Experiment 2) using all available degrees of freedom while keeping their feet flat on the ground (feet were placed in a comfortable position). In the frozen condition participants were instructed to limit the movement production to the ankle joints only (their rationale for this condition was to model the body as an inverted pendulum). The authors' hypotheses were twofold: 1) increased speed of rotation would decrease TtC; and 2) CoP sway velocity would increase as a function of the number of degrees of freedom at play (i.e. the freeze condition would have lower sway velocities when compared to the free condition). The authors also hypothesized that support of TtC as a means of regulating posture would be seen in decreased variability in the TtC time series when compared to the position, velocity, and acceleration profiles of the CoP.

In experiment 1 (A-P sway) TtC was shortest at the boundaries of stability (i.e. smallest values recorded at the toes and heels), while the CoP acceleration and the speed values were largest throughout the middle of the movement, consistent with their predictions. The goal of experiment 2 (rotational motion) was to continue to test TtC as a perceivable variable by changing the postural motion. When comparing A-P versus rotational sway the authors reported that TtC was longer in the A-P direction. In both experiments one and two, as hypothesized, the TtC was shorter in the free condition when compared to the freeze condition; suggesting that the TtC is sensitive to the number of degrees of freedom involved in the control of posture.

To continue testing TtC as a perceptual variable, the authors had individuals assume a variety of postural conditions where the area of the base of support was manipulated. Each trial consisted of two sections: the first 10 s in the flat footed bi-pedal posture, then upon hearing an auditory signal, the individuals would transition to another posture (bipedal stance on the balls of their feet, flat footed on one leg, and one leg on the balls of their feet) for the remaining 15 s of the trial. As a control condition individuals stood in a bi-pedal stance with feet flat on the ground for 25 s. As expected, the speed, area, acceleration increased, and TtC decreased as the area of the base of support decreased. When comparing the TtC coefficient of variability to that of speed, area and acceleration, TtC had the lowest value in the single leg toe standing, suggesting that TtC was "regulated" in this condition, supporting the authors' hypothesis.

Time-to-contact may also predict future instabilities, which may lead to falling. Hasson et al., (2008) examined postural perturbations during upright standing by means of a pendulum strike, where participants were instructed to resist stepping for as long as possible. Using the first minimum time-to-contact of the COM with the anterior boundary of the base of support, the authors were able to accurately predict the transition from static to dynamic postural control (i.e. stepping). The previous study took a modeling approach to predict stepping, but TtC variability can also be used as a means of predicting stepping. Slobounov and colleagues (2009) had individuals stand on one leg (with both right and left leg) with their eyes closed and were asked to stand upright as long as possible. The CoP TtC was broken down into three stages: pre-falling stable state, transition, and falling stage (point at which the subject had to step to regain balance).

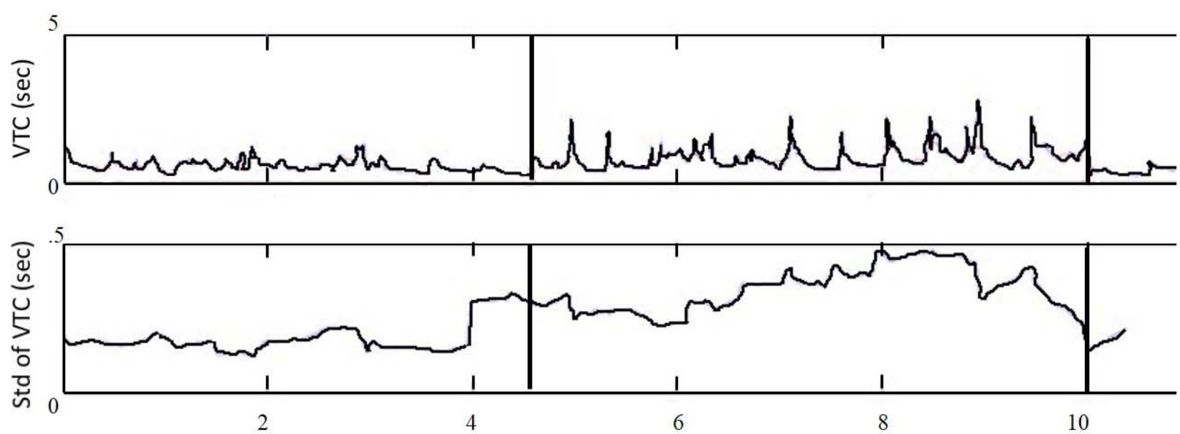

Figure 2: Example of virtual time-to-contact. (A) and virtual time-to-contact standard deviation (B) time series for one subject. From time zero to the first dark line is the pre-falling stable state, the area between the two dark lines is the transition state, and for this subject the 10 s mark denoted the falling stage (figure adapted from Slobounov et al., 2009).

As seen in Figure 2, during the transition stage (area in between the two black lines), the CoP TtC variability (bottom panel) increased, until the individual stepped (at approximately the 10 s mark). When comparing TtC to traditional measures of postural control (i.e. path length, area of sway, sway speed), these results, along with those presented above, demonstrate the robust nature of time to contact variable in identifying and predicting different postural patterns and responses.

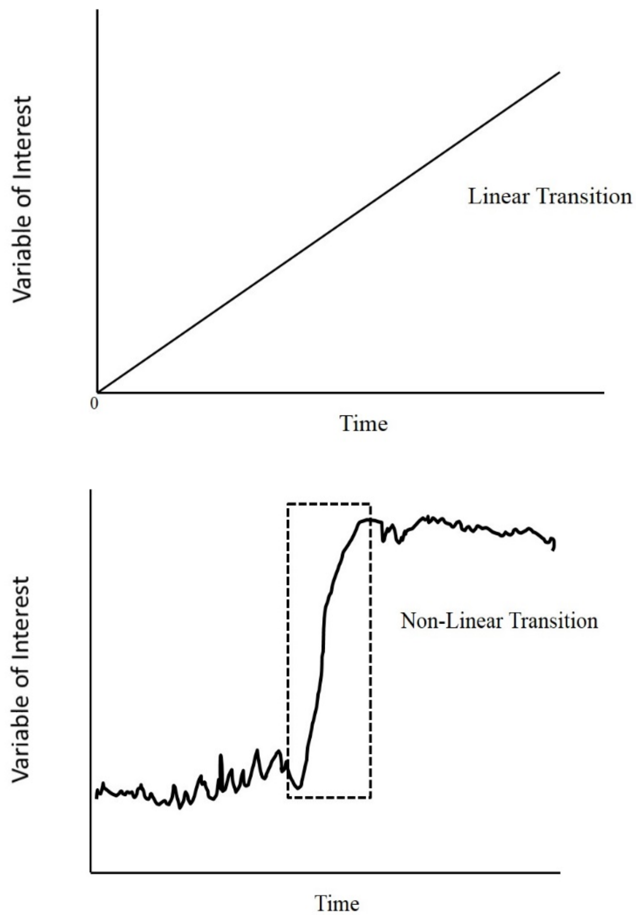

Figure 3: Linear vs non-linear relationship. The perforated box highlights the non-linear transition (bottom panel), or abrupt change from one behavioral pattern to the next.

The behavioral patterns of the TtC time series seen in Figure 2 are typical of a non-linear, self-organizing system. Non-linear systems experiences abrupt shifts in pattern, while linear systems change gradually over time (Figure 3). These changes are a function of constraints placed on this system; causing its elements to reorganize to produce different behavioral patterns (i.e. the system is "self-organizing"). From a dynamic patterns perspective the order parameter is a low dimensional variable which represents the end product of cooperating degrees of freedom. As the control parameter is modulated, critical points are reached, and the cooperative elements of the order parameter rearrange to form new patterns (Kelso, 1995). In the experiments above, the authors were able to identify the transition, from static to dynamic balance (stepping) by observing the behavioral patterns of the TtC (order parameter) as a function of postural constraints such as perturbation magnitude or time of standing (control parameter) (Riccio,1993).

This section has demonstrated that the control of posture is a dynamic process and describing stability with strictly spatial variables is not enough to capture its richness. By taking the rate of change into consideration in its calculation, the time-to-contact variable allows for the identification of upcoming instabilities and potential state changes as a function of constraints placed on the system. Time-to-contact is an example of a variable which is able to condense large degrees of freedom into a low order state space. In the same vein as the current section, the one that follows will examine the use of rhythmic movements to identify a low order parameter to describe inter-limb coordination.

Bi-manual Rhythms and Inter-limb Dynamics

Rhythmic behavior is vital to the reduction of the degrees of freedom because it serves as a constraint which fixes limbs into a known temporal relationship. To characterize ·different emergent patterns of behavior, an observable variable that captures the cooperative effects among the elements of the system is needed. In an important study in the field of motor control, Kelso and colleagues (1984) had participants oscillate their two fingers in transverse plane to a metronome in a 180° anti-phase pattern (homologous muscles activated in an alternating manner). As the metronome increased in frequency, subjects were instructed not to resist any changes in the pattern, and were told to assume the most comfortable pattern. The metronome manipulation produced anon-linear transition to an in-phase relationship. Despite a-reduction infrequency of oscillation, the coordination did not return to the previous anti-phase relationship (hysteresis). When repeating the study, beginning with an in-phase relationship, increases in frequency of oscillation did not prompt a switch to anti-phase coordination (Kelso, 1984). Similar results were reported when participants were instructed to oscillate their index in the frontal plane (Kelso, 1995). The results of these studies demonstrated that the phase relationship between two oscillators captures transitions in movement coordination; making relative phase (φ) and frequency viable order and control parameters to understand inter-limb dynamics (Kelso, 1992; 1995; Turvey, 1990).

The work done by Kelso et al., (1984) led to the development of the elementary law of coordination by Haken and colleagues (1985), which will be referred to as the

HKB model (eq.2). Although the current work will not be using the HKB model, reviewing some of its theoretical underpinnings is necessary to understand inter-segmental coordination. In equation (2) φ dot is the rate of change of relative phase (φ) and scaling of b/a is inversely related to frequency (control parameter). Plotting φ dot against φ results in a vector field of relative phase dynamics (Kelso, 1995). Figure 4 expresses this relationship as a function of the ratio b/a. Stable ("fixed point attractor") relative phase dynamics can possibly emerge when φ dot is equal to zero. In Figure 4 possible stable fixed points are φ= ±π (anti-phase) and φ =0 (in-phase). The arrows denote the direction of flow, with negative slopes representing attractors and positive slopes repellers. As a result of increasing frequency of oscillation (decreasing values of b/a), the stable attractor at φ ≈ ± π is annihilated leaving φ =0 as the only attractor. As a result, at higher frequencies the in-phase pattern is the only stable coordination mode. In Figure 4 stable fixed and unstable fixed points are represented as thick black lines and dashed lines, respectively. The right side of Figure 4 represents the unstable fixed points coalescing at the critical point, showing the annihilation of φ≈ ±π as stable attractors (Haken et al., 1985; Kelso, 1995; Park et al, 2008).

Equation 2: HKB

$$\dot{\phi} = -a \sin\phi - 2b \sin 2\phi$$

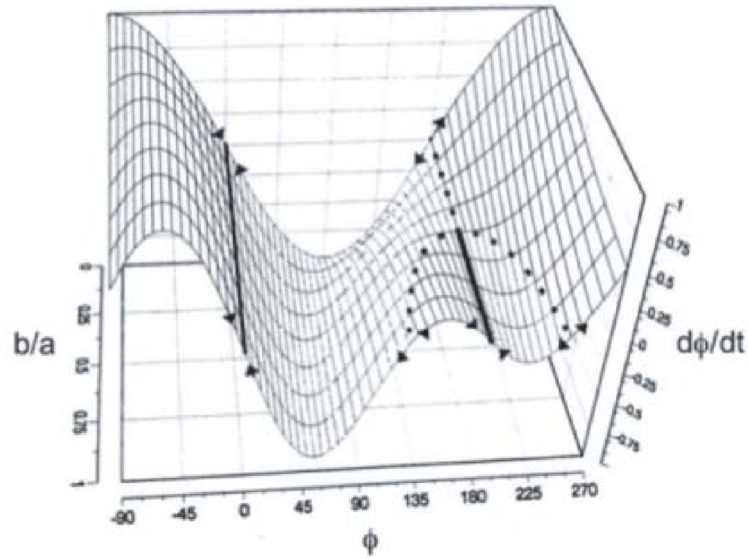

Figure 4: Symmetrical HKB. The resultant vector field when φ (x axis) is plotted against φ dot (z-axis) as a function b/a scaling (y axis), where there are an equal number of unstable states (dotted black lines) on either side of the basin of attraction (solid black lines) at approximately 180^{o} (i.e. symmetry). As the b/a scaling approaches zero (moving from the foreground on the y axis to the background), a critical point is reach, and the attractor state at φ= 180^{o} is annihilated leaving φ= 0^{o} as the remaining basin of attraction. This was behavior was is model by equation 2 (Adapted from Kelso, 1995)

The original HKB model (equation 2) (Haken et al., 1985) assumed the existence of symmetry between the two oscillators (two index fingers) ($-\pi = \pi$). Later research on bimanual coordination showed that symmetry is often broken when oscillators of different natural frequencies are coupled (Kugler & Turvey, 1987; Sternad et al, 1992; 1995). Symmetrical and asymmetrical oscillators can result in different types of phase relations and coordination, initially described by the German physiologist von Holst (1939/1973). In his 1939 study, he reported on the phase relationship between a pectoral and dorsal fin using different stimulation frequencies on a spinal fish. He discovered three principles of coordination, namely superimposition, the magnet effect, and the maintenance tendency, describing different forms of interaction and cooperativity between oscillators. The magnet effect can be described as the attraction of two or more coupled oscillators to one period of oscillation (the period of oscillation can be that of a dominant oscillator within the network or the coupling to an external oscillator such as a metronome). In human coordination the magnet effect coincides with in-phase ($\varphi = 0$) and anti-phase ($\varphi = \pm \pi$) coordination. The maintenance tendency reflects that individual oscillators tend to maintain their natural frequency of oscillation, and superimposition the combination (or addition) of different rhythms to produce a more complex movement (Kelso, 1995; Turvey, 1990; von Holst, 1939).

In attempts to model von Holst's three principles of coordination (the magnet effect, the maintenance tendency, and superimposition), Kugler and Turvey (1987) had subjects oscillate two pendula of different masses and lengths at in-phase and anti-phase modes of coordination. The results demonstrated that when the inertial characteristics of the two pendula are different, the nervous system is able to find a common frequency of oscillation by which both pendula can oscillate within the prescribed coordination mode. The previously mentioned study, along with others that have used pendula of unlike natural frequencies provide support for the theoretical predictions of the HKB model by demonstrating the stability of the in-phase and anti-phase modes of coordination under a variety of conditions (Kelso et al., 1992; Rosenblum, 1988; Schwartz, 1995). Although the original HKB model (equation 2) was able to predict the stability of the coordination patterns in the Kugler and Turvey (1987) and Haken et al., (1985) studies, it was not able to account for the breaking of the symmetry as a result of differences in natural frequencies of each pendulum (a pendulum of shorter length oscillates faster than longer pendulum). As a result, a symmetry breaking or detuning parameter, δ, was added to the elementary law of coordination (equation 3) (Kelso et al., 1990; 1995). The detuning parameter shifts the state away from the stable relative phase relationship of φ = ± π and φ =0 to new values, dependent on the nature of the components in the coupling (Figure 5) (Kugler & Turvey, 1987; Kelso & Jeka, 1992; Jeka & Kelso, 1993; Stenard, 1995; Park et al., 2008).

Equation 3: HKB + Symmetry Breaking

$$\dot{\phi} = -a \sin\phi - 2b \sin 2\phi + \delta + \sqrt{Q}\,\xi_t$$

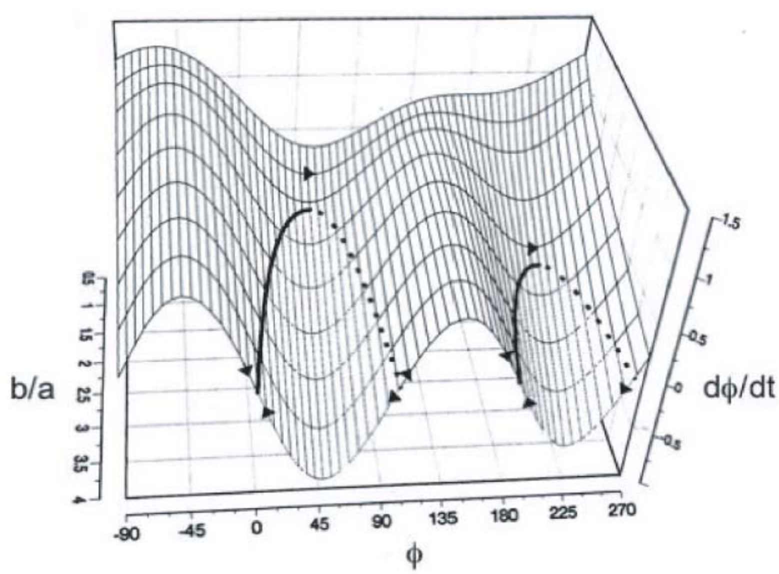

Figure 5: Asymmetrical HKB. As in Figure 4, φ is plotted on the x-axis, the derivative of φ (d φ /dt) on the z-axis, and b/a scaling on they-axis. Important to know is the change in the behavior of the potential field when the symmetry breaking parameter, δ, is added to the elementary law of coordination to form eq 3.The symmetry breaking parameter allows for the existence of multiple stable states (solid black line) and unstable states (dotted black line) for what is known as a saddle node attractor. In this regime the system flexibly fluctuates between stable and unstable states. Just beyond the region where the two lines meet, intermittency energies. Intermittency is when the oscillator loses entrainment but still phase locks periodically with its last stable coupling. (Adapted from Kelso, 1995)

The changes in the dynamics of the system as a result of the detuning can be seen by comparing Figures 4 and 5. In Figure 4 fixed point attractors (the solid black lines) remain unchanged while the stable relative phase relationships (black dots) become progressively more unstable, as b/a approaches zero. At the critical point the system displays a pitchfork bifurcation (on the right side of Figure 4) in which the attractor at $\varphi \approx 180^{O}$ is annihilated resulting in one global attractor at $\varphi = 0°$. In Figure 5, rather than a pitch-fork bifurcation, the system displays a saddle node bifurcation, which has both a stable (saddle, solid black lines) and unstable (node, black dots) portion (Kelso, 1995). Beyond the point at which these two regions coalesce exists the loss of entrainment, and only remnants of attraction to a particular phase exists (Kelso, 1995)

When two or more oscillators are coupled, they compete to maintain their natural frequency of oscillation; this phenomenon is known as the maintenance tendency (von Holst, 1939; Kelso, 1995; Turvey 1990). The maintenance tendency is ever present in human movement when coupling limbs of unlike eigenfrequencies. Many studies in which participants were instructed to move in a phase-locked pattern, in-phase or anti-phase, have demonstrated that absolute coordination seldom exists in human movement;

rather human movement is more relative, reflecting an attraction to a particular phase relationship (magnet affect), while reflecting the natural characteristics of the segments involved in the coupling (maintenance tendency) (Haken et al., 1985; Kelso & Jeka, 1992; Kelso 1995; Sternad, 1995). The distinction between a more relative form of coordination versus absolute coordination is that relative coordination affords a wider range of possible phase relationships, allowing for greater flexibility within the coupling, whereas in absolute coordination the limbs are phase locked to a particular relationship (Figure 6). For example, Rosenblum and colleagues (1988) had participants oscillate two pendula of varying characteristics (i.e. length and mass of pendulum were different) in an anti-phase coordination pattern. As a control they measured the natural period of the right pendulum system individually (T_o) as well as its coupled period (T). When they expressed the coupled period of oscillation of the right pendulum system relative to its characteristic period (T/T_O), there was a decrease in periodic fluctuations when the coupled period approximated the natural frequency. The authors concluded that the increa8e in fluctuations were a result of the differences between the natural frequency of the oscillating segments (Rosenblum et al., 1988).

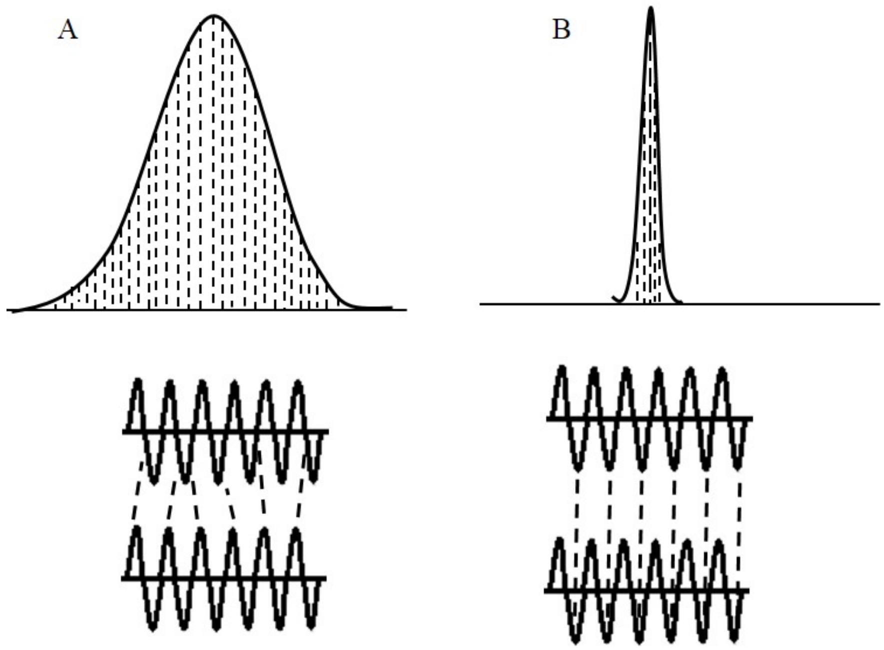

Figure 6: Absolute and relative coordination. The maintenance tendency or relative coordination (A) is seen to be in direct competition with the magnet effect, or absolute coordination (B). The differences can be seen in the relative phase distribution among the different types of coordination. Relative coordination has a large variety of phase relationships while absolute coordination is fixed to a narrow range of relative phase values. The time series below each of the distributions are meant to demonstrate the temporal differences in peak to peak alignment between relative and absolute coordination (Adapted from Kelso, 1995)

As seen above, when two oscillators of different natural frequencies are coupled together, they compete to maintain their natural behavior. To understand how the system resolves the issue of coupling segments of different natural frequencies, we can borrow principles from oscillator theory. Circle maps provide a means of observing the dynamics of coupled oscillators by stroboscopically measuring their phase relationship through iterations of equation (4). For example, if oscillator p is cycling at 2 Hz and oscillator q is cycling at 3 Hz, when coupled, they cycle in a 2/3 ratio. There are infinitely many coupling ratios, but only those that produce rational numbers are stable. In multi-frequency couplings the p/q ratio is known as the bare winding number, Ω. The stability of each coupling is a function of its position in the K- Ω parameter space, where K is the strength of the coupling. The dark regions in Figure 7, Arnol'd tongues, represent regions of resonance or phase entrainment. The area each tongue covers is indicative of the strength of the attractor. As the value of K surpasses the critical value of l (supercritical), the area of the tongues begin expand, eventually bifurcating and overlapping; sending the system into chaos. In a chaotic system the coupled oscillators can transition to overlapping resonance regions or experience quasi-periodicity (space between the tongues). Through each iteration of equation (4), the initial phase value of the forced oscillator, p, changes as a result of the external forcing of oscillator q. The new phase angle, which will serve as the initial phase angle through the next iteration of the circle map, is a function of K and Ω (Figure 8). By varying K and Ω, if the map repeatedly produces the same phase angle, and attraction state has been found; the size of each basin of attraction can then be determined by slightly adjusting the parameters until the system enters another behavioral regime. Of the infinitely many resonance regions, the human system tends to be attracted to those have the largest areas; lower frequency couplings (ratios with smaller denominators) (Kelso, 1995; Schmidt et al., 1991; Peper et al., 1995).

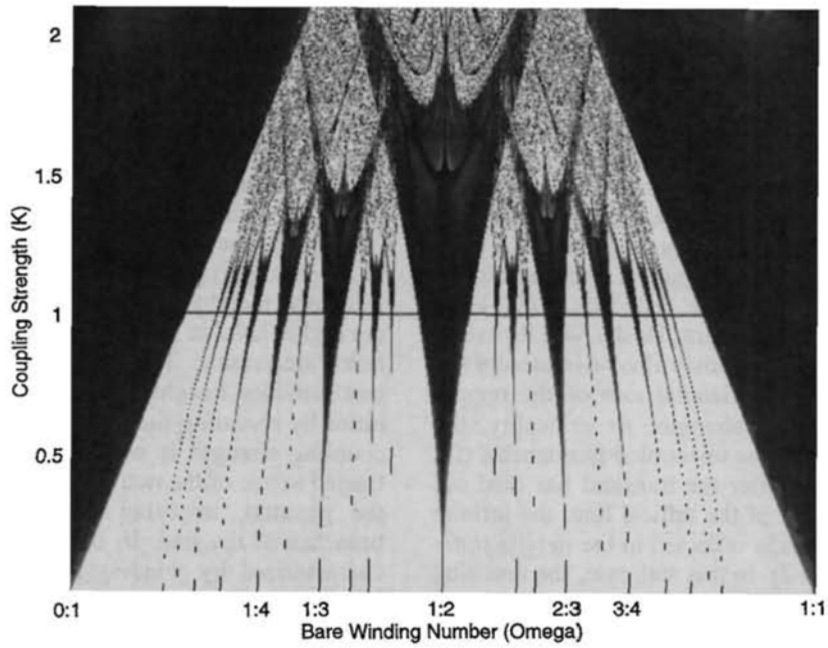

Figure 7: Arnol'd Tongues. The darkly shaded regions or Arnol'd tongues, depicted above represent stable coupling relationships. There are infinitely many relationships, but those that are the most stable are shown here. The areas of the tongues grow larger with increasing coupling strength, K, until they begin to overlap (at which time the coupling transitions into a chaotic order). It is important to note the area covered by the 1:1 coupling relative to all other couplings depicted here. It is for this reason this mode of coordination (in-phase or anti-phase) is more stable than higher order couplings.

Equation 4: Circle Map

$$\theta_{n+1} = \theta_n + \Omega - \left(\frac{K}{2\pi}\right)\sin(2\pi\theta_n)$$

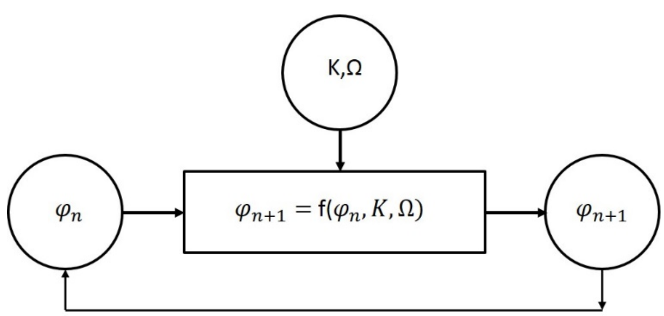

Figure 8: Circle map schematic. (Adapter from Kelso (1995) page 119)

Some of the early work on multi-frequency behavior by DeGuzman and Kelso (1990) demonstrated that when limbs are coupled in a ratio other than 1:1 (e.g. 2:1, 3:2, 3:5) the frequency relationship tends to be attracted toward lower order ratios. The experimental paradigm was set up such that the right index finger would oscillate at one frequency, visually cued by a light, while the other finger was driven by a torque motor. There were a total of six frequency relationships (3:4, 2:3, 3:5, 1:2, 2:5, 1:3) that could exist between the two metronome frequencies (1.5 Hz and 2.0 Hz) and the frequency of the torque motor. The participants were required to maintain the frequency of the right index finger when the visual metronome was turned off. Results showed that participants were not able to maintain higher order frequency relationships, and there was a trend for higher order ratios to transition to easier, more stable, lower order ratios. Supporting these results, Sternad et al., (1999) had participants oscillate two pendula of unlike natural frequencies (different mass and length) at a constant tempo in a 1:2 frequency relationship, and reported a brief switch to a 1: 1 phase relationship as a result of the slow hand speeding up, suggesting that the frequency of the fast hand influences the performance of the slow hand. Similar results, fast hand influencing the oscillation of the slow hand, were reported by Peper and colleagues (1995) when they had experienced drummers perform a 2:3 polyrhythm.

As seen above bi-manual rhythmic behavior is very plastic in the sense that an oscillator's behavior is highly dependent on the presence and nature of other oscillators to which it is coupled. The studies above have demonstrated that rhythmic behavior is affected by the differences in natural frequency ($\Delta\omega$), the coupling frequency (i.e. tempo), and the frequency ratio (Ω) as a function of the coupling strength (K). Although these studies have contributed a great deal of information regarding inter-limb dynamics, they have all been conducted from a seated posture. The sections below will review how the postural system interacts with secondary or focal tasks.

Postural- Focal Dynamics

In activities of daily living, organisms cannot act without considering the context in which the behavior is being performed in. For instance picking up an empty mug versus picking up the same mug filled with hot coffee. The same object, now in a different context, offers consequences for improper handling (getting burnt). Perceptual information pertaining to the environment (the now filled mug) coupled with the intrinsic properties of the organism will affect how the individual controls movement. These same principles can be applied to the control of posture (Riccio & Stroffregen, 1988). Different body configurations facilitate or afford the production of a variety of other movements. There is a clear contrast between the affordances provided by sitting and standing. Although sitting is inherently more stable than standing, standing allows for a greater repertoire of movements; but this does not come without risk of falling (Riccio & Stroffregen, 1988; Riccio, 1993).

The main impetus of the postural system is to remain upright, but this task is often complicated by other concurrent tasks. Postural control inherently involves multi-limb coordination to aid in dynamic stability (Riccio & Stroffregen, 1988). Multi-limb coordination is a self-organizing process, which temporarily, or softly, constructs muscles into functional groupings known as muscle synergies or coordinative structures (Turvey et al., 1988). Patterning of muscles across the body is not a pre-programmed response, but is a result of task and environmental constraint (Riccio & Stroffregen, 1988; Bardy et al., 1999). In the formation of complex movements the nervous system must coordinate the synergies involved in controlling the subtasks (i.e. postural control and a supra-postural task) which make the overall movement possible. For example Ma and Feldman (1995) showed in a simple yet elegant experiment the existence of two synergies in a reaching task. From a seated position participants started with their index finger 20 cm away from their midline and when cued were asked to move to and return from a target at a distance of 40 cm with a 45° offset as fast as possible (participants were also cued to move back to the starting point). In three different experimental conditions the participants moved: (1) their arm only, (2) their arm accompanied by in-phase trunk motion (i.e. flexion and extension accompanied the arm to and from the target), and (3) their arm accompanied by anti-phase trunk motion (i.e. trunk extension while the arm moved to the target and vice versa). Despite the addition of trunk movement (in-phase or anti-phase), arm trajectories, velocity profiles, and positions remained constant across all conditions (Ma & Feldman, 1995).

In a similar experiment, where the authors attempted to understand the coupling between the trunk and the end-effector (in the movement of the body part which is completing the task), Welsh and colleagues (2005) had participants perform a 1:1 rhythmic task in a seated position. Sliding their hands along a linear track (while holding a handle) in different spatial orientations, participants first performed the task with and without trunk constraints (the constrained condition the trunk was strapped to board, thereby reducing as much movement as possible). Although one of the main goals of their experiment was to understand how spatial orientation affected the absolute error and standard deviation of the movement, an important finding relative to the context of the current work was the effect of postural constraints on the variability of the rhythm. When comparing the results of the constrained and unconstrained conditions, the constrained condition across all spatial manipulations reported smaller degrees of error as well as standard deviation. Consistent with the results of the 1: 1 coordination tasks discussed above, the in-phase mode of coordination experienced less absolute error across all spatial manipulation in both postural manipulations.

Similarly, task constraints have been shown to play a role in the coordination of hip and ankle joint in control of quiet stance. For example, Bardy and colleagues (2002) assessed the relative phase between the ankle and hips while having participants move their body in-phase with the target on the screen as it oscillated front-to-back. As the oscillatory frequency of the target increased, participants experienced a change in the relative phase between the ankle and hips from in-phase to anti-phase coordination; the opposite occurred when the frequency of oscillation decreased (Bardy et al., 2002). The authors reported a mean in-phase relation of approximately 30° and an anti-phase at approximately 170°. In a similar task the authors asked two groups, with and without visual feedback, to produce specific relative phase coordination. Regardless of visual feedback no significant differences were reported between the two groups; more importantly, participants across both groups were attracted to the anti-phase mode of coordination (the basin of attraction was between 157.5^{O} -202.5^{O}, but not the in-phase coordinative pattern (0°- 45°); regardless of the tasks being of the same nature (Bardy et al., 2002, Faugloire et al., 2005) different patterns of coordination emerged as the constraints of the task changed (Faugloire et al., 2005).

From the examples above it is clear that goal oriented behavior, or suprapostural tasks, are nested within ongoing postural control. In a manual task, Haddad and colleagues (2011) participants were asked participants to fit a block through an aperture under different task constraints: aperture size (small or large), distance (near or far), and visual (lights on or off). The goal of the study was to examine the coordination between postural control and manual control in children and adults. The movement phase was broken into three segments: wrist acceleration, wrist deceleration, and adjustment phase. During the fitting movement (considered as wrist acceleration and deceleration), when compared to the 7 year old group, adults had significantly lower average trunk velocity during the acceleration portion and significantly lower trunk speed during the deceleration portion. In the near distance condition, when compared to the 7 year olds, adults had lower trunk speeds during the adjustment phase, but the opposite occurred during the far fitting condition (7 year olds had slow trunk velocities). Accompanying the adults' increase in trunk speed during the adjustment stage was an increase in the straightness ratio (total path traveled by the trunk divided by the straight line distance); signifying a greater level of trunk variability. The authors interpreted the increased trunk variability in the older adults as a modulatory behavior which allows for greater precision in the final fitting stages (Haddad et al., 2011).

Of particular importance for to the current work, the most pertinent result reported by Haddad and colleagues (2011) was the wrist-CoP coordination measure, which was determined as the peak wrist speed relative to the CoP. In the far condition, the adult CoP reached its peak speed 235 ms prior to the wrist reaching its peak speed (adult CoP reached its peak 148 ms earlier than the 7 year old group) (Haddad et al., 2011); comparing adults and children, adults were able to stabilize their CoP earlier thereby allowing them to be more precise. Most importantly, these results demonstrate that the movement of the COP is modulated during precision tasks. As discussed above, in the postural control section, changes in postural stability may be perceived through the TtC variable. In a similar block fitting task, done specifically on adults, the authors reported that the TtC values increased as the block neared the aperture. Specifically, TtC values were largest when the task required greater precision (i.e. block being fit through a smaller aperture) (Haddad et al., 2010). The behavior of the TtC variable as a function of the task provides support for the notion that the control of posture is context dependent.

The sections above have reviewed how the behavior of bi-manual rhythmic performance and postural control function independent of each other; concluding with a brief review on postural-focal interactions. Although relatively little research exists on how postural and bimanual tasks interact, the evidence presented in the postural-focal dynamics section suggests that the postural control system is able to tune itself in accordance with the constraints of the task. The purpose of the current work will be to investigate the interaction between the postural control system and bi-manual rhythmic performance. Because of the repetitive nature of rhythmic movements, unlike many activities of daily living which are usually discrete in nature, they lend themselves to continuous analysis while posture is manipulated. Although future studies may not use the same paradigm as the current study employs, the results will allow others to understand how the postural system and manual tasks interact under various postural perturbations.

CHAPTER 3

METHODOLOGY

Introduction

To understand how the organism integrates drumming and postural control into one cohesive action unit, the proposed study will have participants play a 1: 1, 2:3 and a 6:4 polyrhythm in several postural states (i.e. sitting, standing, and standing on one foot). The experiment will be completed during an hour and a half session in the University of Massachusetts Biomechanics Laboratory.

Participants

The study will consist of twelve healthy males between the ages of 18 and 26. Participants will be excluded if they have recently sustained any lower body injuries that may prevent from standing on one foot, a history of wrist tendonitis, or any neurological disorder that may impair their sense of balance. Standing and drumming, for a novice, is a difficult task that requires a great deal of training. Novice drummers are highly variable in their timing and have poor understanding of rhythmic structure. Thus for the greatest understanding of the interaction between postural control and bi-manual rhythm, participants will be drawn from a pool of high specialized marching percussionists. Marching percussionists were chosen over stationary percussionists because their postural system is continually perturbed by the weight of the instrument. The assumption here in that their postural systems are more robust to perturbations while playing. Participants will be recruited directly from the University of Massachusetts Amherst Drumline. The study will focus on males because the university's marching battery section, by chance, is an all-male section. Before being accepted into the study, a screening phone call will be administered to identify any neurological or musculoskeletal impairment that may exist (Appendix 1). Once they have passed the screening, they will be asked to read and sign an Informed Consent Form approved by the University Institutional Review Board upon arrival to the laboratory (Appendix 2).

Research Design

This study will be completed over the course of one session lasting approximately 1.5 hours. There will be three postural conditions: seated (Se), standing (S2), and standing on one foot (S1) and three rhythmic conditions (1:1, 2:3 and 4:6). In total there will be 9 total experimental conditions (see Figure 9). Over the course of 27 trials each of the experimental conditions will be randomly presented three times. Each trial will be 30 seconds long. Throughout the course of the experiment the individual will required to take a five minute break after trials 6 and 12, and 18.

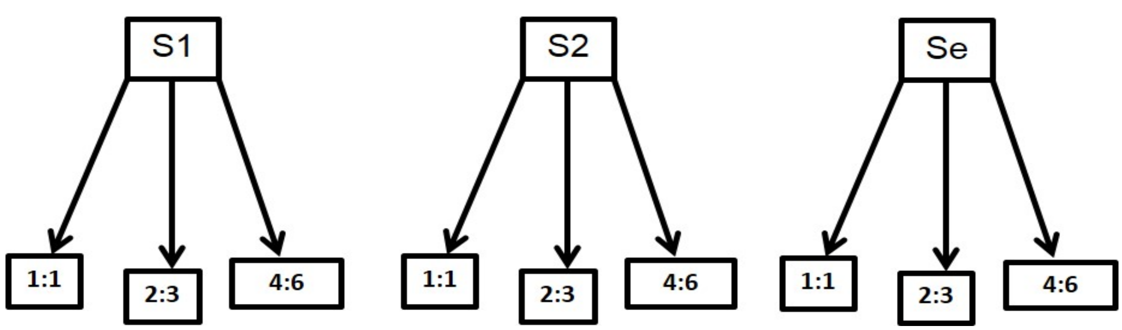

Figure 9: Experimental conditions. Postural conditions: seated (Se), standing (S2), and standing on one foot (S1) and three rhythmic conditions 1:1, 2:3 and 4:6.

Protocol

Upon entry into the lab height, weight, dominant hand (i.e. which hand the individual prefers to play the fast rhythms) and dominant leg of the individual will be recorded. To determine the participant's dominant leg, he will be asked "If you were to stand on one leg for a period of time which leg would it be?" For consistency, the hand selected to play the fast rhythm and the leg the individual selected to stand on in the S1 condition will remain fixed throughout the experiment. As a baseline measurement of postural stability, individuals will complete a total of 6 trials in which there is no playing (3 for standing on two legs (S2) and 3 for standing on one leg (S1)). (Note: the term "standing posture" will be used as a general term which encompasses both S2 and S 1). For the S1 condition, participants will be instructed to keep the non-dominant leg flexed at 90° for the duration of the trial. In the baseline trials the participant will be instructed to leave hands in the playing position and to focus primarily on staying upright and balanced. The playing position is defined as both beads together resting slightly above the playing surface (Figure 10).

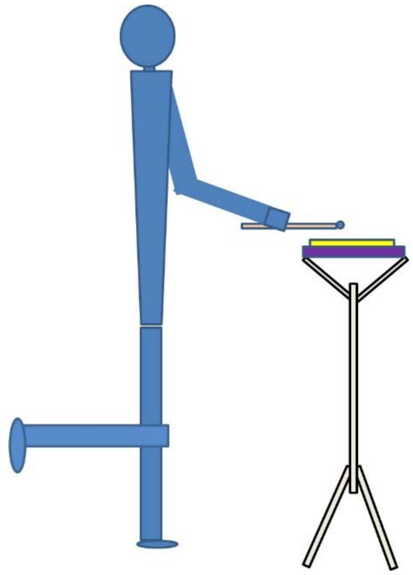

Figure 10: S1 Baseline condition. Note how the stick in the resting position is hovering slightly over the playing surface

Once baseline conditions are complete the rhythmic movement trials will begin. When the participants are standing and drumming, they will be informed that the goal of the task is to maintain upright, while playing the prescribed rhythm as accurately and temporally consistent as possible throughout the duration of the trial. Rhythmic accuracy is defined as the maintenance of proper note placement in a one beat space (i.e. one metronome click). To provide temporal structure to the task, the participant will be instructed to play the rhythms as if they were to play a 12/8 musical phrase (i.e. four repetitions of the rhythm in one musical bar; see Figure 11). Consistent with the basics of drumming, individuals will be asked to play in the center of the drum pad. During the S1 condition, if the participant feels as though he is going to fall, he will be told he is allowed to do whatever is necessary to maintain upright, bearing in mind the overall goal of the experiment (i.e. balance and performance). If he stops playing to regain his balance, there will be no penalty, but he will be asked to recover as quickly as if he were performing in a show.

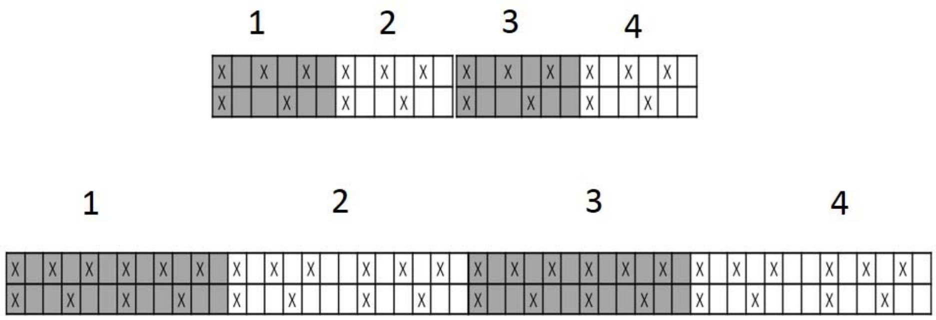

Figure 11: Rhythmic structure. Each rhythm (2:3 (top) and 4:6 (bottom) will be played in a 12/8 meter (In musical terms this means four beats per music phase). The numbers above the shaded regions represent a beat, and the bars tie these four beats into a measure. Note: in the 4:6 conditions the number of notes doubles in the same temporal space. Within each of the shaded regions the "x" represent the striking of a note

Experimental Setup

Three dimensional kinematic data will be collected using passive reflective markers recorded at 240 Hz (Oqus, Qualysis, Sweden); kinetic data will be recorded at 1200 Hz by a 600 x 1800 AMTI force plate (Watertown, MA). A diagram of the full marker set up can be seen in Figure 12.

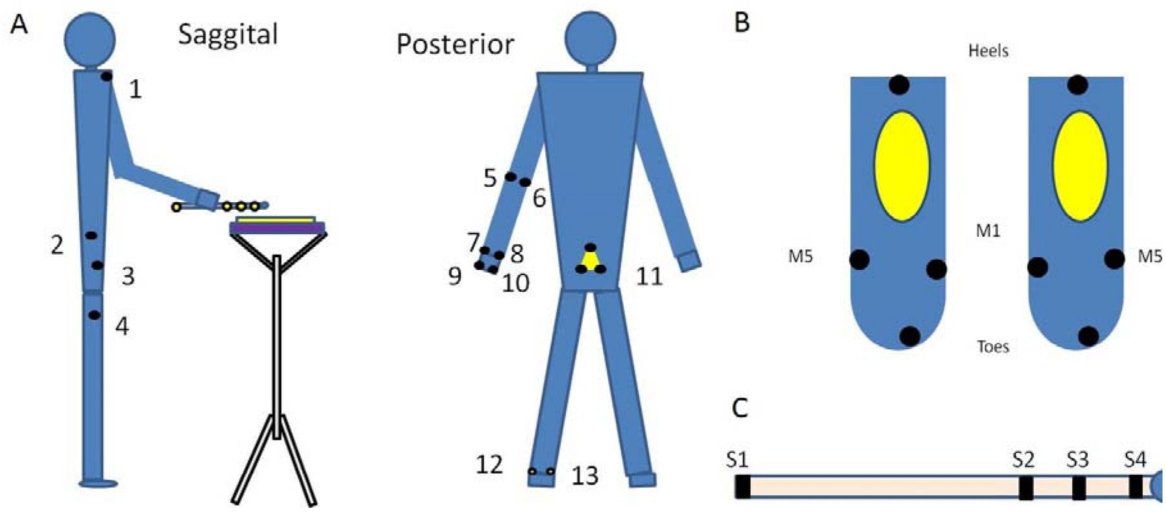

Figure 12: Marker setup. A) Bi-lateral full body marker setup was used to collect kinematic data. Saggital: 1) acromioclavicular joint; 2) illiac crest; 3) anterior superior illiac spine; 4) greater trochanter Posterior: 5-6) medial and lateral humeral epicondyle, respectively; styloid process of the radius; 8) styloid process of the ulna; 9-10) 2^{nd} and 4^{th} phalanges, respectively; 11) pelvic triad; 12-13) lateral and medial malleolus, respectively. B) Markers of the feet: first and fifth metatarsal head (M1 and M5 respectively), toes, and heels. C) Bi-lateral stick marker setup from the most proximal to distal end (S1-S4).

Data Analysis

The initial processing of marker data will begin in the Qualysis Tracking Manager (Qualysis, Gothenburg, Sweden). Here all the markers will be labeled and filling of any potential gaps in the data will occur (when appropriate). The tracked marker data and ground reaction forces will then be exported to Visual 3D (C-motion, Germantown, MD) where a model will be made. The V3D model will be used to filter data and calculate the CoP. Before any data is filtered a spectral analysis will be run to determine the appropriate cut off frequency for the digital filter. Once the data is filtered the next stages of data analysis will be to calculate the primary and secondary dependent variables. The sections below will outline how each dependent variable will be obtained.

Time-to-Contact

The primary variable which will be used to quantify postural stability will be the time-to contact (TtC) variable. Time-to-contact will be calculated according to Slobounov (1997). This method, opposed to the Riccio (1993) method, uses the instantaneous x (anterio-posterior) and y (medio-lateral) acceleration of the CoP rather than position and velocity only to calculate the rate of change (Haddad, 2006). The time-to-contact with the BoS will be calculated by solving equation 4, for τ_b The A, B, and C coefficients are defined in equations 5-7 respectively. In these equation $r_{Ox}(t_i)$ is the instantaneous x positions, and $V_{ox}(t_i)$ is the instantaneous x velocity, τ is the time variable, and a_{ox} and a_{oy} are the instantaneous x and y acceleration respectively. Equation 8 is the equation of a line that is used to reconstruct the trapezoidal boundary of stability, defined by the outside markers of the feet (Figure 13), where m is the slope and X_b and Y_b are random points on a line (Haddad et al., 2006).

Equation 5: Time to Boundary

$$At_b^2 + Bt_b + C = 0$$

Equation 6: A Coefficient

$$A = \frac{a_{oy}(t_i) - ma_{ox}(t_i)}{2}$$

Equation 7: B Coefficient

$$B = V_{oy}(t_i) - \mathrm{m}V_{ox}(t_{i})$$

Equation 8: C Coefficient

$$C = r_{oy}(t_i) - y_b - m(r_{ox}(t_i) - X_b)$$

Equation 9: Calculation of the boundaries of the BoS

$$y - y_b = m(X - X_b)$$

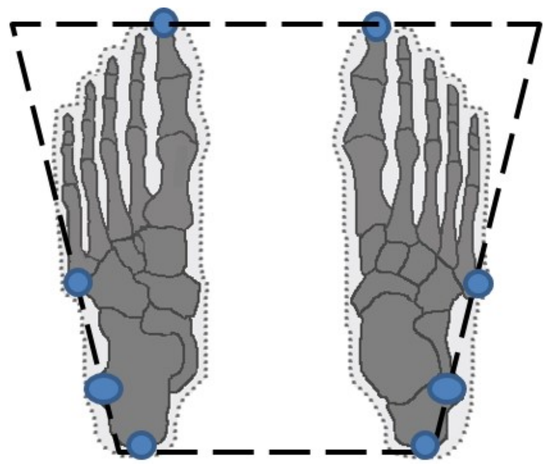

Figure 13: Example of the geometry of the base of support

Discrete Relative Phase

Discrete relative phase (DRP) will be the primary dependent variable to quantify the changes in coordination dynamics as a result of postural changes. DRP is calculated using equation 10,where Rh_i is the position of the right stick at an instance in time, Lh_i is the position of the left stick at an instance in time, Δt is the average cycle time (for 1:1 that of the right stick; for the 2:3 and 4:6 of the slow rhythm). By considering each strike of a stick as part of one time series, equation 10 can be used to determine how the temporal relationship between notes change throughout a trial. An example of how DRP will be calculated in the 2:3 and for each instance in time can be seen in Figure 14.

Equation 10: Discrete Relative Phase

$$\varphi = \frac{|Rh_i - Lh_i|}{\Delta t} * 360$$

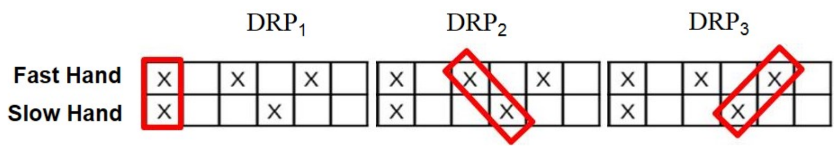

Figure 14: Calculation of DRP. The Discrete Relative Phase time series will be created by calculating the difference between each of the stick strikes.

Cross Mutual Information

The purpose of the current project is to understand how a bi-manual task is nested within the ongoing postural control. The Cross Mutual Information (CMI) technique will be used to measure the degree of coupling which exists between these two tasks. Cross Mutual Information is a form of conditional entropy. In information theory entropy is a measure of uncertainty of a particular result before it is measured; once the measurement has been made, the previous uncertainty of the outcome becomes information gained. Once all the desired data has been collected, the time series is separated into bins, which will be used to calculate the probability of a particular event occurring over the entire time series. Entropy (H) (equation 11) is a measure of uncertainty of one variable, whereas CMI (I_{xy}) is a measure which seeks to quantify the degree of uncertainty of a particular event occurring in variable X, given that variable Y has already been measured

(Jeong et al., 2001). The relationship between entropy and CMI can be seen in equations (12) and (13).

Equation 11: Entropy

$$H(X) = -\sum P_x(X_i) log_2 P_X(x_i)$$

Equation 12: Entropy-CMI relationship

$$I_{xy} = H(X) - H(X|Y)$$

Equation 13: CMI

$$I_{XY} = \sum_{x_i, y_i} P_{XY}(x_i, y_i) log_2 \frac{P_{xy}(x_i, y_i)}{P_x(x_i)\, P_y(y_j)}$$

Statistical Analysis

For specific aim 1, to quantify the changes in bi-manual coordination dynamics as a function of postural and rhythmic constraints, we will use a 3x3 Repeated Measures ANOVA. If the ANOVA returns significant interaction between postural condition and rhythm, a Tukey's honestly significant difference (HSD) post-hoc analyses will be used to find where the interactions occurred. The factors will include the three rhythms (1:1, 2:3, and 4:6) and the three postural conditions (sitting, standing, standing on one foot).

For specific aim 2, to quantify the changes in the postural control as a function of postural and rhythmic constraints, a 2x3 Repeated Measures ANOV A will be used compare the two rhythmic conditions with the average Time-to-Contact values of the of the two postural conditions. If the ANOVA returns significant interaction between postural condition and rhythm, a Tukey's honestly different post Hoc analyses will be used to find where the interactions occurred.

For specific Aim 3, to quantify the changes in postural-focal dynamics a function of postural and rhythmic constraints, a 2x3 repeated measures ANOVA will compare Cross Mutual Information values for the two standing postures (i.e. standing on two feet and standing on one foot), and the three rhythmic conditions.

CHAPTER 4

POSTURAL INSTABILITIES AND THE MAINTENANCE OF BI-MANUAL RHYTHMIC MOVEMENTS

Abstract

Most research on bimanual rhythmic coordination has occurred with the participants in a seated posture. Many activities of daily living, however, require the interaction of standing postural and manual tasks. A population of individuals that are ideal for studying the integration of a manual task into the ongoing control of posture are expert marching percussionists; they have learned to produce rhythmic movements accurately under a variety of temporal and postural constraints. The purpose of the current study was to investigate the integration of bimanual rhythmic movements and posture in expert marching percussionists. Participants (N=11) were recruited from the University of Massachusetts Drumline, and were asked to perform three rhythmic tasks [1:1, 2:3, and 2:3-F (2:3 rhythm played faster at a self-selected tempo)] in one of three postures: sitting, standing on one foot, and standing on two feet. Discrete relative phase, postural time-to-contact, and coherence analysis, were used to analyze the performance of the manual task, postural control, and the integration between postural and manual performance. Across all three rhythms, discrete relative phase mean and variability (SD) results showed no effects of posture on rhythmic performance. The complexity of the manual task (1:1 vs 2:3) had no effect on postural time-to-contact. However, increasing the tempo of the manual task (2:3 vs. 2:3=F) did result in a decreased postural time-to-contact in the two-footed posture). Coherence analysis revealed that the coupling between the postural and manual task significantly decreased as a function of posture (going from a two footed to a one footed posture) and rhythmic complexity (1:1 vs. 2:3). Taken together, these results demonstrate that expert marching percussionists systematically decouple postural and manual fluctuations in order to preserve the performance of the rhythmic movement task.

Introduction

The performance of a skilled action is the materialization of a system that has explored its degrees of freedom, and has organized them in accordance with the demands of the task (Bernstein, 1967). A growing body of literature has begun to explore the adjustments in degrees of freedom across the entire system as a function of task constraints, demonstrating that the means by which each task is controlled is context specific (Bardy et al., 1999; Haddad et al., 2010, Huys et al., 2003). However, the substantial body of literature on bimanual coordination dynamics that has served as a backdrop for our understanding of rhythmic movement has been conducted in a seated posture focused on the manual task (Huys et al., 2003; Kugler & Turvey, 1987; Schmidt et al., 1993; Sternad et al., 1995). As a result, how coordinative dynamics in the upper extremities are impacted by different postural constraints, or how focal task performance impacts postural stability is still largely unknown.

Marching percussion is an activity where postural control is crucial for precise visual and musical performance. Scoring of the visual performance is generally based on the uniformity of the spacing of the performers relative to one another, as well as uniformity of the marching technique; musically all of the notes being played must be synchronous. When learning a routine, music is always learned first in a static posture, making drumming in an upright stance the first stages of integration of postural and manual control. Static posture is generally considered stable if the position of the center of pressure (CoP) changes slowly over time with respect to the boundary of support defined by the geometry of the feet, resulting in a long time-to-contact (TtC) to the support boundary (Galgon et al., 2010; Haddad et al., 2006; Riccio, 1993). High precision manual tasks have been shown to affect these postural dynamics. For example, when performing a block fitting task, participants increased their TtC as the block approached the opening; decreasing the size of the aperture caused further increases in the time-to-contact (Haddad et al., 2013). Similarly, in a 2010 study Galgon and colleagues had participants perform a serial pointing task 300 times while recording their postural dynamics. Over the course of practice, the authors reported a longer TtC to the boundary of support. The increased TtC in the above research demonstrates posture is modulated with respect to the task constraints; it also suggests that postural stability can increase with practice (Galgon et al., 2010; Haddad et al., 2010, 2013).

Juggling, like drumming, is a complex rhythmic movement which requires the control of a manual and postural task for smooth cascading of the balls (Huys et al., 2003, 2004). In learning to juggle, the juggler begins to incorporate the frequency of the ball movements into the control of posture. In a 3-ball cascading juggling task several control strategies emerge, such that postural sway and ball movements predominantly form multi-frequency mode locking behaviors, such as 1:3 and 2:3. Huys and colleagues (2003, 2004) reported that with practice some individuals displayed both patterns (1:3 and 2:3) concurrently, while others abruptly switched their control strategies (from 1:3 to 2:3), suggesting the existence of multi stability when performing complex tasks. With practice the authors also reported changes in coupling strength between the control of posture and the juggling task. As the individuals became more proficient, the degree of coupling between the control of posture and the manual task decreased (as indicated by cross spectrum analysis). The authors concluded that while the juggling is embedded into the control of posture, it is advantageous for the two tasks to be loosely coupled, allowing for greater flexibility in light of a perturbation (Huys et al., 2003, 2004).

Coordination is also affected by movement frequency, tempo, (Haken et al., 1985; Kelso, 1983, 1984), where increased tempo has been shown to decrease rhythmic stability (Haken et al., 1985; Schmidt et al., 1991, 1993; Sternad et al., 1992). Rhythmic instabilities, for simple (1:1) and complex rhythms (any rhythm with a numerator and denominator greater than 1), are characterized by increased deviation from intended relative phase and increased relative phase variability (De Guzman & Kelso 1991; Schmidt et al., 1991, 1993; Sternad et al., 1992, 1995; Treffner & Turvey, 1993). For example, Peper and colleagues (1995) had professional drummers tap a 2:3 rhythm at various speeds, and demonstrated the fast hand was relatively unaffected as the frequency of oscillation increased, while the slow hand began to display frequency signatures of the fast hand in its own dynamics; demonstrating a decrease in coupling strength (Peper et. al. 1995).

The information presented above suggests that coupling between functional units decreases with increasing tempo constraints as well as with skill level. This decrease in coupling strength may ultimately allow the performer to adjust to perturbations in a more effective manner. The caveat of such results are that these studies have been conducted from a stable posture (seated or standing with feet shoulder width apart) (Greene 1972; Huys et. al., 2003; Peper et. al., 1995). When postural and manual stability are altered both act to constrain the body's degrees of freedom. If overly constrained, the system becomes increasingly unstable due to the limited available degrees of freedom; thus one may predict that the coupling between two concurrent tasks increases as a result (Lipsitz, 1992). Given that bi-manual rhythmic coordination has served as the back drop for most of the current understanding of coordination dynamics, it would be a logical next step to understand how the performance of a manual task is affected by posture. Due the nature of their activity, expert marching percussionists are ideal candidates for studying such interactions. In any musical activity, tempo and rhythmic complexity constrain the performer's degrees of freedom, but for marching percussionist posture serves as an additional constraint.

The purpose of this study was to examine the integration between postural control and bimanual rhythmic movements in expert marching percussionists. Aim one assessed the effects of posture on bimanual coordination. We hypothesized that rhythmic task stability would decrease with increasing postural difficulty (indicated by: greater deviation from intended relative phase, increased relative phase variability). Aim two focused on the effects of manual task difficulty (rhythmic complexity and tempo) on postural stability. There were two associated hypotheses: that increasing rhythmic complexity decreases postural stability, and that increasing tempo decreases postural stability (reduction in CoP time-to-contact with the boundary of support). Aim three examined the coupling between posture and manual movements. We hypothesized that with increasing postural and rhythmic task constraints, the coupling between the postural and focal task would increase (indicated by increased coherence between the postural and manual task).

<u>Methods</u>

Participants

Eleven University of Massachusetts Drumline members (height (m): 1.83 $\pm$ .13, weight (kg): 77.19 $\pm$ 16.3, age: 20 $\pm$ 2, years of experience: 9 $\pm$ 3) participated in the study, and signed a university approved consent form. Participants were excluded if they had a history of tendonitis of the wrist, neurological disorders, or lower leg injury that prevented them from standing on one leg for an extended period of time.

Experimental Design

The study was set up as a factorial design (Figure 15). There were three postural conditions in which the participants played from: a seated posture (Se) standing on two feet (S2), and standing on one foot (S1). There were three drumming conditions: 1:1 (180^{O} anti-phase), 2:3, and 2:3-F (this condition was the 2:3 played faster at a self-selected tempo (see procedures for details). Each condition was randomly performed three times for a total of 27 trials, each trial lasting 30 seconds.

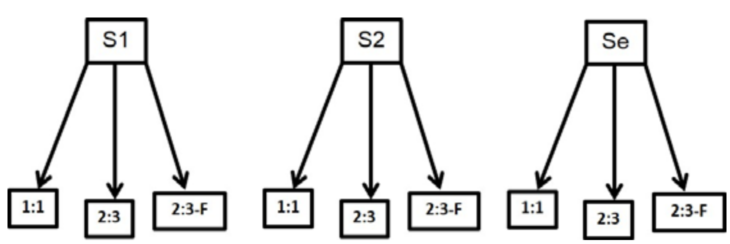

Figure 15: Experimental design. The participants stood in three postures: standing on one foot (S1), standing on two feet (S2), and sitting (Se) and played two rhythms (1:1, 2:3). In the third condition, the 2:3 rhythm was played faster, 2:3-F.

Procedure

A brief survey administered before the protocol determined the leg the participant preferred to use in a one footed stance, as well as the hand used to play the faster of the two frequencies during the multi-frequency rhythm (these designations were maintained for the duration of the experiment). To avoid forcing the participants to play with an unnatural grip, they were allowed to perform the drumming tasks with their preferred grip (matched or traditional). T-tests comparing key variables, discrete relative phase and time-to-contact, confirmed that there were no differences between two grips types (matched= 7, traditional= 4), allowing us to pool participants.

In the seated posture participants were instructed to keep the tempo as consistent as possible throughout the trial while playing as rhythmically accurate as possible. While standing (S1 and S2), the participants were given the same instruction as given for the manual task in the seated posture while maintaining as balanced a stance as possible. In the S1 posture, participants stood on their preferred leg, while keeping the opposite leg flexed in a 90^{O} position (this posture was maintained for the duration of the trial). Participants were instructed to do whatever was necessary to complete the task while avoiding falling over. In the event that the participant had to stop playing to regain stability they were asked to recover as fast as possible. All rhythms we performed at a self-selected tempo that could be consistently maintained for the duration of the trial.

Data Collection and Processing

Kinematic data were collected at 240 Hz using nine Oqus cameras (Qualysis, Gothenburg, Sweden). To capture the base of support, markers were bi-laterally placed on the heel, big toe, first and fifth metatarsal heads. Drumstick kinematics (SRH2 model, Vic Firth, Dedham, MA, USA), were collected using four strips of retro reflective tape placed along the length of each stick. Center of pressure data were collected at 240 Hz (600 x 1200, AMTI, Watertown, MA, USA). All data were processed using Qualysis Tracking Manager (QTM). Filtering and data analysis occurred in MATLAB (Mathworks, Natick, MA, USA) using custom software. All kinematic and center of pressure data were filtered using a 4th order dual pass, low pass Butterworth filter. Fast Fourier Transforms were applied to representative samples of the data to determine appropriate cut off frequencies. Markers of the feet as well as COP data were filtered with a cutoff frequency of 10 Hz. Because the analysis focused on strike timing, only the vertical (Z) direction of stick movement was analyzed. Vertical kinematics of all four markers, for both the left and right sticks were filtered at a cutoff frequency of 15 Hz.

Data Analysis

Bi-manual Coordination

The stability of manual task was assessed by discrete relative phase (DRP) (Eq 14).

Equation 14: Discrete Relative Phase

$$\varphi = \frac{|Rh_i - Lh_i|}{\Delta t} * 360$$

Where Rh_i and Lh_i are time stamps of the right and left stick strikes in their respective time series, and Δt is the cycle time. Cycle time is defined as the timing difference between each successive strike of one hand. For the 1:1 rhythm, the cycle time was defined by the timing differences of the dominant hand. For the 2:3 and 2:3-F rhythms, the cycle time was defined by the hand playing the fast rhythm. To obtain moments of impact of the drumstick and the surface, a custom program was designed in MATLAB to identify the minima in the vertical (Z) motion component of one of four drumstick markers.

1:1 DRP

In the case of the 1:1 anti-phase rhythm, timing differences were calculated between successive stick strikes of the right and left hands. For convention, each of the motion files started and ended with a right hand, and the last right hand was omitted to ensure there was an even number of right and left hand strikes.

2:3 DRP

The 2:3 rhythm was divided into three phases (see Figure 16). In a perfect 2:3 rhythm the phase relationship at DRP_1 is 0^O, and DRP_2 and DRP_3 are both 180^O (these relationships were calculated from a generated 2:3 rhythm using equation 1). To obtain the DRP_{1-3} values, the original signal was split into three separate time series (beat 1, 2,

3) for the fast hand, and two time series for the slow hand (beat 1 and 2). These newly created time series were then used to calculate DRP for each phase of the 2:3 rhythm. To ensure that the time series started on a cycle, each motion file was cropped to start and end on DRP_1.

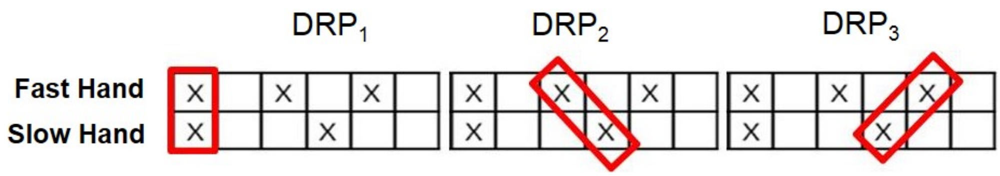

Figure 16: DRP_{1-3} description. The 2:3 rhythm was subdivided into three phases: DRP_1 (left, $\varphi = 0^O$) is the temporal difference at the phase locking region of the rhythm, DRP_2 (center, $\varphi = 180^O$) is the temporal difference between the second note of the fast hand (top row) and the second note of the slow hand (bottom row), DRP_3 (right, $\varphi = 180^O$) is the temporal difference between the last note of the fast hand and the second note of the slow hand.

Postural Variables

Postural stability was measured by the average TtC to the boundaries of the base of support across the entire trial using the Slobounov method (Haddad et al., 2006, Slobounov et al., 1997). For the S2 condition the boundary of support was set up as a trapezoid, with the lateral boundaries being defined by a line containing the position of the lateral malleoli and 5th metatarsal heads (Figure #). Because all subjects stood with their feet parallel, a straight line across the toe and heel markers defined the anterior and posterior boundaries, respectively. For the S1 condition the boundary of support was set up as a box around the foot. Lateral boundaries were defined by vertical lines through the

1st and 5th metatarsal heads, and the anterior and posterior boundaries were defined by horizontal lines through the toe and heel markers, respectively (Figure 17).

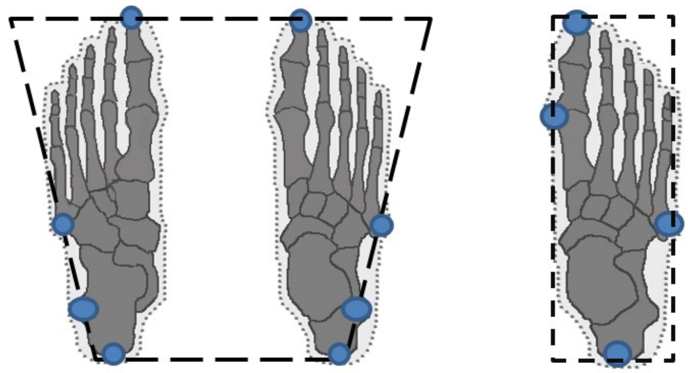

Figure 17: Definition of the base of support.S2 condition (left) and the S1 condition (right).

Postural-Manual Interaction Variables

Coherence analysis was performed to assess changes in postural-manual coupling as a function of task complexity. The analysis individually compared the vertical (Z) component of each drumstick to the anterior-posterior (A-P) and medio-lateral (M-L) components of the CoP, respectively, using the "mscohere" function in MATLAB. Because of its low side lobes and high roll off rate, the best suited window to target specific frequencies was the Blackman-Harris window. For each trial, to identify the dominant frequency of each drum stick (which would serve as the targeted frequency for statistical analysis), a power analysis (using the Welch's overlapped segment averaging estimator) was conducted on both the slow and fast hand. Once the dominant frequency was identified, a custom built MATLAB software program was used to select the specified frequency and its level of coherence from the time-series created using the mscohere function.

Statistical Analysis

Aim 1: The effects of posture on bimanual coordination

The mean and standard deviation of the DRP time series was obtained for each trial. The trials where then averaged together, and were used for statistical analysis. To assess the effects of posture on the focal task, a one-way repeated measures (RM) ANOVA with posture as a factor (3 levels: S1; S2; and Se) was performed on the 1:1 DRP mean and SD measures separately. To assess the effects of tempo and posture on the focal task (Aim 1), a 2-way RM ANOVA was performed on the 2:3 rhythm (2 levels: 2:3 and 2:3-F) and posture (3 levels: S1;S2; and Se) as factors. The 2-way RM ANOVA design was performed on the DRP mean and SD individually for each portion of the 2:3 rhythm (DRP_{1-3}).

Aim 2: The effects of manual task difficulty (rhythm and frequency) on postural stability

Mean TtC was calculated for each trial, then averaged across all three trials. To assess how posture was affected by rhythm complexity, a 2-way Posture (S1; S2) by Rhythm (1:1; 2:3) RM ANOVA was performed on mean TtC values. A second 2-way RM ANOVA, Posture (S1; S2) by Tempo (2:3; 2:3-F) was performed on mean TtC values to assess the effects of tempo on posture.

Aim 3: Coupling between posture and manual movements

Prior to statistical analysis, raw coherence data were scaled with a Fisher-Z transformation-and averaged across the three trials for each condition. The average of the trial means where then used for statistical analyses. To assess how coupling between the postural and manual task changed with task complexity, a 2-way RM ANOVA, Posture (S1; S2) by Rhythm (1:1; 2:3; and 2:3-F), design was used. Four separate statistical analyses using the same model were conducted. The analyses compared the 1:1 rhythm to the 2:3 and 2:3 fast hand in the A-P and M-L directions, respectively. The data presented in the results section were transformed back into correlation values, again using the Fisher-Z transformation.

Results

Bi-manual Coordination

1:1 DRP

No main effects of posture were observed for DRP mean and variability (Table 1).

Table 1: 1:1 DRP mean (± SD) and variability of DRP (± SD)

		DRP Mean (Degrees)	DRP Variability (Degrees)
S1		177.96 (2.61)	6.06 (.950)
S2		178.34 (1.95)	6.21 (1.20)
SE		177.87 (1.67)	6.06 (1.11)
Posture	P-value	0.78	0.85
	F(2,10)	0.23	0.17

2:3 DRP

No main effect of posture was observed for DRP mean and variability. In both measures, a significant main effect of tempo was observed (Table 2; Figure 18).

Table 2: $DRP_{1\text{-}3}$ mean (± SD) and variability of $DRP_{1\text{-}3}$ (± SD) 2:3 and 2:3-F

		Mean (Degrees)		Variability (Degrees)	
		2:3	2:3-F	2:3	2:3-F
DRP1					
S1		6.79 (2.32)	11.82 (3.81)	5.32 (1.84)	9.16 (2.83)
S2		7.11(3.22)	11.92 (3.54)	5.78 (3.01)	9.68 (2.72)
SE		6.81 (2.38)	12.75 (3.66)	5.54 (1.48)	9.85 (2.42)
Posture	F(1,10)		31.48		34.803
	P-value		< 0.001		< 0.001
Tempo	F(2,20)		0.891		1.32
	P-value		0.426		0.289
Posture x Tempo	F(2,20)		2.28		0.258
	P-value		0.129		0.775
DRP2					
S1		178.42 (3.92)	175.18 (6.23)	9.26 (2.39)	14.76 (3.78)
S2		179.38 (3.18)	173.26 (5.64)	8.91 (2.13)	15.08 (4.18)
SE		180.01 (4.08)	174.51 (4.23)	8.75 (1.93)	15.51 (3.63)
Posture	F(1,10)		12.98		22.39
	P-value		0.005		0.001
Tempo	F(2,20)		1.1		0.113
	P-value		0.351		0.894
Posture x Tempo	F(2,20)		1.44		1.97
	P-value		0.26		0.165
DRP3					
S1		182.44 (4.07)	177.97 (4.06)	8.83 (2.15)	14.11 (3.38)
S2		182.79 (4.08)	177.47 (3.68)	7.72 (1.91)	13.99 (3.27)
SE		181.92 (4.50)	177.42 (4.10)	8.01 (2.17)	14.19 (2.92)
Posture	F(1,10)		20.09		30.792
	P-value		0.001		< 0.001
Tempo	F(2,20)		0.191		1.762
	P-value		0.828		0.197
Posture x Tempo	F(2,20)		0.143		2.67
	P-value		0.867		0.115

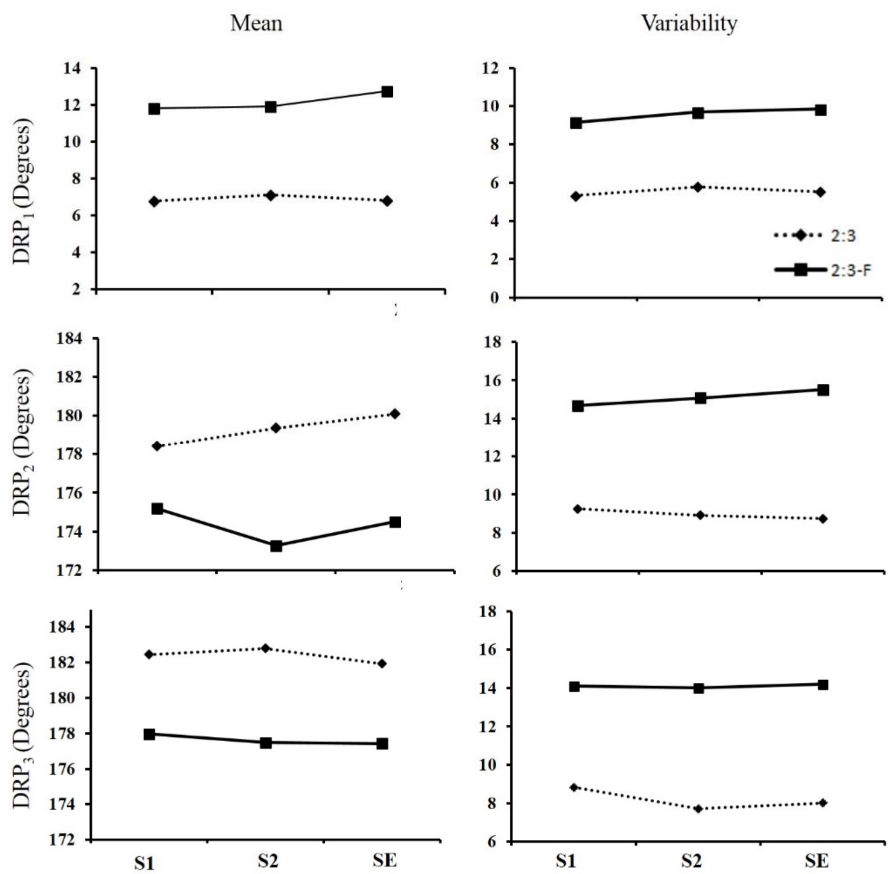

Figure 18: DRP 2:3 results. DRP1- DRP3 (top to bottom) mean (degrees) and variability (degrees) (left and right respectively) for the 2:3 (dotted line) and 2:3-F rhythms (solid line)

Postural Control

A main effect of Posture was observed in the Rhythm (1:1 vs 2:3) x Posture RM ANOVA, but not of Rhythm ($p=.27$) on TtC (Table 3; Figure 19, left panel); TtC decreased from S2 to S1. Tempo and Posture were main effects (Table 3) in the Frequency (2:3 vs. 2:3-F) by Posture RM ANOVA. Tempo and Posture significantly interacted ($p= 0.047$). Post hoc analyses showed TtC decreased significantly in the S2 at the faster tempo (p= .01), but not in the S1 posture (p=0.46) (Table 3; Figure 19, right panel).

Table 3: TtC mean (± SD) for S1 and S2 across all experimental conditions

	S1 (s)	S2 (s)
1:1	.50 (.08)	.62 (.16)
2:3	.48 (.06)	.63 (.17)
2:3-F	.47 (.06)	.55 (.12)

	1:1 vs 2:3	
Posture	F(1,10)	17.25
	P-value	0.002
Rhythm	F(1,10)	0.042
	P-value	0.84
Rhythm x Posture	F(1,10)	1.35
	P-value	0.272

	2:3 vs 2:3-F	
Posture	F(1,10)	12.59
	P-value	0.005
Tempo	F(1,10)	5.14
	P-value	0.047
Tempo x Posture	F(1,10)	19.23
	P-value	0.001

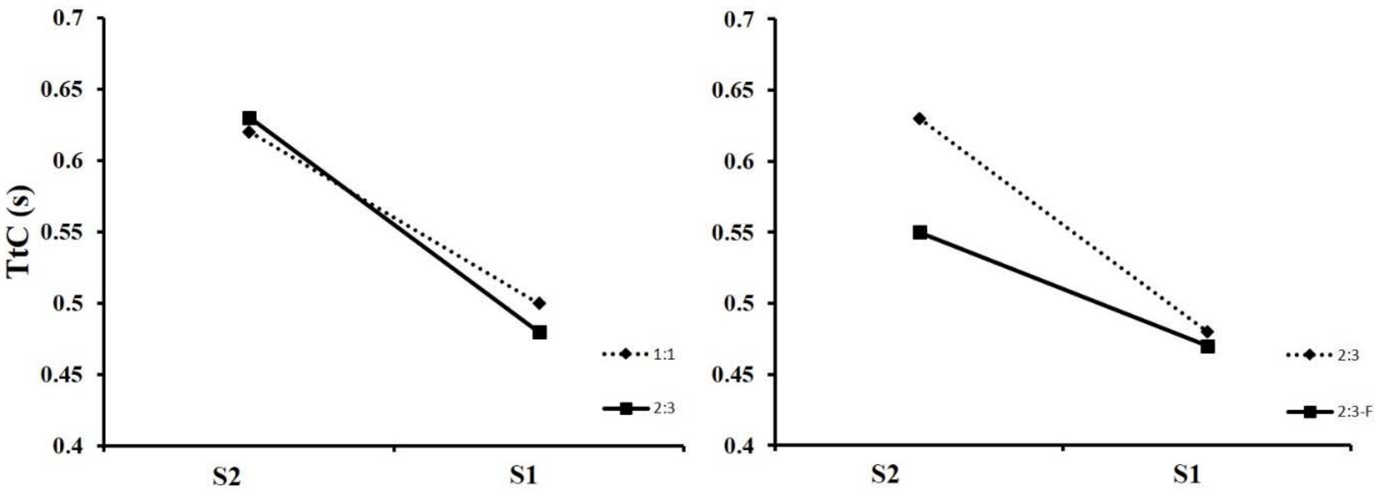

Figure 19: TtC Results. The effects of rhythmic complexity (left) and tempo (right) on postural control.

Postural-Manual Coupling

A main effect of Posture was observed in both the anterior-posterior (AP) and medio-lateral (ML) directions: coherence decreased from S2 to S1; main effects of rhythm were observed in the M-L direction but not the AP direction (Table 4; Figure 20). Posture and Rhythm interacted in the M-L direction (Table 4); post hoc analyses revealed the 1:1 rhythm had significantly larger coherence values in the S2 posture (p= .01) but not the S1 posture (p=.58).

Table 4: Coherence mean (± SD) for S1 and S2 in the A-P and M-L direction

		S1	S2	Rhythm		Posture		Rhythm * Posture	
A-P	1:1	.65 (.19)	.81 (.26)	F(2,20)	2.65	F(1,10)	28.47	F(2,20)	0.87
	2:3	.74 (.33)	.85 (.33)	P-value	0.09	P-value	< 0.001	P-value	0.43
	2:3-F	.78 (.22)	.90 (.16)						
M-L	1:1	.58 (.16)	.95 (.04)	F(2,20)	5.53	F(1,10)	114.47	F(2,20)	4.49
	2:3	.50 (.28)	.82 (.31)	P-value	0.01	P-value	< .001	P-value	0.02
	2:3-F	.49 (.26)	.83 (.18)						

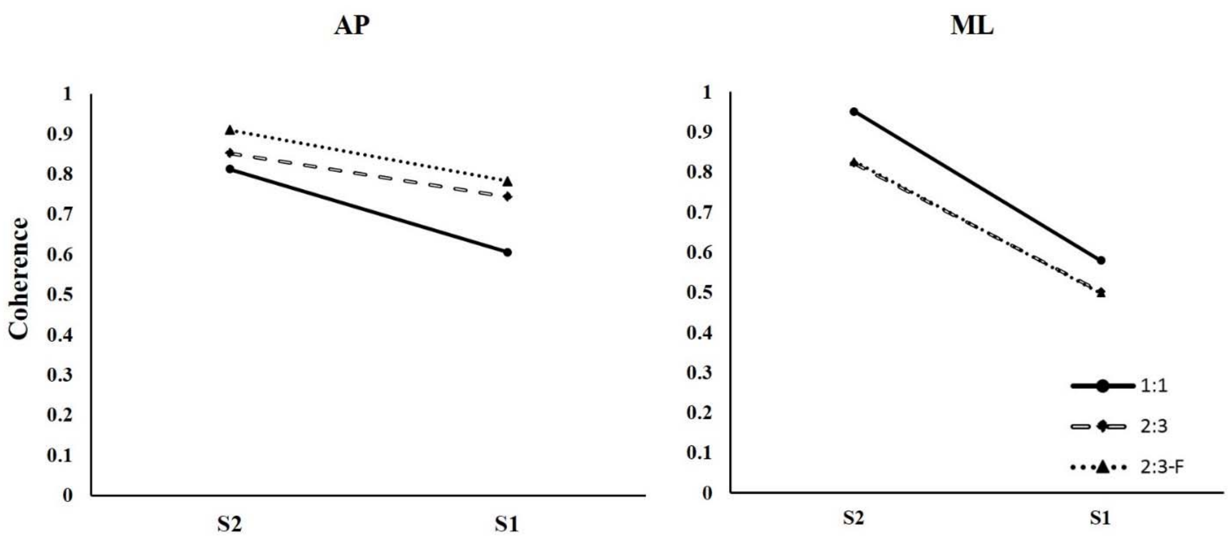

Figure 20: Coherence results. The effects of task complexity on coherence between postural and manual movements in the anterior-posterior direction (A-P, left), and medial-lateral (M-L, right)

Discussion

This study examined the integration between postural control and bimanual rhythmic movements in expert marching percussionists. No changes were observed in mean DRP and DRP variability values, providing no support for our hypothesis that posture would affect rhythmic stability (Aim 1). Postural analysis using TtC revealed rhythm (1:1 vs 2:3) had no effect on the control of posture, providing no support for our hypothesis that rhythmic complexity decreases postural stability (Aim 2). Increasing the tempo of the manual task reduced TtC, supporting our hypothesis that frequency of oscillation would reduce postural stability (Aim 2). Coupling, as measured by coherence analysis, between the postural and manual task decreased as a function of posture (A-P and M-L) and rhythm (M-L), providing no support for our hypothesis that increasing the number of constraints on the participant increases the coupling (Aim 3).

The current study adds to a growing body of literature that examines the interaction between postural and manual control (Haddad et al., 2010; Huys et al., 2003). Similar to previous work on bi-manual rhythms, we used mode locking regimes, 1:1 and 2:3, which have been shown to be stable and robust under a number of task manipulations (Park & Turvey 2008; Peper et al., 1995). The paradigm presented here differs from previous work in the sense that the production of rhythm was not constrained to the movement of the wrist or fingers, but it incorporated all degrees of freedom of the arms as well as postural control, allowing us to understand the control of a multi-joint system on end-effector movement and coordination. Expert marching percussionists, an uncommon experimental model for understanding postural-focal interaction, were ideal participants as extensive practice and high levels of skill allowed them to play different rhythms accurately under a variety of postural constraints.

The absence of a postural effect on bi-manual rhythmic coordination across all playing conditions provides support for previous work on bi-manual coordination performed in a seated posture. Expert performers examined here were are able to stably perform the required rhythm despite changes in postural constraints (Kugler & Turvey 1987, Rosenblum & Turvey 1988). Previous work has shown simple 1:1 anti-phase rhythm is stable under different spatial configurations, different frequencies of oscillation, and over a wide range of Ω values (ratio of the natural frequencies of the uncoupled oscillators) (Park & Turvey, 2008). Our results add to the current literature by showing that the 1:1 rhythm is also stable over a variety of upright postural configurations. Although it was originally hypothesized that posture would affect rhythmic stability, these results should be viewed in the context of the expertise of the participants as well as the common nature of the 1:1 anti-phase in many activities of daily living. The more surprising result was the stability of the 2:3 and 2:3-F rhythms with changes in posture. Due to the multi-frequency nature of the 2:3 rhythm, we expected that it would be more susceptible to postural fluctuations. Research on multi-frequency behavior has shown that the coordination in human movement is attracted to lower order multi-frequency couplings (a coupling consisting of a small numerator and denominator), but due to systemic noise it may tend to shift to a less complex, and more stable coupling (De Guzman & Kelso, 1991; Treffner & Turvey, 1993; Peper et al., 1995). It was the original thought that transitioning from a seated to a standing posture would introduce enhancement of fluctuations in bi-manual coordination even in the expert performers, but this was not observed as postural condition had no effect on the variability of the discrete relative phase between the two hands.

Historically research on the control of posture has been conducted in the absence of context (Hasson et al., 2008; Nashner & McCollum, 1985; Newell & Slobounov, 1993; Slobounov et al., 1997, Slobounov et al., 2009). This has led to the traditional interpretation that a shorter TtC value represents an unstable system (Hasson et al., 2008; Haddad et al., 2010; Slobounov et al., 1997, Slobounov et al., 2009). This perspective reflects our original rationale for formulating the hypotheses for Aim 2 of the current study (i.e. reductions in TtC increases coordinative variability of the manual task). Because the coordination of the manual task remained stable (DRP and DRP variability) regardless of the state of the postural system, changes in TtC cannot be interpreted as a reflection of systemic stability in complex tasks that integrate many subsystems. The results of the current study suggest when the control of posture is nested within a secondary task, a range of TtC values may be used to satisfy task constraints in which decreased TtC may not necessarily be a reflection of loss of postural stability.

Manipulation of rhythmic complexity (i.e. 1:1 vs. 2:3) had no effect on postural control (TtC of the CoP). Post hoc analysis of the frequency content of the right hand of the 1:1 rhythm and the fast hand of the 2:3 rhythm revealed a peak power for both rhythms at approximately 3.5 Hz (<u>S1</u> 1:1 vs 2:3: $p=.28$; <u>S2</u>: 1:1 vs 2:3: $p=.89$) (Figure 21). Despite differences in rhythmic complexity, the organization of the postural control did not change potentially due to the invariant frequency content between the two rhythms. When tempo of the rhythm was increased in the 2:3-F condition the dominant frequency of the fast hand increased to approximately 5 Hz (2:3 vs 2:3-F: $p < .001$, for both postural conditions) (Figure 21). Participant's experienced significant reductions in TtC when performing the 2:3-F in the S2 posture only (Figure 19); this may be explained by the reduction in the area of the base of support. The larger area in the S2 posture affords participants a faster rate of fluctuations because there is enough room for postural corrections, such that there are no real threats to postural or rhythmic stability. In the S1 condition the fluctuations of the CoP, regardless of frequency, are limited by the area of the base of support, suggesting there may be a lower limit at which the CoP is allowed to fluctuate before performance is affected, or before the maintenance of the one footed stance is not possible. The original rationale for believing rhythmic complexity would change the organization of the postural response was due to competing frequencies. The post hoc analysis demonstrates this is not the case, but it is tempo of the dominant hand in conjunction with the constraints placed on the configuration of the base of support which influences CoP dynamics. The changes to CoP fluctuation addressed above were accompanied by adjustments to the degree of coupling between postural and manual dynamics which may have also aided the conservation of the manual task.

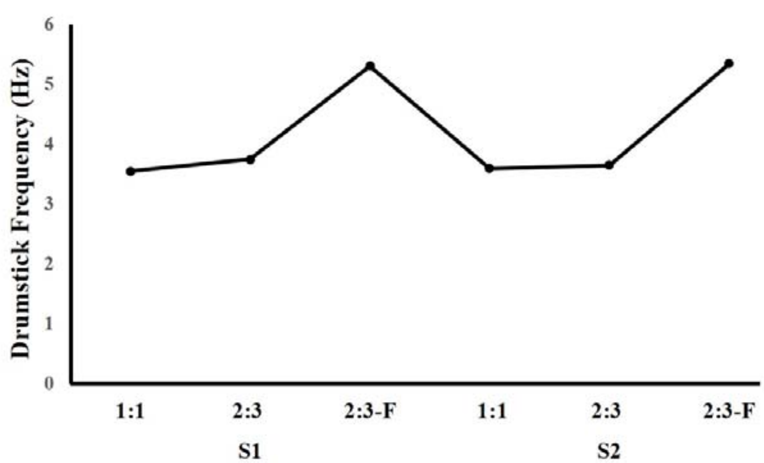

Figure 21: Spectral content of the right hand (1:1) and the fast hand (2:3 and 2:3-F) in the one legged (S1) and two legged (S2) stance conditions.

In the M-L direction the 2:3 rhythm significantly reduced the coherence compared to the 1:1 rhythm; increasing the tempo (2:3-F) did not cause any further decreases in coupling. This result suggests it is the competition between the natural frequencies of the 2:3 pattern which affects systemic coupling, supporting previous findings of decreased pattern stability as the ratio of the natural frequencies, Ω, departs from one (Peper et al., 1995; Schmidt et al., 1991, 1993). In both the A-P and M-L directions, coherence decreased as a function of posture suggesting postural dynamics serve as a source of information for adjustments made along the kinematic chain. The observed stability in manual performance under increased postural constraints and reductions in TtC, supports the position that reductions in coupling strength are advantageous in preventing postural fluctuations from affecting the manual task (Riccio, 1993; Riccio & McDonald, 1998).

Simon (1969, 1973) theorized complex systems, like the human body, are able to adjust the strength of the coupling between its subcomponents both vertically (i.e. alterations of the coordinative relationship across different time scales) and horizontally (i.e. alterations of the coordinative relationship within the same time scale). The manual task demonstrated horizontal adjustments, while decoupling as a function of posture and rhythm was an example of a vertical adjustment. Although our analysis focused on whole body coordination, the current results possess similar features to those reported in Schmidt et al., (1991); coupling strength decreased as a function of the difference in the frequency content of each oscillator, reflecting a loss of entrainment between the two tasks (in the M-L direction only). The downward shift in systemic coupling may be an adaptation to offset the destabilizing forces of each hand occurring at different frequencies. When considering the results of the TtC analysis, alongside those of the A-P coherence results, the claim that the loss of coupling strength is adaptive is supported. As individuals went from a two legged to a one legged stance, the area of the base of support decreased and the fluctuation rate of the CoP relative to the boundary of support increased. In order to keep the manual performance from being affected by the increased fluctuations at the base of support, the system decreased the strength of the coupling.

Conclusions

This study examined the integration between postural control and bimanual rhythmic movements in expert marching percussionists. The results demonstrated that 1) the manual task was left unaffected by changes in posture; 2) the control of posture was only affected by the tempo of the manual task and not rhythm complexity (1:1 vs. 2:3) and 3) the coupling between the postural and manual task decreased as postural task difficulty and rhythmic task complexity increased. The evidence suggests expert performers make adaptations along the kinematic chain so the performance of the manual task is left unaffected. Furthermore these results contribute to the growing body of literature which suggests that complex behaviors are the result of the interacting subsystems which tunes themselves in accordance with the constraints of the task.

APPENDIX A

HEALTH HISTORY QUESTIONNAIRE

Instruction: Please answer the following questions as truthfully as possible.

	Y	N
1) Have you been diagnosed with a neurological disorder that may affect your ability to complete a balance task?		
1a) If so, are you currently on any medication aimed at treating your condition?		
2) Have you had a knee or ankle injury that has required surgery?		
3) Do you have any metal plates, rods, or screws in your ankle?		
4) Have you been diagnosed with chronic tendonitis of knee or ankle joint?		
5) In the last 6 months have you experienced any lower extremity injuries that may compromise your ability to stand on <u>one foot</u> or <u>an uneven surface?</u>		
6) In the last 6 months have you been diagnosed with acute tendonitis of the wrist?		
7) Have you been diagnosed with chronic tendonitis of the wrist?		
7a) If so, can you still drum for 1.5 hours without experiencing pain?		
8) Have you received any balance training prior to this study (e.g. Yoga, Physical Therapy, etc.)?		

APPENDIX B

CONSENT FORM FOR PARTICIPATION IN A RESEARCH STUDY

University of Massachusetts Amherst

Principal Investigator: Avelino Amado, B.S.; Richard E.A. Van Emmerik

Study Title: Postural instabilities and the maintenance of bi-manual rhythmic movements

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1. WHAT IS THIS FORM?

This consent form will give you the information you will need to understand why this study is being done and why you are being invited to participate. It will also describe what you will need to do to participate and any known risks, inconveniences or discomforts that you may have while participating. We encourage you to take some time to think this over and ask questions now and at any other time. If you decide to participate, you will be asked to sign this form and you will be given a copy for your records.

2. WHO IS ELIGIBLE TO PARTICIPATE?

Male and female UMass Drumline Members in the 18 and 25 age group.

3. WHAT IS THE PURPOSE OF THIS STUDY?

The purpose of this study is to investigate the effects of postural disruptions on the performance of a rhythmic bi-manual coordination task.

4. WHERE WILL THE STUDY TAKE PLACE AND HOW LONG WILL IT LAST?

The study will take place in room 24 of the Totman Physical Education Building, 30 Eastman Lane University Massachusetts Amherst. The overall testing procedure will take approximately 1.5 hours

5. WHAT WILL I BE ASKED TO DO?

1) You will be asked to read and complete a health history questionnaire, as well as an informed consent form
2) We will begin by:
    a. Measuring your height and weight
    b. Assessing your dominant hand and leg
3) You will be asked to change into form fitting gym clothes (spandex or running shorts), in order to prepare for data collection
4) Next you will be outfitted with a full body marker set up. The position of the reflective markers will be recorded by high-speed infrared cameras around the room.

5) Before any experimental manipulations are done, a standing calibration will be taken. This will ensure all of the markers are being detected by the cameras.
6) There will be two major sessions, each consisting of 16 trials that will be separated by a ten minute break. In one session you will drum with a metronome at 55 beats per minute and in the next session the metronome will be turned off. The order of these sessions will be randomized across all participants.
7) Within each metronome or non metronome session there will be two postural conditions (standing on both feet or on one foot) , two balance conditions (standing on the force plate or on the air filled balance disk) and four rhythms (1:1, 2:3, 3:4, 4:6). A trial will consist of a randomly selected combination of: one postural condition, one balance condition, and one rhythm. Each of the four possible postural and balance combinations will be randomly repeated until every rhythm has been played once in each combination.
8) Once the study is completed you will be debriefed and informed on what we were attempting to learn from the study.

6. WHAT ARE MY BENEFITS OF BEING IN THIS STUDY?

You may not directly benefit from this research; however, we hope that your participation in the study may help us as researchers gain a better understand how the body reacts when it receives an unexpected challenge to balance.

7. WHAT ARE THE RISKS OF BEING IN THIS STUDY?

There are no risks to your health being involved in this study.

8. HOW WILL MY PERSONAL INFORMATION BE PROTECTED?

Information concerning you that is obtained in connection with this study will be kept confidential by the testing facility. The records will be coded to protect your identity. In addition, the Investigational Review Board may inspect the records of this study. Information obtained in the study may be used for scientific publication, but your identity will remain confidential. Data will be stored in a locked filing cabinet in a locked office. Only staff involved in this study will have access to the data.

9. WHAT IF I HAVE QUESTIONS?

We will be happy to answer any question you have about this study. If you have further questions about this project or if you have a research related problem, you may contact the researcher(s), Avelino Amado via email (aamado@cns.umass.edu) or Dr. Richard van Emmerik via email (rvanemmerik@kin.umass.edu). If you have any questions concerning your rights as a research subject, you may contact the University of Massachusetts Amherst Human Research Protection Office (HRPO) at (413) 545-3428 or humansubjects@ora.umass.edu.

10. CAN I STOP BEING IN THE STUDY?

You are under no obligation to participate in this project. You are free to withdraw your consent and participation at any time, for any reason.

11. WHAT IF I AM INJURED?

The University of Massachusetts does not have a program for compensating subjects for injury or complications related to human subjects research, but the study personnel will assist you in getting treatment.

12. SUBJECT STATEMENT OF VOLUNTARY CONSENT

I have read this from and decided that I will participate in the project described above. The general purposes and particulars of the study as well as possible hazards and inconveniences have been explained to my satisfaction. I understand that I can withdraw at any time.

By signing below I indicate that the participant has read and, to the best of my knowledge, understands the details contained in this document and has been given a copy.

___________________________	_______________________	___________
Participant Signature:	Print Name:	Date:
____________________________	_______________________	___________
Signature of Person	Print Name:	Date:

APPENDIX C

THE EFFECTS OF CYCLE TIME ON DRP

When comparing the mean 2:3 vs 2:3-F DRP, the results demonstrated the mean DRP shifted. Because the cycle time of the fast hand in the DRP 2:3-F is shorter than the cycle time of the fast hand in the 2:3, there may be a possibility that the shifts seen in the mean DRP in the 2:3-F condition was a function of a smaller denominator, cycle time. To ensure the differences seen in the DRP mean values weren't confounded by the cycle time we compared the absolute difference between the fast hand (FH) and the slow hand (SH), |FH-SH|Δ, for DRP_1 2:3 and 2:3-F, Φ=0º. If DRP values were confounded by a shorter cycle time, then |FH-SH|Δ would stay relatively the same; if they were not confounded, then |FH-SH|Δ then there would be a larger difference between the two oscillators. The results (Table 5) demonstrate |FH-SH|Δ got larger, suggesting DRP values were not affected by the cycle time.

Table 5: Absolute difference between the fast hand and slow hand

	Standing on one foot				Standing on two feet			
	2:3		2:3-F		2:3		2:3-F	
	|FH-SH| Δ	DRP_1	FH-SH Δ	DRP_1	|FH-SH| Δ	DRP_1	FH-SH Δ	DRP_1
Sub1	0.0039	4.46	0.0073	15.31	0.0038	4.3	0.0054	11.62
Sub2	0.0034	4.43	0.0062	10.7	0.005	5.3136	0.0056	9.85
Sub3	0.0073	10.81	0.0079	14.13	0.0094	15.25	0.0086	15.87
Sub5	0.0039	4.78	0.0074	15.26	0.0039	4.73	0.0083	17.42
Sub6	0.0085	9.78	0.0078	17.03	0.0068	8.47	0.0087	19.2
Sub7	0.0053	8.42	0.0055	10.52	0.0051	8.27	0.0057	10.93
Sub8	0.0063	9.62	0.0081	15.65	0.0056	6.4883	0.0086	16.99
Sub9	0.0036	4.06	0.0069	13.35	0.004	4.25	0.0056	10.62
Sub10	0.0048	6.92	0.0051	8.32	0.0049	5.25	0.0045	7.8
Sub11	0.0055	7.02	0.0061	9.92	0.004	4.74	0.0063	10.84
Sub12	0.0042	5.2	0.0044	7.71	0.0039	4.93	0.0035	5.69

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