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Supra-Postural Task Performance in Children with Cerebral Palsy:
The Importance of Functional Context

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All your life you are told the things you cannot do. All your life they will say you’re not good enough or strong enough or talented enough; they will say you’re the wrong height or the wrong weight or the wrong type to play this or be this or achieve this. THEY WILL TELL YOU NO, a thousand times no, until all the no’s become meaningless. All your life they will tell you no, quite firmly and very quickly. AND YOU WILL TELL THEM YES.

- Nike
ABSTRACT

Postural instability is a classical characteristic of cerebral palsy (CP), but it has not been examined in the context of other behaviors children perform when standing because recent work demonstrates that when motor tasks are made functionally more relevant, performance improves, even in individuals with movement pathology (Volman et al., 2001). If supra-postural tasks provide a functional context for postural control, children with CP might improve postural stability when performing supra-postural tasks.

Thirty children with CP participated in this study. Their postural sway was quantified during performance of two different supra-postural manual tasks (a steadiness task involving keeping a pointer inside a target, and a task requiring balancing a marble inside a hollow tube), and compared to a control group (n = 30) of comparably aged, typically developing children. A baseline condition (no supra-postural task) was also included. Traditional measures of postural sway variability and non-linear quantification of patterns in the time-evolution of postural sway were analyzed using analyses of variance and appropriate simple-effects and post-hoc tests.

I hypothesized supra-postural task performance would reduce postural sway variability in both typically developing and CP children. I also hypothesized the postural sway of children with CP would exhibit rigid, stereotypical behavior and a decrease in complexity, in accordance with a growing body of research on the loss of behavioral and physiological complexity accompanying “dynamical
diseases” (West, 2006). I furthermore hypothesized that the latter difference would be attenuated during performance of the supra-postural tasks.

The outcomes supported the hypotheses. Children with CP demonstrated changes in postural stability consistent with supra-postural task effects. The results were also consistent with the loss of complexity hypothesis, in that CP children demonstrated rigid and stereotypical postural sway patterns. However, their sway patterns became more complex and less predictable during supra-postural task performance, indicating that the functional context provided by the supra-postural task promoted a “healthier,” more complex sway pattern. These findings illustrate a degree of motor flexibility and adaptability in the postural control system, despite the pathological features associated with CP.
CP and SPT performance
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CHAPTER 1

Introduction

*Posture: Stability, Variability, and Sway Dynamics*

Posture refers jointly to the mutual relationships of the body segments, the global orientation of the body in the gravito-inertial field, and the orientation of the body relative to a surface of support (Blaszczyk & Klonowski, 2001). Postural control is essentially a matter of achieving postural stability—the body’s center of mass must be kept within critical boundaries of space that define body position (e.g., the position of the feet; Shumway-Cook & Woollacott, 1995). This challenging task is compounded by the small, but ubiquitous forward-backward (anterior-posterior; AP) and side-to-side (medial-lateral; ML) motion of the body termed postural sway. Postural sway is the collective result of unstable body mechanics, intrinsic and extrinsic perturbations, and the coordinated actions of the postural control system. Postural control can be conceptualized as the adaptive control of postural sway for the purpose of postural stability. It can also be conceptualized as a task-specific maintenance of a particular body orientation to the surrounding layout of surfaces and to the direction of balance (Riley, Baker, Schmit, & Weaver, 2005). Postural control involves the visual, haptic, and vestibular systems (Howard, 1986), and requires the coordination of neuromuscular synergies (muscle complexes engaged simultaneously over multiple joints of the body, constrained to act as single units).

Although postural control is a fundamental behavior, it remains relatively poorly understood. Postural sway is recognized as an informative source for
learning more about postural control. This continuous and highly variable output signal can be measured using dynamic posturography techniques, like rotation of the support surface (toe-up and toe-down perturbations) or movement of the support surface in response to the participant’s sway pattern (i.e., sway-referencing; Horak, Nutt, & Nashner, 1992). Postural sway can also be examined by employing static posturography, which involves measurements of spontaneous postural sway without the introduction of perturbations.

These methodologies traditionally quantify postural activity by statistically describing the amount or variability of postural sway (e.g., the standard deviation of a postural sway time series). Although postural sway is variable, it reflects the interplay of the aforementioned factors and thus should not be considered a reflection of “neuromuscular noise” (Newell, Kugler, van Emmerik, & McDonald, 1989; Newell & Slifkin, 1998; Newell, van Emmerik, Lee, & Sprague, 1993; Riley, 2001; Riley & Turvey, 2002; Slifkin & Newell, 1999). Many studies have demonstrated that patterns of physiological and behavioral variability characterize the dynamics of normal, healthy physiological processes (Costa, Goldberger, & Peng, 2003; Goldberger, Amarel, Hausdorff, Ivanov, Peng, & Stanley, 2002; Marsh, Osborn, & Cowley, 1990; Peng, Mietus, Liu, Lee, Hausdorff, Stanley, Goldberger, & Lipsitz, 2002); variability arises naturally from the interactions among numerous structural and functional units, operating at different temporal and spatial scales to enable adaptive behavior (cf. Goldberger, Peng, & Lipsitz, 2002).
The preceding comments about variability suggest that a comprehensive quantification of postural sway must also examine the dynamics (e.g., the spatiotemporal evolution) of postural sway. Changes in the dynamics of a system can be detected using nonlinear time series analyses. Analyses of the temporal evolution of a postural sway time series indicate that posture contains both deterministic and stochastic structure. Both recurrence quantification analysis (RQA; Webber & Zbilut, 1994, 1996, 2005) and sample entropy (SEn; Richman & Moorman, 2000) have been particularly useful nonlinear techniques used to examine the dynamical structure of postural sway (see Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008; Pellecchia & Shockley, 2005; Richman & Moorman, 2000; Riley, Balasubramaniam, & Turvey, 1999; Schmit, Regis, & Riley, 2005; Roerdink, De Haart, Daffertshofer, Donker, Geurts, & Beek, 2006; Schmit; Schmit, Riley, Dalvi, Sahay, Shear, Shockley, & Pun, 2006). Variability and the measures provided by recurrence quantification and sample entropy analyses will be used in the present study with the goal of enhancing our understanding of normal postural control and to explore changes in postural control when it is challenged by disease.

Posture in Children: Normal Development

Grossly, postural control reaches adult-like maturity by between the ages of 7 and 10 years (Shumway-Cook & Woollacott, 1995). Postural control studies examining postural sway in children indicate that children under the age of 7 years demonstrate greater amounts of postural sway and sway variability than older children (e.g., Forssberg & Nashner, 1982) and that postural sway
decreases linearly as children age (Riach & Hayes, 1987). Additionally, in young children, greater amplitudes of muscle activity are required to maintain a posture than in older children (Berger, Quintern, & Deitz, 1985); consequently, as a child ages, the number of muscles and degree of co-contraction required in order to achieve stability decreases.

The development of postural control is best characterized as the continuous development of multiple sensory and motor systems, though it manifests behaviorally as a discontinuous progression. Sometimes, the maturation of postural control will appear to regress, secondary to the developing child’s incorporation of new strategies that gradually incorporate intersensory integration (Woollacott & Sveistrup, 1994). For example, the results of dynamic posturography studies have led researchers to believe that postural stability may be affected by an important transition occurring between the dominance of the visual system and the dominance of the somatosensory system for the control of standing balance (Deitz, Richardson, Atwater, Crowe, & Odiorne, 1991; Riach & Hayes, 1987; Shumway-Cook & Woollacott, 1985). Children between the ages of 4 and 6 demonstrate increased highly variable muscle responses and slow onset of muscular contractions in response to changing environmental conditions in the visual surround and the contact surface. Shumway-Cook and Woollacott (1985) suggest that this is when a child learns to reweight the sensory systems involved in postural control in order to rely on the most efficient sensory input.

Because the systems contributing to postural control do not all develop at the same rate, a rate-limiting subsystem will curb the emergence of postural
control. The last critical component in the postural control system to develop is the emergence of postural synergies. Organized postural responses begin to occur at about 3-4 months in the neck musculature and 5 months in the trunk. A study by Hirschfield and Forssberg (1994) indicated that by the time children are able to sit independently (7-8 months), all neck flexors and trunk flexors are activating in synergistic patterns. Other research suggests that the development of these synergies is gradual and dependent on experience within a specific posture (Shumway-Cook & Woollacott, 1995). Muscle synergies play a significant role in the control of inherently unstable posture; without the coordinated efforts of the musculoskeletal system, a seemingly infinite number of possibilities typical of everyday motor tasks must be separately managed (e.g., direction of movement, muscle activation patterns, control at the level of the neuron, etc.) for each joint involved in the activity – a tremendous task for a developing postural control system.

Abnormal Development: Cerebral Palsy

Cerebral palsy (CP) is an umbrella term for a group of non-progressive but variable motor impairment syndromes secondary to lesions or anomalies of the brain that arise in the early stages of brain development (Rosenbaum, Paneth, Leviton, Goldstein, & Bax, 2007). The lesion leads to an arrest in normal development and a pathological deviation (Bobath, 1971). According to the Merck Manual (Beers, 1999), the movement deficits associated with CP are a result of either prenatal developmental abnormalities (e.g., defect of the neural tube closure, lissencephaly, intraventricular hemorrhage), or peri/post-natal
damage to the developing central nervous system occurring before age 5 (e.g., periventricular leukomalacia, anoxia, blunt head trauma). Although there are categorically different types of CP, common features of the disease include alterations in gait (e.g., scissoring, crouching) and muscle properties (contractures), exaggerated reflexes, tremor, and difficulty with fine motor activity (precision movements; National Institutes of Health, 2007).

CP is also associated with disruptions in postural control and subsequent postural instability. Children with CP exhibit postural instability secondary to physiological deficits (e.g., changes in muscle fiber distribution and diameter, motor unit firing) and upper motor neuron involvement due to the location of the supraspinal central nervous system lesion (e.g., primary motor cortex, basal ganglia, or cerebellum). It has been hypothesized that changes in the postural control system associated with CP are due to anatomical alterations in muscle fiber diameter and Type I muscle fiber distribution (Dietz & Berger, 1995). When muscle activity is reduced at an early age, abnormalities in myosin composition in the muscles develop and deviations occur in the mononeural innervation patterns (IjKema-Paassen & Gramsbergen, 2005). This pathophysiology and the central nervous system dysfunction associated with CP lead to corresponding decreases in motor unit firing (Rose & McGill, 1998) and poorly organized muscle responses and force production.

Although abnormal development in CP stems largely from the neurological type, location, and extent of insult, children with CP also experience musculoskeletal changes that influence postural stability (e.g., ankle equinus,
muscle contracture). A habitual posture can alter the length-tension relationship in muscles and alter the way that muscle is recruited. Children with CP (typically spastic diplegia) often develop a “crouched” posture. In this position, a child’s body segments are not aligned appropriately, compounding the difficulty of the inherently difficult task of maintaining upright posture. Effectively, the child must use greater force in order to counter gravitational effects. In a recent study (Burtner, Qualls, & Woollacott, 1998), typically developing children asked to assume this “crouched” position also demonstrated greater agonist-antagonist muscle co-activation patterns.

Basic coordination patterns in healthy children are also altered in children with CP. Motor adaptation problems manifest in this population, secondary to a reduction in the number of isolated movements available in the movement repertoire. In children with CP, mass flexion or mass extension will often dominate a movement strategy regardless of the task at hand. Subsequently, the strategies typically used in the control of balance are also altered. Healthy children rely on ankle, hip, and stepping strategies in order to manage the complexity of neuromuscular control. In children with CP, ankle and hip synergies are altered (e.g., they are characterized by the aforementioned mass flexion and extension). In order to compensate, protraction/retraction of the limbs and transverse body rotation are adopted and appear to play a critical role in the balance control of children with CP. Any slight change in biofeedback (including visual input) in children using these mechanisms will cause further instability and increase the risk of fall (Ferdjallah, Harris, Smith, & Wertsch, 2002).
The underlying neuromuscular characteristics of deficient balance control in CP have been thoroughly documented with regard to postural responses to perturbations and in gait. In perturbation studies, participants are exposed to unanticipated, externally imposed movements generated by a moveable platform (e.g., Wade, Lindquist, Taylor, & Treat-Jacobson, 1995). Investigators are able to manipulate the speed, distance, type of movement (angular or linear), and direction of the perturbation. Research suggests that although children with CP have an intact basic level of postural control (e.g., they activate the appropriate musculature—a direction-specific response), they demonstrate inadequacies in the fine tuning of motor activity (van der Heide & Hadders-Algra, 2005). For example, CP is associated with poor timing of muscle response (greater latencies), failure to utilize appropriate control strategies in recovery (decreased use of ankle strategies, increased use of on-toes posturing), disordered muscle activation sequences (healthy pattern: distal-to-proximal; CP pattern: proximal-to-distal), an inability to enhance the amplitude of muscle response when balance is threatened, and inflexible co-contraction of agonist and antagonist muscles (see Brogen, Hadders-Algra, & Forssberg, 1998; Burtner, Qualls, & Woollacott., 1998; Crenna & Inverno, 1994; Liu, 2002; Liu, Zaino, & Westcott, 2000; Nashner, Shumway-Cook, & Marin, 1983; Roncesvalles, Woollacott, & Burtner, 2002; Shumway-Cook, Hutchinson, Kartin, Price, & Woollacott, 2003; Woollacott, Burtner, Jensen, Jasiewicz, Roncesvalles, & Sveistrup, 1998; Zaino, 2000).

Postural control during quiet (i.e., unperturbed) stance in CP has also been studied, typically with a focus on the role of sensory input on balance in this
population. During quiet stance, children with CP produce profiles of postural sway that are typically larger (e.g., greater sway area, path length) and more variable than healthy developing control subjects (Cherng, Su, Chen, & Kuan, 1999; Ferdjallah, Harris, Smith, & Wertsch, 2002; Liao & Hwang, 2003; Liao, Jeng, Lai, Cheng, & Hu, 1997; Rose, Wolff, Jones, Block, Oehlert, & Gamble, 2002).

This is typically most evident in conditions that challenge postural control or create unreliable sensory information. CP children appear to be more reliant on but also less adept at reweighting somatosensory information when it conflicts with vision and vestibular input (Wescott, Lowes, Richardson, Crowe, & Dietz, 1997). Decrements in postural control occur when vision or somatosensory information is inaccurate and show high levels of instability when only vestibular information is available (e.g., Nasher, Shumway-Cook, & Marin, 1993).

Together, the perturbation and quiet stance studies indicate that CP patients show a general decline in postural stability, although some researchers have cautioned that differences between controls and neurologically impaired patients could indicate in part a change in postural control strategies rather than simply a decline in postural control (e.g., Bloem, Visser, & Carpenter, 2001; Schiepatti & Nardone, 1991).

**Loss of Complexity**

According to the loss-of-complexity hypothesis (Glass & Mackey, 1998; Goldberger 1997; Goldberger, Peng, & Lipsitz. 2002), in the case of pathology the multi-scale, nonlinear complexity characteristic of healthy physiological
systems breaks down and the adaptability of the physiological process is reduced. This loss of complexity has been demonstrated in many different physiological measurements. For example, prior to epileptic seizure, the EEG recordings of a patient become characteristically less complex because of a synchronization between seizure-related discharging neurons (Le Van Quyen, Martinerie, Navarro, Boon, D'Have, Adam, Renault, Varela, & Baulac, 2001). The same phenomenological patterns have also been detected in the respiratory function of patients with congestive heart failure or central nervous system dysfunction. Patients with these diagnoses present clinically with a Cheyne-Stokes breathing pattern—characteristically long, sinusoidal oscillations of ventilation dynamics. The regular, predictable oscillations become congruent with cardiac interbeat intervals, ventilatory amplitude, and arterial oxygen saturation (Goldberger, Findley, Blackburn, & Mandell, 1984) and illustrate the regularity and predictability of a dynamic system in a disease state. Heart rhythm loss of complexity in infants has also been examined. Longer gestational age (greater than 35 weeks) is associated with ECGs that are highly irregular and characteristically nonlinear; this complexity is absent in preterm infant heart rhythms, where sympathetic and parasympathetic interaction and function are presumed to be less well developed (Sugihara, Allan, Sobel, & Allan, 1994).

The loss of complexity and increase in the periodicity or regularity in physiological signals associated with disease has also been discovered in postural sway of patients with known motor and postural deficits. Schmit, Riley, Dalvi, Sahay, Shear, Shockley, and Pun (2006) compared the space-time
evolution of postural sway in Parkinson’s disease patients to healthy control participants and found that Parkinson’s disease was associated with a more predictable and patterned, but less flexible, dynamic profile of postural sway. These results compliment other studies reflecting a high degree of constraint on the coordination dynamics in Parkinson’s disease (van Emmerik & Wagenaar, 1996) and a reduced dimensionality of postural control in individuals with tardive dyskinesia (van Emmerik, Sprague, & Newell, 1993). Another study examining the effects of stroke on postural stability demonstrated that in contrast to healthy participants, the postural sway of patients was characteristically regular, but became progressively less so (more “healthy-looking”) over a twelve week period of standard rehabilitation (Roerdink, De Haart, Daffertshofer, Donker, Geurts, & Beek, 2006). Most recently, the COP trajectories of children with CP have been described as exhibiting greater regularity than those of typically developing children, reflecting less effective physiological control (Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008). Moreover, in that study the “automatisms” of pathological postural behavior were disrupted by directing attention away from the task of postural control via visual feedback regarding task performance; postural sway in children with CP increased in complexity when receiving feedback relative to an eyes-closed condition.

Supra-Postural Tasks

In most of the aforementioned studies, an inherent assumption is that during quiet stance, a participant’s priority is to reduce postural sway variability to the greatest extent possible. This notion is contested by an approach to postural
behavior that instead places emphasis on how posture must be controlled in order to accomplish other behaviors. Goal-directed tasks that are super-ordinate to (above and beyond) the simultaneous control of posture are called supra-postural tasks (Riccio & Stoffregen, 1988). Supra-postural tasks are the purposive behaviors that we engage in every day, like carrying a briefcase while we walk, reading a magazine while we are in line at the grocery, or signing a credit card receipt at a cash register.

When an individual is standing, the postural control system must work to stabilize the center of mass. Stance, however, is not achieved and maintained for its own sake (Riccio & Stoffregen, 1988). Instead, it can be thought of as a means to an end (e.g., a facilitator of supra-postural behavioral goals) and can be controlled in many different ways. Usually, the goals of supra-postural tasks do not mirror the goals of postural control. Keeping the center of mass within the base of support is a conclusively different objective than holding a cup of coffee. When stance and supra-postural tasks are concurrently performed, however, the two are necessarily coupled; the degree and nature of postural activity (e.g., more or less postural sway) can directly influence the likelihood that a supra-postural task can be accomplished successfully. In the context of many supra-postural tasks, the goal of postural control changes. For example, a large amount of postural sway would jeopardize the precision of a surgeon’s incision but facilitates dancing or rhythmic activity. Coordination of postural control with supra-postural activity may require that postural sway is modulated in order to avoid interfering with and in some cases to directly facilitate supra-postural
activity (Bernstein, 1967; Reed, 1982; Riccio & Stoffregen, 1988). The success of postural control can therefore be defined in terms of its impact on the achievement of supra-postural goals (cf. von Hofsten, 1997).

Research on the influences of supra-postural tasks on postural control by Riley, Stoffregen, Grocki, and Turvey (1999b) indicated that participants reduced their postural sway when asked to lightly touch a curtain during static stance. The reduction in sway presumably facilitated the control of precision touching. Similarly, Stoffregen, Pagulayan, Bardy, and Hettinger (2000) demonstrated that when participants were asked to visually search for letters in a block of text displayed in front of them, postural sway was reduced relative to when looking a blank piece of paper. These kinds of supra-postural task effects have been replicated in other studies involving listening, manual manipulation, visual fixation, leaning, and intentional head movement (e.g., see Aruin & Latash, 1995; Balasubramaniam, Riley, & Turvey, 2000; Bardy, Marin, Stoffregen, & Bootsma, 1999; Marin, Bardy, Baumberger, Fluckiger & Stoffregen, 1999; Moore, Sveistrup, Massion, Hu, & Woollacott, 1992; Oullier, Bardy, Stoffregen, & Bootsma, 2002; Riley, Mitra, Stoffregen, & Turvey, 1997; Smart, Mobley, Otten, Smith, & Amin, 2004; Stoffregen, Smart, Bardy, & Pagulayan, 1999; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen, Hove, Bardy, Riley, & Bonnet, 2007; Sviestrup, Massion, Moore, Hu, & Woollacott, 1991). The relationship between postural control and supra-postural tasks has been reliably demonstrated; the two are tightly intertwined.
One factor that may moderate the influence of a supra-postural task on postural control is the actor’s focus of attention. Attention can either be directed toward movements of the body itself (internal focus) or to the effects of body movement on the environment (external focus; see Shea & Wulf, 1999; Wulf, Höb, & Prinz, 1998; Wulf, Lauterbach, & Toole, 1999; Wulf, McNevin, & Shea, 2001). Research by Wulf and colleagues on attentional focus indicates that when performing a supra-postural task (e.g., minimizing the effect of postural sway on movements of a curtain that the participant is touching—McNevin & Wulf, 2002; keeping a ball centered in a hollow tube—Wulf, Weigelt, Poulter, & McNevin, 2003; or maintaining the alignment of markers attached to a stabilometer—Shea & Wulf, 1999) performance can be improved by employing an instruction set that encourages the participant to focus on the external, environmental effects of their actions. The advantages of adopting an external attentional focus appear to be robust and have been explained in terms of the constrained action hypothesis, which states that trying to consciously control one’s movement (internal focus of attention) interferes with automatic motor control processes that would normally regulate the movement autonomously and efficiently (cf. Wulf et al., 2001). EMG studies indicate that during externally focused supra-postural task performance, muscle activity is decreased, reflecting a greater economy of movement production (Vance, Wulf, Tollner, McNevin, & Mercer, 2004). These neuromuscular effects appear to be pervasive—externally directed attention decreases the level of muscle activity not only at the point of focus (e.g., the hand), but also in other anatomical regions (Zachry, Wulf, Mercer, & Bezodis,
This global reduction in activity has been associated with the minimization of muscle “noise” that would otherwise hamper fine motor control and render the accuracy of movements less reliable.

**Supra-Postural Tasks in Clinical Populations**

The effects of a functional task context (e.g., postural control in the presence of concurrent goal-directed activity) on movement patterns has also emerged as an area of research in neurological rehabilitation (Charlton, 1992; Newell & Valvano, 1998), and the importance of continued research in this area has been underscored (Dunn, Brown, & McGuigan, 1994). Engaging in purposeful activity is a daily life routine (Hinojosa, Sabari, & Pedretti, 1993). Because supra-postural tasks are everyday activities, studying postural activity during supra-postural task performance may be a way to achieve the functional context necessary to develop a more applicable and valid understanding of postural control. This is an especially critical consideration when studying the movement behavior of children with impairments. Physical impairments limit the available resources an individual can exploit in order to complete a task, but supra-postural goals can still be accomplished using different or unique anatomical and neurological mechanisms (Davis & Burton, 1991). In populations with established motor deficiencies, although the pattern of movement used to successfully complete a task may be atypical, it may not be ineffective. The modulation of stance in order to facilitate performance of these necessarily distinct tasks may illuminate aspects of pathological motor control that have been previously misunderstood.
For example, a supra-postural task study involving patients with bilateral vestibular loss (BVL) produced results that illustrate the changes in postural behaviors elicited by simply engaging in a concurrent activity. In a study by Creath, Kiemel, Horak, and Jeka (2002) patients with BVL were asked to maintain finger contact with a touch plate. Although they differed from control participants in no-touch conditions, the groups presented with equivalent variability when asked to perform the non-postural task.

Recent work by Volman, Wijnroks, and Vermeer (2001) helps to illustrate the influence of task context on motor behavior in CP and has implications for the proposed research. In that experiment, children with CP reached to (a) press a light switch to turn on a red light (functional task context), (b) press the light switch without turning on a light (semi-functional task context), or (c) reach to a marker (non-functional task context). Volman and colleagues found that the functional task context improved the kinematics of reaching movements. Based on that result, they argued that when a task is functionally more relevant, motor performance will be more precise and less variable, even for individuals with a movement pathology.

These findings are buttressed by other clinical studies manipulating task context by varying object availability and object affordances. For example, children with CP were asked to pronate and supinate a drumstick in a study by van der Weel, van der Meel, and Lee (1991). When children were permitted to bang a drum with the drumstick as they moved it, they were able to produce
subsequently larger ranges of motion than when the drumstick was pronated and supinated in the absence of the drum.

Other neurological studies indicate that patients with peripheral nerve injuries were able to achieve greater overhead reaching heights if they were attempting to reach an actual elevated object, relative to simply reaching as high as they could (Leont’ev & Zaporozhets, 1960), and that patients who suffered from a cerebrovascular accident produced smoother, faster, more forceful movements when reaching for their favorite food or for an active telephone versus a spatial location or a stick (Trombly & Wu, 1998). The physical presence of objects used to complete a task also improved kinematic movement variables in stroke patients (e.g., Trombly & Wu, 1999; Wu, Trombly, Lin, & Tickle-Degnen, 2000) and in individuals with multiple sclerosis (Mathiowetz & Wade, 1995).

Differences in the object characteristics influence the modulation of action via the contextual richness of the task to be performed. For example, mimicking (pretending to eat food) or mimicking in an impoverished condition (pretending to eat food with a saucer and a spoon) resulted in motor performances that were less efficient and kinematically different than actual task performance (eating applesauce in a saucer, with a spoon) in patients with multiple sclerosis. Similar findings have been established with neurologically intact populations (Lin, Wu, & Trombly, 1998).

The informational or semantic attributes of an object also influence movement kinematics. Symbolic information about the content or function of
drinking a real can of soda fostered the organization of a more appropriate action in normal adults relative to an unlabeled can (Wu, 1995).

Comprehensively, these studies illustrate that in task-relevant conditions, different motor behaviors can emerge. Although atypical motor performance in individuals with a movement disorder is inherent, this is not equivalent to the supposition that behavior is inflexible. It may be that in a disease state, the underlying control mechanisms that are associated with healthy behavior must be elicited. To the extent that this is true, prior interpretations of postural dysfunction in children with CP should be enhanced by research findings gathered in functional, task-specific environments.

The influence of directed attention on the interaction between postural control and supra-postural tasks has also recently been explored in clinical populations. Landers, Wulf, Wallmann, and Guadagnoli (2005) instructed patients with Parkinson’s disease to either put equal amounts of pressure on their feet (internal focus) or on rectangular pieces of contact paper under each foot (external focus) while standing in conditions employed in the Sensory Organization Test (Nashner, 1976). They found increased postural sway in conditions where attention was focused internally, and a significant decrease in postural sway in patients identified as fallers when attention was directed externally under difficult stance conditions (when the force platform was sway-referenced). Similarly, Fasoli, Tromboy, Tickle-Degnen, and Verfaellie (2002) found improvements in movement times and velocities in stroke patients when
they performed activities of daily living under instructions that encouraged them to adopt an external attentional focus.

It has also been hypothesized that feedback can be used to generate an external attentional focus and enhance the effectiveness of motor re-learning. This proposal has been examined clinically in stroke patients and in children with CP. Although no direct relation between feedback and the amplitude of postural sway has been demonstrated, feedback does appear to increase the complexity of postural sway (Donker, Ledebt, Roerdink, Savelsergh, & Beck, 2008). Exploratory studies also suggest that sway symmetry (Sackley & London, 1997) and symmetrical body-weight distribution during the sit-to-stand task (Enghardt, Ribbe, & Olsson, 1993) can be fostered with visual or auditory feedback, respectively.

Directing the focus of attention during task performance appears to mediate the supra-postural task effect, especially under conditions of heightened postural demand (Mitra & Frazier, 2004). The combined influences of supra-postural tasks and a focus of attention that is directed toward the effects of movement on the environment should more closely approximate the way that purposeful activity constrains the motor control system during activities of daily living. As such, manipulating directed attention during supra-postural task performance may more accurately expose the postural facilities of patients with known motor deficits. Further, according to the constrained action hypothesis, if a child with CP can focus their attention on the external effects of body movements on task performance, this may allow the child to more efficiently and effortlessly
control postural activity, resulting in improved postural control during concurrent supra-postural task performance. This might permit the development of new rehabilitation and balance-training exercises to promote postural stability during daily activities and reduce the risk for falling in children with CP.

*Cerebral Palsy and Supra-Postural Task Performance: An Opportunity*

Although previous studies have presented objective characterizations of the balance deficiencies associated with CP, both dynamic posturography and quiet-stance studies of postural control lack ecological validity. Platform-induced perturbations do not approximate the environmental demands that any participant is likely to encounter in everyday activity. According to Stoffregen, Adolph, Thelen, Gorday, and Sheng (1997), the magnitude, velocity, and acceleration of moveable platforms are much greater than postural motion found in normal, unperturbed stance. The results of this approach are corrupted by lurching, staggering, and falling (Lee & Aronson, 1974; Stoffregen, Schmuckler, & Gibson, 1987). Furthermore, standing (controlling posture) rarely occurs in isolation; we are typically concurrently engaged in other cognitive, perceptual, or motor behaviors, like reading, holding an object, or having a conversation. The typical laboratory instruction in quiet-stance studies to “look straight ahead and stand as still as possible” (e.g., Lee & Lishman, 1975) does not emulate typical behaviors. The assumption in quiet-stance studies is that the participant makes postural stability (i.e., the minimization of postural sway) the primary objective. This position fails to take into account changes in postural control that may occur as a function of other behaviors people perform while standing. In quiet-stance
research, the relevant influences of purposeful, non-postural activity are, by and large, intentionally disregarded. In the absence of supra-postural tasks, postural activity is instead a reflection of intrinsically unstable mechanics and the subsequent corrective postural control actions employed to keep the center of mass within the base of support (e.g., the boundaries of the feet).

Geuze (2005) stated that a child’s degree of postural control (or lack thereof) hampers the development of other specific motor skills. Other researchers have adopted this position with regard to CP, and propose that the poor postural control noted in children with CP triggers subsequent delays and disparities in motor skill acquisition and development (see Berger, Altenmueller, & Dietz, 1984; Liao et al., 1997; Liao & Hwang, 2003). However, these conclusions are based on experimental protocols that lack a functional context for postural control. Supra-postural tasks harness the postural control system with the same constraints on concurrent actions that are encountered in everyday activity. This project investigated postural stability in children with CP during performance of non-postural (supra-postural) tasks that provide a functional context for balance control. If the supra-postural task effect generalizes to children with CP, the current understanding of postural deficiency associated with this pathology would be challenged. Modulating control strategies in response to supra-postural task constraints would reflect an adaptive change in the postural control system—a response to the constraints imposed by supra-postural behaviors (e.g., Evarts, Teravainen, & Calne, 1981; Kugler & Turvey, 1987; Teasdale & Stelmach, 1988). Alternatively, successful
performance of the task without postural sway modulation might indicate that children with CP are able to de-couple manual activity from postural control in order to accomplish the supra-postural task goal. Strategic de-coupling would allow children with CP to elude the damaging effects of increased postural sway on manual control without reliance on postural facilitation.

Teasdale and Stelmach (1988) proposed that by changing the context within which movements are studied in pathological populations we will gain insight into how the motor system is organized and how it may be compromised by disease. In the proposed research the postural control strategies of children with CP was examined during performance of concurrent manual activity. The integration between postural control and concurrent supra-postural activity is of particular relevance during precision hand movements because the hands are linked to the trunk via a kinematic chain spanning the joints and segments of the arm. Excursions of the trunk can be transmitted to the hands and can impact manual performance, requiring attendance to postural control in order to successfully perform the task. This project will explore the influence of two different supra-postural tasks on postural activity in functional contexts. Task I will examine the supra-postural task effect and the role of task difficulty: Is there a reorganization of postural control when children simultaneously perform a precision manual supra-postural task, and does such an effect scale with task difficulty? Task II will investigate the influence of manipulating attentional focus on a manual ball-centering task (borrowed from Wulf et al., 2003) and on changes in posture elicited by action constraints. Together, they address a
larger question: Do children with CP still have the ability to modulate the quantity and quality of postural sway in order to best meet the demands of a supra-postural task?

Because the requirements of supra-postural manual activity provide a more functional context for the control of posture in CP, the present studies should render a more interpretable picture of associated postural deficiencies, expose aspects of motor control that remain intact, and examine the assertion that poor posture control engenders subsequent motor limitations (e.g., Berger et al., 1984; Liao et al., 1997; Liao & Hwang, 2003). Additionally, this project seeks to evaluate whether CP children exhibit postural sway dynamics consistent with the loss of complexity hypothesis. This additional aim will be achieved by employing nonlinear time series analyses (recurrence quantification analysis, RQA; sample entropy, SEn).

Predictions

Postural sway will be operationalized as the center of pressure (COP), the point location of the resultant ground reaction forces acting at the feet, in both the AP and ML axes. Standard assessments of postural stability will include measures of the within-trial standard deviation of the AP and ML COP. Higher values of each of these measures (i.e., higher COP variability) are assumed to reflect poorer postural stability.

I expect to see a pathological profile of postural stability in children with CP that (relative to the control group) is more variable (larger standard deviation of COP in both the AP and ML planes), but also (as quantified by RQA) more
regular (higher % determinism, higher maxline, lower entropy) and more stationary (lower trend magnitude). I also expect to replicate the sample entropy findings of Roerdink et al. (2006) and Donker and colleagues (2008). CP patients should exhibit higher values of sample entropy, indicating greater COP regularity. Comprehensively, these findings would indicate that CP is accompanied by a loss of postural sway complexity.

Per previous research using supra-postural methodologies and healthy participants (e.g., Riley et. al., 1999b), I expect to see a fine-tuning of postural control (e.g., a decrease in COP variability) in order to facilitate performance of the steadiness task during supra-postural trials in Task I. Further, I anticipate a larger postural effect when greater constraints are placed on postural control (difficult condition, smaller hole) in both typically developing control participants and CP participants. Although CP is widely known to affect the postural control system, previous research has largely focused on postural control without reference to other behaviors. Assuming that supra-postural tasks simulate constraints on postural control that are encountered in daily activity, I hypothesize that there will be a significant group by supra-postural task interaction in Task I; any difference between children with CP and children who are TD should be attenuated when they are engaged in the supra-postural steadiness task. Additionally, I hypothesize that there will be a significant group by task difficulty interaction in Task I; group differences may be pronounced in the easy condition (with CP children exhibiting greater COP variability), but should diminish when minimized postural sway must be moderated in order to
facilitate performance of a more challenging manual task condition (hard condition).

Wulf, McNevin, and colleagues have reliably and empirically demonstrated that adopting an external focus of attention improves postural stability. Their work with a supra-postural tube-leveling task (Wulf et al., 2003) motivates the prediction in Task II that a supra-postural task effect should be evident. Further, externally directed attention should produce a profile of postural sway that is less variable. In conditions where the participant is asked to keep the ball in the center of the tube, postural activity should decrease relative to conditions that direct focus to the position of the hands. Given previous work in this area with clinical populations (Fasoli et al., 2002; Landers et al., 2005), again I hypothesize that this effect will be present in children with and without CP. Additionally, if the constrained action hypothesis applies to CP and during the external-focus condition postural control becomes more efficient, in this condition the influences of more voluntary and perhaps inefficient postural control strategies should dissipate. Accordingly, I anticipate a significant group by focus interaction in Task II for measures of COP variability.

I also expect to find effects of supra-postural task constraints, task difficulty, and focus of attention on measures of COP dynamics. Costa and colleagues (2007) recently demonstrated that when a stimulus known to promote postural stability—sub-sensory-threshold vibratory white noise—was applied to the feet of elderly participants, COP dynamics became more complex and analogous to the postural sway profiles of healthy control participants. Their
results are consistent with those of Roerdink and colleagues (2006), who found that rehabilitation promoted a “healthier” pattern of COP dynamics in stroke patients, and Donker and colleagues (2008), who elicited greater complexity in postural sway with visual feedback. These findings have implications for the proposed research. If the functional contexts employed in the proposed research promote “healthier” functioning of the postural control system, sway complexity may re-emerge during performance of the supra-postural tasks. While such effects could be likely in both CP and control participants, the postural deficits associated with CP may result in there being greater room for improvement of postural stability in children with CP. Accordingly, I would expect to find group by supra-postural task performance, group by task difficulty (Task I), and group by attentional focus (Task II) interactions. The sway profile of children with CP should more closely resemble control participants and look “healthy” in conditions that are expected to promote postural stability (lower determinism, lower maxline, higher entropy, lower trend, and lower sample entropy while performing a supra-postural task trial, a difficult task trial, or an external focus of attention trial).

Findings indicating that concurrent supra-postural activity results in a modulation of postural control in CP will have significant implications for future research. Affirmation of the aforementioned hypotheses would indicate that postural control and supra-postural tasks are tightly intertwined. Studies employing perturbations or static stance do not accurately describe the pragmatic characteristics of postural control, and greater attention to the influence of experimental method would be paramount in studies linking deficient postural
control to subsequent disruptions in motor development in CP. Examining postural control in the context of supra-postural tasks should render a more interpretable picture of existing postural deficiencies associated with CP. More importantly, it may also expose aspects of motor control that remain intact in children with CP. Significant group × supra-postural task interactions in Tasks I and II reflecting an attenuation of differences in supra-postural task conditions would indicate that the postural control of children with CP does not differ radically from healthy children in more functional contexts (during task performance),
CHAPTER 2

Method

Participants

Postural stability during supra-postural task performance was measured in 60 children. Postural stability measures obtained from patients with CP (n = 30; mean age = 8.30 years, SD = 2.26 years, range = 5-12 years; 17 males, 13 females) were compared to stability measures taken from typically developing (TD) children (n = 30; mean age = 9.28 years, SD = 1.98 years, range = 6-12 years; 13 males, 17 females). TD children and children with CP did not differ significantly in age, $F(1, 58) = 3.10, p > .05$. These 60 participants each completed baseline trials, Task I trials, and Task II trials, as described below.

Children with CP were referred for participation in this study from colleagues at the Cincinnati Children’s Hospital Medical Center (CCHMC; Division of Pediatric Physical Medicine and Rehabilitation, Division of Developmental and Behavioral Pediatrics, and Division of Occupational and Physical Therapy). Patients were referred for inclusion by treating physicians and therapists and often completed study participation prior to or immediately following services for treatment of CP at CCHMC. Typically developing participants were recruited from a convenience sample of friends and relatives of the study team.

In order to meet requirements for participation, all children were between the ages of 5 and 12 years. Moreover, children were minimally able to stand without the aid of braces or devices for more than one minute and were able to
follow simple commands. Participants in the study reported no history of fracture, diabetes, arthritis, chronic back pain, legal blindness, or a vestibular disorder. In order to minimize the effects of spasticity treatment interventions on stability measures, children with CP qualified for participation in this study only if they had not undergone a selective dorsal rhizotomy or other orthopedic/surgical procedure (e.g., tendon release, tendon lengthening) 12 months prior to the test date or botox injections within 3 months of the test date.

Legal guardians provided general demographic information about each child. Achievement ages for major motor milestones were reported (CP mean sitting age = 9.57 months, CP mean walking age = 26.96 months; TD mean sitting age = 6.05 months, TD mean walking age = 11.46 months). Baseline motor function was also established using Dimension D of the General Motor Function Measure (GMFM; Russell, Rosenbaum, Cadman, Gowland, Hardy, & Jarvis, 1989). This measure is a criterion-referenced observational measure that assesses standing motor skills, designed and validated for children with CP (mean CP score = 88.57%; mean TD score = 100%). A legal guardian of the CP patient also provided an account of CP classification and the anatomical distribution of motor involvement with which CP patients presented, gross motor function and ability to handle objects in daily activity (Gross Motor Function Classification System—Palisano, Rosenbaum, Walter, Russell, Wood, & Galuppi, 1997; Manual Ability Classification System—Eliasson, Krumlinde-Sundholm, Röslad, Beckung, Arner, Öhrvall, & Rosenbaum, 2006). These sample descriptors and others are summarized in Tables 1 and 2.
Table 1

*Characteristics of the Sample (Mean Values).*

<table>
<thead>
<tr>
<th></th>
<th>CP (Mean)</th>
<th>TD (Mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>8.3</td>
<td>9.2</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>128</td>
<td>137</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>25.2</td>
<td>35.7</td>
</tr>
<tr>
<td>Education Level (grade level)</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Independent Sitting (months)</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Independent Walking (months)</td>
<td>27</td>
<td>11</td>
</tr>
<tr>
<td>Gross Motor Function Measure (score)</td>
<td>88</td>
<td>100</td>
</tr>
</tbody>
</table>

Note. CP = children with Cerebral Palsy; TD = typically developing children.

Table 2

*Characteristics of the Sample (Percentage of Group).*

<table>
<thead>
<tr>
<th></th>
<th>CP (%)</th>
<th>TD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>43</td>
<td>57</td>
</tr>
<tr>
<td>Male</td>
<td>57</td>
<td>43</td>
</tr>
<tr>
<td>Handedness</td>
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</tr>
<tr>
<td>Left</td>
<td>53</td>
<td>14</td>
</tr>
<tr>
<td>Right</td>
<td>47</td>
<td>86</td>
</tr>
<tr>
<td>Race</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caucasian</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>African American</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Asian</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Gross Motor Functional Classification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>63</td>
<td>100</td>
</tr>
<tr>
<td>II</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Manual Ability Classification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>37</td>
<td>100</td>
</tr>
<tr>
<td>II</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>10</td>
<td></td>
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<tr>
<td>Distribution of Cerebral Palsy</td>
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<tr>
<td>Diplegia</td>
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<tr>
<td>Hemiplegia</td>
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<tr>
<td>Mixed</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Orthotic Use</td>
<td>87</td>
<td>0</td>
</tr>
<tr>
<td>Relative difficulty: “Hard”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.175 cm (duck)</td>
<td>43</td>
<td>83</td>
</tr>
<tr>
<td>4.425 cm (monkey)</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>5.675 cm (pig)</td>
<td>37</td>
<td>4</td>
</tr>
<tr>
<td>Relative difficulty: “Easy”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.675 cm (pig)</td>
<td>43</td>
<td>83</td>
</tr>
<tr>
<td>6.925 cm (lion)</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>8.175 cm (hippo)</td>
<td>37</td>
<td>4</td>
</tr>
</tbody>
</table>

Note. CP = children with Cerebral Palsy; TD = typically developing children.
Because participants in this study were characterized as minors, a legal guardian provided written informed consent (parental permission) prior to their participation. Children in the sample who were between the ages of 11 and 12 years also provided written assent. This study was reviewed by both the University of Cincinnati and the CCHMC Institutional Review Boards.

**Apparatus**

Postural stability data were obtained using an AMTI AccuSway PLUS portable force platform system (Advanced Mechanical Technology, Inc., Watertown, MA). The system is a six-component load transducer that measures the three orthogonal components of the resultant force acting on the platform, and the three components of the generated moment in the same orthogonal coordinate system. The force platform system implemented a low-pass, anti-aliasing hardware filter with a cut-off frequency of 500 Hz. No other filtering or signal conditioning algorithms were applied to the raw data. Data were sampled at 100 Hz. A PC and *Balance Clinic* software (Advanced Mechanical Technology, Inc., Watertown, MA) were used to acquire force and moment data sampled by the force platform and to calculate the center of pressure (COP; a measure of the displacement of the resultant ground reaction force vector on the force platform, which is equal to the weighted average of the points of application of all vertical forces acting on the force platform; Hamill & Knutzen, 1995). *Balance Clinic* was also used to compute standard statistical descriptors of the COP from the recorded COP time series. Custom *Matlab* routines and freeware nonlinear time
series analysis programs were used to provide indices of postural sway variability and dynamics.

Task I

This supra-postural task was performed using a steadiness tester. The tester is a device containing five differently sized circular copper tubes, each one 1.25 cm larger than the next (smallest diameter = 3.175 cm). To fashion an engaging device for children, animal puppets were mounted to the steadiness tester. An aperture was made near the location of the animal's mouth and the copper tubes were inserted through each opening (see Figure 1). Participants were informed that these animals did not feel well and that as the doctor in this study, they could help to determine if a specified animal was sick by checking its temperature. This was accomplished by asking the children to position a 12.7 cm (length) × 2.5 cm (width) × 1.9 cm (depth) wooden thermometer with a 5 cm metal tip (stylus length) in the animal’s mouth and to maintain the thermometer’s position in the center of the mouth. If the stylus inadvertently contacted the perimeter of the copper tube, a low-voltage circuit was completed and a feedback light in the center of the tester illuminated; the tester functions like the children’s game Operation™, but uses a light in lieu of a buzzer. The tester was vertically oriented on a height-adjustable hospital bedside table so that each participant performed the task while standing with 90° of shoulder flexion, full elbow extension, and neutral forearm/wrist alignment. The number of errors (operationalized as the number of times the light was triggered) was recorded as a performance measure during each trial.
Task II

Task II was a modification of a method used by Wulf and colleagues (2003) to examine how changing the focus of attention can influence supra-postural task performance and postural control. Participants were asked to hold a 45 cm (length) $\times$ 5 cm (diameter) translucent plastic tube. The hollow inside of the tube contained a colored marble (3.5 cm diameter), detained in the tube by small bells mounted at either end of the tube (see Figure 2). If the marble rolled to either boundary of the tube, it would strike a bell and produce an audible chime. The tube was wrapped in 0.5 cm of Polyethylene foam sheeting in order to eliminate tactile cues regarding marble position in the tube. The tube was covered in an opaque fabric, and a 15 cm detachable (Velcro) viewing window was constructed in the middle of the tube. In conditions eliciting an internal focus of attention during supra-postural task performance, this window remained covered. During experimental trials when attention was instead directed externally, the cover of the viewing window was removed and participants were asked to maintain the position of the marble in the mid-section of the tube, where it would remain visible. In all conditions of this task, participants were asked to

Figure 1. Steadiness tester used for Task I.
hold the tube at the approximate height of the anterior-superior iliac crests (near the belly button). Approximately 63% of the children with CP in this study were identified as having a hemiparetic distribution of motor involvement. Because of subsequent upper extremity limitations in these patients, all participants were encouraged to adopt the functional grip position on the tube that best enabled them to complete the task. Characteristically, this involved an underhand grip on the tube for typically developing children and children with diplegia. Children with hemiplegia more often hooked fingers through the rings securing the bells to the tube (see Figure 2). This hooked position helped to accommodate for diminished ability to grip the tube with the hemiparetic hand. The number of errors (operationalized as the number of times a bell chimed) was recorded as a performance measure during each trial. A post-hoc comparison between diplegic and hemiplegic patients did not indicate that the groups differed significantly on task errors in any Task I or Task II conditions.

![Figure 2. Tube used for Task II.](image)

**Procedure**

Participating children were informed that this research would help the investigators to learn more about balance. They were told that the study would
explore the how the body moves and how the body may be helping them when they are busy doing other things. Children were asked to remove their shoes and orthotics when standing on the force platform. No support from assistive devices was permitted during data collection. In all trials, participants were encouraged to relax and not to speak, gesture, or make any large-scale voluntary movements (e.g., put hands in pockets, wave).

All participants began the study by completing six 20 s static stance trials. In these trials, no supra-postural task was performed. These trials were conducted in order to establish baseline postural differences between children who are typically developing and children who have CP. Three of the trials were performed with the feet shoulder-width apart. The remaining three trials were performed with the feet in a Tandem Romberg position (heel to toe, with the foot corresponding to the participant’s self-reported dominant side in front). This stance narrowed the base of support in the medio-lateral plane (the same plane in which task manipulations occurred) and was expected to magnify baseline stability differences between the two groups. The order of the six trials was randomized for each participant. In addition to the aforementioned instructions, during this initial stage of data collection children were also directed to relax and to allow the arms to suspend naturally and comfortably at their sides. Acquisition of postural sway data from the force platform began when participants indicated that they were ready to start.

Children were next presented with two supra-postural manual tasks (Task I, Task II). The presentation sequence of Task I and II was counter-balanced
across participants in order to control for order effects. In order to examine postural stability during these functional activities, each supra-postural manual task was performed while the children were concurrently standing on the force platform. As per the baseline trials, duration for all Task I and Task II trials was 20 seconds. Total study session time lasted approximately 40 minutes. Children were required to take a seated rest break in between the three phases of the study (baseline trials, Task I, and II); they were permitted to take other rest breaks as needed.

*Task I Procedure.*

Task I included two independent variables: Group (between subjects: CP versus TD participants) and supra-postural task difficulty (within subject: easy versus hard). The within-subject manipulation was chosen to create task demand that varied in difficulty and was representative of situations encountered in day-to-day manual activity. Easy and hard supra-postural task conditions were repeated three times, yielding a total of 6 randomly ordered trials for each participant (in addition to the baseline trials described earlier).

Prior to Task I data collection, participants were asked to position the stylus of the thermometer in a tube on the steadiness tester without touching the perimeter for 10 seconds. The smallest “animal mouth” for which each child was able to successfully perform the task was used in “hard” task conditions. An animal two sizes larger was used in “easy” task conditions. This procedure established relative task difficulty for each child participating in the study. All
children were minimally able to complete this task in the 5 cm tube for 10 seconds without error.

As noted, participants were told that the animals on the steadiness tester did not feel well and that they could be of assistance by helping to check the animals' temperatures. They were asked to hold the wooden thermometer (the stylus) in the designated “easy” or “hard” animal’s mouth without touching the sides (metal contact producing light feedback) for 20 seconds, which was the full duration of the trial (see Figure 3). The steadiness tester and light feedback were demonstrated prior to beginning data collection and children were instructed not to stop the task if they contacted the tube perimeter, causing the light to turn on. Children grasped the thermometer with the hand that the child reported preferring to color or write with. Postural sway data collection for each trial began when the stylus was appropriately positioned within the designated hole.

Participants were required to make $\leq 3$ errors on the steadiness tester task during a trial. Trials that did not meet this performance criterion were repeated but children were not informed that they had failed or that a trial was being redone. All children demonstrated task awareness, followed instructions, and were able to complete Task I within a 10-minute period.
Task II also examined the effect of group (CP versus control participants) on postural control. A second independent variable, directed focus of attention (within-subject: internal versus external), was manipulated by changing the instruction set given to children before each trial (instructions are described below). This manipulation was chosen in order to explore the moderating effect of the locus of attentional focus during supra-postural task performance (see Shea & Wulf, 1999; Wulf et al., 1998, 1999, 2001). As in the first task, each focus of attention condition was repeated three times, yielding a total of 6 randomly ordered trials for each participant.

Participants were asked to hold a hollow tube containing a rolling marble. During conditions intended to foster an internal focus of attention, participants were asked to keep the relative position of their hands straight, or aligned
(horizontally) while holding the tube (see Figure 4). Before beginning, the investigator demonstrated different tube positions. A child’s comprehension of the instruction “straight” was confirmed when they correctly identified the position reflecting a horizontal orientation. In internal focus conditions, visual information about the marble’s location in the covered tube was not available; the viewing window was covered. Children were instructed to watch their hands and the relationship between them during these trials, in order to accomplish the task. Additionally, this helped to minimize the potential influence of differences in looking distances between the internally and externally focused conditions (Stoffregen et al., 1999).

In order to elicit an external focus of attention during performance, participants were asked to direct their attention to the effects of their movement on the task by “keeping the marble in the middle of the tube, where it could be seen.” They were able to confirm this central ball position via the viewing window in the tube, which was exposed during external focus conditions.

Because the distinction between an external and internal locus of attention required that children carefully adhere to the instruction set, prior to each Task II trial all participants were asked to confirm their current assignment (e.g. “Now I am supposed to watch my hands and to make the tube stay straight” or “Now I am supposed to try to keep the marble in the part of the tube where I can see it”). Children followed these simple commands well and appeared to comprehend the task instructions without difficulty.
Before beginning of data collection, the audio feedback (chime) from the tube was demonstrated and children were encouraged not to stop the task if the marble struck the end of the tube and caused the bell to ring. All children were able to complete Task II within a 10-minute period. Per Wulf and colleagues’ (2003) approach to this task, although the number of errors were recorded, no performance criterion was established for Task II. Trials were repeated only if the tube was inadvertently dropped; although hemiparetic patients adopted a compensatory grip on the tube, they were not always able to sustain it for the full data collection period and this resulted occasionally in the tube slipping out of the involved hand. More than half of the CP participants were identified as having a hemiplegia distribution of CP and 1-2 trials were repeated for each of those patients.

Data Analysis and Reduction

There were two primary sets of dependent measures used in this study to index all baseline trials and supra-postural task trials associated with Tasks I and
II. Each of the postural sway measures described in the following paragraphs were computed and then averaged over repeated trials in the same condition. In all analyses, an alpha level of .05 was used to establish statistical significance.

The first set of measures incorporated a standard index of postural stability, the within-trial standard deviation of the COP time series. COP standard deviation is a measure of postural sway variability, and higher values are widely assumed to reflect reduced postural stability.

The second set of dependent measures included nonlinear time series analyses of the COP data, computed to quantify the temporal dynamics of postural sway. Recurrence quantification analysis (RQA) was employed to provide multiple indices of the time-varying properties of postural sway, including measures of the degree of randomness (percent determinism), mathematical stability (maxline), complexity of the deterministic structure (entropy), and degree of non-stationarity (trend) in each COP time series (see Pellecchia & Shockley, 2005; Riley, Balasubramaniam, & Turvey, 1999; Webber & Zbilut, 2005). RQA is a quantitative extension of the graphical method of recurrence plots, an analysis designed to locate recurrent patterns (hidden rhythms) or nonstationarity (drift) in a time series. A detailed description of RQA is provided in Appendix B (see also Webber & Zbilut, 1994, 1996, 1998, 2005).

A second nonlinear estimate, sample entropy (Richman & Moorman, 2000), was used to provide a concurrent measure of order and regularity in the COP data. Sample entropy (SEn) is the negative natural logarithm of an estimate of the conditional probability that a subseries that repeats itself for $m$
points will also match at the next point \((m + 1)\). Accordingly, smaller SEn values reflect self-similarity or regularity in the time series: an indication that the data did not arise from a random process (Lake, Richman, Griffin, & Moorman, 2002). Sample entropy has been utilized to quantify complexity in COP times series and has proven to be a useful tool for the studying the dynamics of postural stability (e.g., Donker et al., 2008; Roerdink et al., 2006). Additional information about this time series measure can be found in Appendix C (see also Lake et al., 2002; Richman & Moorman, 2000).

Preliminary exploration of the data using Levene’s test (Levene, 1960) indicated that samples of children with CP and TD children did not reflect an equality of variance. Many inferential statistics assume a homogeneity of population variances. Although distribution-free (e.g., non-parametric) methods are a reasonable alternative when sampling from non-normal populations or when other ANOVA assumptions are violated (Everitt, 1996), they are generally less powerful than corresponding parametric techniques (Gravetter & Wallnau, 2002). An alternative to non-parametrics is to perform a data transformation. The benefits of transforming are usually said to be (1) simpler relationships, (2) more stable variance, and (3) improved normality; as such, the transformation aids interpretation directly by allowing the central information in the data to be expressed more succinctly (Kruskal, 1868). Data in this study were subjected to a monotonic, variance stabilizing transform, wherein \(y' = \sqrt{y}\).

All baseline group differences were examined in the absence of concurrent supra-postural task performance. Participants were exposed to two
conditions in the baseline trials; they were asked to adopt a foot position that
aligned with the width of the shoulder, or to assume the tandem Romberg (heel-
to-toe) position with the dominant foot forward. Each dependent measure was
subjected to a $2 \times 2$ (group $\times$ foot position) analysis of variance (ANOVA).

In order to detect the presence of a supra-postural task effect (task versus
no task) in the steadiness and tube tasks, within-subject manipulations of task
difficulty in Task I, and focus of attention in Task II, were averaged across
respective task conditions for each of the six dependent measures. Task effects
were established using a $2 \times 2$ (group: CP vs. TD $\times$ task vs. no task) mixed-factor
ANOVA for each postural measure.

Variables identified in the aforementioned task versus no-task analysis as
demonstrating a significant task effect were then analyzed further in order to
determine how task difficulty in Task I or locus of attention in Task II moderated
the significant task effect. Again, $2 \times 2$ mixed factor ANOVAs were used to
establish the relative influence of each variable (here, group $\times$ task difficulty/locus
of attention) on each dependent measure.

Finally, errors in supra-postural task performance in Task I and Task II
were averaged over repeated trials in the same condition, yielding for each
participant an average number of errors in each experimental condition for Task I
and for Task II. The relationship between average task performance error in a
condition and each of the six dependent measures was examined using the
Pearson product moment correlation coefficient. The statistical significance of
variable relationships using the correlation coefficient were determined with z-
scores. A $2 \times 2$ ANOVA on condition errors was computed in order to evaluate differences in group performance and the relative influence of task difficulty and locus of attention on task performance.
CHAPTER 3

Results

Sample Time Series Plots and Recurrence Plots

Figure 5 illustrates a typical COP time series for a CP and a TD participant. The CP patient clearly demonstrates a larger sway amplitude in this pair of sample trials (see Figure 5). The pattern of change over time appears to differ in TD children and children with CP.

![Time Series Plot]

*Figure 5.* 20 s samples of a typical ML COP time series for a TD (top) and a CP (bottom) participant.
A recurrence plot is constructed by plotting a pixel at specific coordinates (i, j) whenever pairs of data points (points i and j) are proximal (e.g., recurrent—less than the threshold distance selected in this study of 8% of the mean Euclidean distance separating points in the reconstructed 13-dimensional phase space selected in this study; Eckmann, Kamphorst, & Ruelle, 1987). Structure that may not be observable in the one-dimensional COP time series can often be identified in a recurrence plot as specific patterns within constellations of recurrent points (Webber & Zbilut, 1998). Recurrence plots of a CP and TD COP time series are shown in Figure 6. Compared to the recurrence plot for the TD participant, in the recurrence plot of the CP patient’s data a greater proportion of recurrent points fall along line segments parallel to the main diagonal (strings of vector patterns in the time series that repeat themselves multiple times over the observation period), implying a greater degree of determinism or predictability and increased regularity (e.g., an oscillatory pattern) in the time series of the CP patient (Eckmann, Kamphorst, & Ruelle, 1987; Riley et al., 1999; Webber & Zbilut, 1994, 1996, 1998).
Baseline Measures

Postural Sway Variability

Baseline postural variability differences between CP and TD children were explored by submitting the COP SD data to two-factor (Group × Foot Position) mixed-design analyses of variance (ANOVAs). There were two significant effects involving Group (CP vs. TD). The standard deviation of the AP COP was significantly higher for CP patients ($M = 1.107 \pm SD = 0.365$ cm) than for the TD
participants (M = 0.715 ± 0.138 cm), \( F(1, 58) = 58.53, p < .05 \). ML COP standard deviation was also significantly higher for CP patients (M = 1.007 ± 0.282 cm) than TD participants (M = 0.644 ± 0.120 cm), \( F(1, 58) = 85.75, p < .05 \).

Foot Position had a significant effect on postural sway in the AP plane for both CP and TD participants. The COP was less variable when the feet were aligned under the shoulders (M = 0.867 ± 0.294 cm) than when in the heel-to-toe tandem Romberg position (M = 0.977 ± 0.368 cm), \( F(1, 58) = 7.63, p < .05 \). This same trend was observed in the ML plane. The COP was less variable when the feet were aligned under the shoulders (M = 0.794 ± 0.284 cm) than when in the heel-to-toe tandem Romberg position (M = 0.884 ± 0.328 cm), \( F(1, 58) = 85.75, p < .05 \).

_Spatiotemporal Profile_

_Recurrence Quantification Analysis_

Significant Group \( \times \) Foot Position interactions were detected in the % determinism measure, \( F(1, 58) = 22.82, p < .05 \), and \( F(1, 58) = 21.30, p < .05 \), for AP and ML sway, respectively (see Figure 7). Simple-effects ANOVAs indicated that foot position had a significant impact on TD participants, \( F(1, 29) = 28.89, p < .05 \), and \( F(1, 29) = 23.19, p < .05 \), for AP and ML, respectively. Relative to a shoulder width stance, in the tandem Romberg position, the COP time series of TD participants were more deterministic (predictable). In contrast, for CP patients % determinism remained relatively unchanged across foot positions. At each level of foot position, significant group differences were detected. CP patients demonstrated higher % determinism than TD children, \( F(1, 58) = 29.86, \)
$p < .05$ and $F(1, 29) = 4.59, p < .05$, in the shoulder and tandem-Romberg positions, respectively.

Main effects of group were also found in the % determinism ANOVA. In both the AP and ML planes, the spatiotemporal profile for CP patients revealed higher % determinism for the CP patients than the TD participants, $F(1, 58) = 29.74, p < .05$, and $F(1, 58) = 30.59, p < .05$, for AP and ML sway, respectively. A main effect of Foot Position was also noted for this measure. Postural movements became more predictable when participants were in the tandem Romberg position than in a normal, shoulder-width alignment $F(1, 58) = 24.44, p < .05$, and $F(1, 58) = 20.68, p < .05$, for AP and ML sway, respectively. However, as noted in the description of the interaction, this effect was limited to the TD group.
Mathematical stability (maxline) of the AP time series was found to be significantly greater for CP patients (M = 1317 data points ± 1140 data points) than for TD participants (M = 1112 data points ± 1165 data points), $F(1, 58) = 4.65, p < .05$. This pattern of results was also demonstrated in the ML time series. CP patients exhibited more mathematically stable COP trajectories (M = 1484 ± 398 data points) than TD participants (M = 1091 ± 463 data points), $F(1, 58) = 16.30, p < .05$. A marginally significant Group × Foot Position interaction in
the ML COP times series, $F(1, 58) = 3.88, p < .0536$, indicated that maxline values for TD patients increased in the tandem Romberg position compared to the shoulder-width position, while maxline (mathematical stability) of CP patients appeared to be relatively constant across Foot Position conditions (see Figure 8).

![Figure 8. Marginally significant ML group × foot position interaction for maxline (± SE).](image)

Significant Group × Foot Position interactions for the RQA entropy measure were detected, $F(1, 58) = 4.57, p < .05$, and $F(1, 58) = 12.54, p < .05$, in the AP and ML COP time series, respectively. Simple-effects analyses indicated that TD participants exhibited significantly higher RQA entropy (greater complexity of the deterministic structure of the COP) in the tandem Romberg position in relation to shoulder-width stance, $F(1, 29) = 5.82, p < .05$, and $F(1, 29) = 22.35, p < .05$, for AP and ML, respectively, whereas CP children showed no significant changes across foot position conditions. Further, group differences were present in both levels of the Foot Position variable. Children with CP had higher ML RQA entropy relative to TD children, $F(1, 58) = 54.39, p < .05$ and $F(1, 58) = 22.38, p < .05$, in the shoulder width and tandem Romberg positions,
respectively. Comparably, children with CP had higher AP RQA entropy relative to TD children, $F(1, 58) = 54.14, p < .05$ and $F(1, 58) = 17.10, p < .05$, in the shoulder width and tandem Romberg positions, respectively. Figure 9 depicts the AP and ML RQA entropy interactions.

Figure 9. Significant AP (top) and ML (bottom) group × foot position interactions for RQA entropy (± SE).

Several main effects were also significant for RQA entropy. RQA entropy of AP COP time series was significantly greater for CP patients than for TD children, $F(1, 58) = 51.88, p < .05$. In the ML COP time series, main effects of
both Group and Foot Position were found. As in the AP plane, children with CP exhibited greater RQA entropy than TD children, $F(1, 58) = 43.84, p < .05$. RQA entropy also increased when participants assumed a tandem Romberg position relative to standing with the feet and shoulders aligned, $F(1, 58) = 10.93, p < .05$.

With respect to trend, main effects of Group were observed in both the AP and ML COP. CP patients demonstrated more COP non-stationarity or drift (AP $M = -1.437 \pm 0.989\%$ recurrence:1000 data points, ML $M = -1.580 \pm 0.925\%$ recurrence:1000 data points) than TD participants (AP $M = -0.678 \pm 0.434\%$ recurrence:1000 data points, ML $M = -0.757 \pm 0.418\%$ recurrence:1000 data points), $F(1, 58) = 26.49, p < .05$, and $F(1, 58) = 31.94, p < .05$ for AP and ML, respectively. ML trend was also greater in the shoulder width foot position ($M = -1.292 \pm 0.904\%$ recurrence:1000 data points) than in the tandem Romberg ($M = -1.045 \pm 0.725\%$ recurrence:1000 data points), $F(1, 58) = 4.81, p < .05$.

**Sample Entropy**

As in the recurrence quantification estimation of complexity (RQA entropy), ANOVAs on the sample entropy of the COP times revealed a Group × Foot Position interaction in the ML COP time series, $F(1, 58) = 44.77, p < .05$. A simple-effects analysis indicated that the SEn of TD postural sway increased from the shoulder-width to the tandem Romberg foot position, indicating a decrease in the complexity of the COP time series, $F(1, 29) = 31.25, p < .05$. Further, group differences were present in both levels of the Foot Position variable. Children with CP had higher ML sample entropy relative to TD children, $F(1, 58) = 29.54, p < .05$ and $F(1, 58) = 24.90, p < .05$, in the shoulder width and
tandem Romberg positions, respectively. These findings are illustrated in Figure 10. Main effects of group, $F(1, 58) = 28.04$, $p < .05$, and $F(1, 58) = 44.77$, $p < .05$, in the AP and ML COP time series respectively, also reflect a higher SEn (lower complexity) in children with CP relative to children who are TD.

![Graph showing ML Sample Entropy (bits) for CP and TD across Shoulder and Tandem foot positions](image)

*Figure 10. Significant ML group × foot position interaction for sample entropy (± SE).*

**Steadiness Task**

**Postural Sway Variability**

Two-way mixed factor ANOVAs exploring the effect of group and supra-postural steadiness task difficulty revealed a Group × Task interaction, $F(1, 58) = 85.92$, $p < .05$ and $F(1, 58) = 42.76$, $p < .05$, in the variability of the AP and ML COP time series. Simple-effects analysis of the AP interaction revealed a supra-postural task effect, $F(1, 29) = 72.07$, $p < .05$, for CP patients. These children exhibited reduced AP sway variability during the puppet task relative to the No-Task condition. A significant effect of task condition was also detected for TD patients, $F(1, 29) = 17.48$, $p < .05$, but in the opposite direction (task sway
variability > no task sway variability). Significant group differences were detected at each level of the steadiness task. During the No-Task condition, CP patients exhibited greater sway variability than TD participants, $F(1, 58) = 38.64, p < .05$. However, during performance of the steadiness task, this trend reversed and TD patients exhibited significantly greater sway variability $F(1, 58) = 43.40, p < .05$.

Simple-effects analyses of the ML interaction revealed a supra-postural task effect for CP patients, $F(1, 29) = 47.04, p < .05$. CP patients exhibited less ML sway variability during the puppet task relative to the No-Task condition. No such effect was found for TD participants. Further, although a significant group difference (CP > TD) existed in the No-Task condition, $F(1, 58) = 50.07, p < .05$ the difference was attenuated and no longer statistically significant ($p > .05$) in the Task condition (TD > CP). Figure 11 highlights these AP and ML Group × Task interactions.
Figure 11. Significant AP (top) and ML (bottom) group × task interaction for COP standard deviation (± SE).

Spatiotemporal Profile
Recurrence Quantification Analysis

CP patients exhibited higher % determinism of the AP COP (M = 94.74 ± 4.339%) than the TD participants (M = 90.126 ± 5.883%), $F(1, 58) = 18.80, p < .05$. ML COP % determinism was also significantly higher for CP patients (M = 95.028 ± 4.162%) than for TD participants (M = 86.130 ± 9.957%), $F(1, 58) = 35.59, p < .05$. During task performance, % determinism in the ML plane was
lower when performing the steadiness task (M = 91.151 ± 6.152%) than in the absence of task performance (M = 93.71 ± 4.803%), $F(1, 58) = 11.613, p < .05$.

CP patients demonstrated a higher maxline (greater mathematical stability) of the AP COP time series (M = 1387 ± 455 data points) than TD children (M = 1124 ± 523 data points), $F(1, 58) = 6.63, p < .05$. This was also the case for the ML COP time series (CP M = 1472 ± 382 data points, TD M = 1017 ± 467 data points), $F(1, 58) = 28.23, p < .05$.

In the AP COP time series, a significant Group × Task interaction was observed for RQA entropy, $F(1, 58) = 4.050, p < .05$ (see Figure 12). CP patients demonstrated a significant task effect in the AP COP time series, $F(1, 29) = 10.79, p < .05$. They exhibited lower RQA entropy during performance of the steadiness task than during quiet stance. This effect was absent for TD children. Overall, children with CP had COP profiles with greater RQA entropy, $F(1, 58) = 19.66, p < .05$ and $F(1, 58) = 54.14, p < .05$.

![Figure 12](image_url). Significant AP group × task interaction for RQA entropy (± SE).
Main effects of group and task performance were also found for the RQA entropy measure. CP patients exhibited greater RQA entropy relative to TD participants, $F(1, 58) = 47.16, p < .05$, and $F(1, 58) = 55.61, p < .05$, for AP and ML COP, respectively. Additionally, RQA entropy was lower during task performance than in no-task conditions, $F(1, 58) = 6.91, p < .05$, and $F(1, 58) = 4.050, p < .05$, for AP and ML, respectively.

ANOVA on trend yielded significant main effects of group in the AP and ML COP time series. TD patients exhibited greater stationarity (AP $M = -0.896 \pm 0.672\%$ recurrence:1000 data points, ML $M = -0.966 \pm 0.542\%$ recurrence:1000 data points) than CP patients (AP $M = -1.984 \pm 2.189\%$ recurrence:1000 data points, ML $M = -2.163 \pm 2.262\%$ recurrence:1000 data points) in the COP, $F(1, 58) = 12.75, p < .05$, and $F(1, 58) = 16.88, p < .05$, for AP and ML, respectively.

Sample Entropy

ANOVA on sample entropy for the AP time series indicated a significant Group effect, Task effect, and interaction between those factors (see Figure 13). Simple-effects analysis of the AP Group $\times$ Task interaction $F(1, 58) = 13.56, p < .05$ reflected a supra-postural task effect, $F(1, 29) = 26.28, p < .05$ and $F(1, 29) = 92.81, p < .05$, for both CP patients and TD participants, respectively. Participants in both groups produced a spatiotemporal profile with lower sample entropy (greater complexity) during task performance than they did in the absence of concurrent activity. Significant group differences were observed in both the Task and No-Task conditions. CP patients produced characteristically higher sample entropy (lower complexity) than TD participants in the absence of
concurrent activity and during steadiness task performance, $F(1, 58) = 15.89, p < .05$ and $F(1, 58) = 19.86, p < .05$, respectively.

A main effect of group revealed that children with CP exhibited higher AP sample entropy than TD children, $F(1, 58) = 17.97, p < .05$, and a main effect of task revealed significantly higher sample entropy (decreased complexity) for the No-Task condition, $F(1, 58) = 41.78, p < .05$.

Sample entropy in ML time series yielded the same pattern of results. Again, simple-effects analysis of the ML Group $\times$ Task interaction, $F(1, 58) = 24.07, p < .05$, reflected a supra-postural task effect, $F(1, 29) = 49.07, p < .05$ and $F(1, 29) = 66.60, p < .05$, for CP patients and TD participants, respectively. Participants in both groups produced a spatiotemporal profile with lower sample entropy (greater complexity) during task performance than they did in the absence of concurrent activity. Significant group differences were observed in both the Task and No-Task conditions. Sample entropy was higher (less complex) in CP patients than in TD participants, $F(1, 58) = 23.19, p < .05$, and $F(1, 58) = 29.54, p < .05$, during the Task and No-Task conditions, respectively.

A main effect of group revealed that children with CP exhibited higher sample entropy than TD children, $F(1, 58) = 33.19, p < .05$, and a main effect of task revealed that higher sample entropy (decreased complexity) in the No-Task condition, $F(1, 58) = 75.98, p < .05$. 

Task Difficulty

The influence of task difficulty as a moderator of the steadiness task effect was examined by submitting the data to a 2 × 2 (Group × Difficulty) mixed-design ANOVA. The difficulty of the steadiness task had a significant effect on maxline (mathematical stability) and RQA entropy (complexity) of the AP COP time series. In both cases, easier conditions (larger apertures) were coupled with increases in these variables. In easy conditions, maxline was comparatively
larger (M = 1345 ± 568 data points) than the same measure in the participant’s hard condition (M = 1163 ± 550 data points), \( F(1, 58) = 11.917, p < .05 \).

Similarly, during easy trials participants generated COP time series with a higher RQA entropy value (more complex; M = 3.341 ± 1.073 bits) than difficult trials (M = 3.149 ± 1.027 bits), \( F(1, 58) = 4.89, p < .05 \).

In the ML COP time series a significant interaction between group and task difficulty emerged in the standard deviation analysis, \( F(1, 58) = 9.49, p < .05 \) (see Figure 14). Simple-effects analysis indicated that TD children altered their sway variability as a function of task condition, \( F(1, 58) = 10.19, p < .05 \). In difficult conditions, the SD of the ML COP times series decreased relative to easy conditions. Although this trend was observed in children with CP, the effect was not statistically significant. Simple-effects analyses also indicated that the groups differed statistically in difficult trials \( F(1, 58) = 10.19, p < .05 \); this effect was absent in easy trials.

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**Figure 14.** Significant ML group × task difficulty interaction for COP standard deviation (± SE).
Analysis of Error

Overall performance on the steadiness task was evaluated in terms of the number of times that the light was triggered on the steadiness device during each measurement period. A $2 \times 2$ (group $\times$ difficulty) ANOVA using error as the dependent measure of interest produced significant main effects of group and task difficulty. CP patients committed more errors on the steadiness task ($M = 1.900 \pm 1.011$ errors) than TD children ($M = 0.975 \pm 0.924$ errors), $F(1, 58) = 23.02, p < .05$. Participants made more errors during hard task conditions ($M = 1.794 \pm 1.054$ errors) than during easy task conditions ($M = 1.081 \pm 0.969$ errors), $F(1, 58) = 28.92, p < .05$.

The relationship between task performance and postural stability was assessed by examining correlation z-scores with all measures for which significant steadiness task effects were detected. In the AP and ML COP time series, superior task performance (a lower number of errors) was directly associated with increases in the sample entropy measure (a decrease in COP complexity), but inversely associated with an increase in RQA entropy (an increase in complexity of the deterministic structure of the COP). In the AP COP time series, superior task performance was also directly associated with decreased % determinism, or predictability. In both the AP and ML planes, higher COP variability (SD) was associated with better performance on the steadiness task. These correlations are summarized in Table 3.
Table 3
**Correlation Summary: Association Between Error and Significant Supra-Postural Task Effect Measures**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlation (r)</th>
<th>Alpha (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steadiness Task</strong></td>
<td></td>
<td></td>
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<tr>
<td>ML SEn</td>
<td>0.677</td>
<td>&lt; .05</td>
</tr>
<tr>
<td>AP SEn</td>
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<td>&lt; .05</td>
</tr>
<tr>
<td>ML Recurrence Entropy</td>
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<td>&lt; .05</td>
</tr>
<tr>
<td>AP Recurrence Entropy</td>
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<td>&lt; .05</td>
</tr>
<tr>
<td>AP Determinism</td>
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<td>&lt; .05</td>
</tr>
<tr>
<td>ML SD</td>
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<td>&lt; .05</td>
</tr>
<tr>
<td>AP SD</td>
<td>-0.391</td>
<td>&lt; .05</td>
</tr>
<tr>
<td><strong>Tube Task</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ML SEn</td>
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<td>&lt; .05</td>
</tr>
<tr>
<td>AP SEn</td>
<td>-0.408</td>
<td>&lt; .05</td>
</tr>
<tr>
<td>ML Maxline</td>
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<td>AP Maxline</td>
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</tr>
<tr>
<td>ML SD</td>
<td>-0.176</td>
<td>&gt; .05</td>
</tr>
</tbody>
</table>

Note. ML = medial-lateral; AP = anterior-posterior; SEn = sample entropy; SD = standard deviation.

**Tube Task**

**Postural Sway Variability**

Two-way mixed-factor (group × supra-postural tube task performance)

ANOVA revealed a group × task interaction in the AP postural variability measure, $F(1, 58) = 86.92$, $p < .05$. Simple-effects analysis indicated that AP COP variability decreased during performance of the tube task, $F(1, 29) = 33.27$, $p < .05$ and for CP children. TD children also demonstrated a significant change in sway variability over levels of condition, but in the opposite direction, $F(1, 29) = 77.4$, $p < .05$. TD patients exhibited sway variability that increased during performance of the tube task. Moreover, there were significant group differences in both the Task and No-Task conditions. In the absence of concurrent task activity, CP patients demonstrated greater AP variability relative to TD
participants, $F(1, 58) = 38.64, p < .05$. This trend reversed during SPT performance; CP patients demonstrated less AP variability relative to TD participants during tube task performance, $F(1, 58) = 49.05, p < .05$. See Figure 15.

ANOVA also revealed a group $\times$ task interaction in the ML postural variability measure, $F(1, 58) = 61.35, p < .05$ (see Figure 15). Simple-effects analysis indicated that ML COP variability decreased during performance of the tube task in CP patients, $F(1, 29) = 64.89, p < .05$, but this effect of task performance was not significant in TD participants. There were significant group differences in both the Task and No-Task conditions. In the absence of concurrent task activity, CP patients demonstrated greater ML variability relative to TD participants, $F(1, 58) = 61.35, p < .05$. This trend reversed during tube-task performance; CP patients demonstrated less ML variability relative to TD participants during tube task performance, $F(1, 58) = 12.64, p < .05$. 
Main effects of group were observed for AP and ML measures of COP variability. The standard deviation of the AP COP was greater overall for CP participants than for the TD patients, $F(1, 58) = 4.55, p < .05$ and the ML COP standard deviation was greater overall in CP participants than in the TD group, $F(1, 58) = 12.08, p < .05$. The ML COP time series also reflected a main effect of task. COP variability decreased during tube task performance relative to the No-Task condition, $F(1, 58) = 46.51, p < .05$. 

*Figure 15.* Significant AP (top) and ML (bottom) group × task interaction for COP standard deviation (± SE).
Spatiotemporal Profile
Recurrence Quantification Analysis

A significant group effect was found for AP % determinism, in which the spatiotemporal profile for CP patients was more deterministic (M = 96.403 ± 1.969%) than that of TD participants (M = 91.373 ± 4.524%), $F(1, 58) = 34.66, p < .05$. The same finding was detected for ML % determinism. Determinism of the ML COP was significantly higher for CP patients (M = 96.343 ± 2.007%) than for the TD participants (M = 87.835 ± 9.069%), $F(1, 58) = 36.54, p < .05$.

Mathematical stability (maxline) of the AP and ML time series was found to be significantly greater for CP patients (AP M = 1478 ± 440 data points, ML M = 1575 ± 347 data points) than for TD children (AP M = 1256 ± 481 data points, ML M = 1056 ± 491 data points), $F(1, 58) = 4.72, p < .05$, and $F(1, 58) = 35.15, p < .05$, for AP and ML sway, respectively. Additionally, maxline was significantly lower in the absence of task activity (AP M = 1257 ± 195 data points, ML M = 1238 ± 514 data points) than during performance of the tube task (AP M = 1478 ± 424 data points, ML M = 1393 ± 471 data points), $F(1, 58) = 16.53$ and $p < .05$, $F(1, 58) = 5.84, p < .05$, in AP and ML sway respectively.

ANOVA yielded a significant main effect of group for RQA entropy in the AP direction. RQA entropy was greater for CP patients (M = 4.197 ± 0.843 bits) than it was for TD participants (M = 2.896 ± 0.691 bits), $F(1, 58) = 53.72, p < .05$. These results were duplicated in the ML time series. RQA entropy was larger for CP patients (M = 4.278 ± 0.787 bits) than TD participants (M = 2.749 ± 0.750 bits), $F(1, 58) = 79.00, p < .05$. 


Finally, a significant group effect was found for AP and ML trend. Postural sway patterns were more stationary (lower trend) for TD participants (AP M = -0.858 ± 0.422% recurrence:1000 data points, ML M = -0.935 ± 0.545% recurrence:1000 data points) than for their CP counterparts (AP M = -1.510 ± 0.927% recurrence:1000 data points, ML M = -1.840 ± 0.930% recurrence:1000 data points), \( F(1, 58) = 12.75 \) and \( p < .05 \), and \( F(1, 58) = 35.23 \), \( p < .05 \), in the AP and ML time series, respectively.

**Sample Entropy**

The sample entropy ANOVA for the AP time series indicated a significant group effect, task effect, and interaction. Simple-effects analysis of the significant AP group × task interaction, \( F(1, 58) = 20.30 \), \( p < .05 \), indicated lower sample entropy (greater complexity) during tube task performance than in the No-Task condition, \( F(1, 29) = 29.55 \), \( p < .05 \) and \( F(1, 29) = 26.30 \), \( p < .05 \), for both CP and TD participants, respectively. Group differences were significant at each level of Task in simple-effects analyses. Sample entropy was comparatively higher (less COP complexity) in CP patients relative to TD participants, \( F(1, 58) = 15.89 \), \( p < .05 \), and \( F(1, 58) = 46.41 \), \( p < .05 \), in No-Task and Task conditions, respectively. This interaction is illustrated in Figure 16.

Main effects of group and task were also detected in the AP time series. Children with CP had overall higher time series sample entropy (less complexity) than children who were TD, \( F(1, 58) = 11.86 \), \( p < .05 \). Higher sample entropy (less complexity) was also observed in the absence of task performance. During
the tube task, the AP COP time series became more complex, $F(1, 58) = 38.62$, $p < .05$.

The aforementioned results are complimented by similar findings in the ML COP time series. Based on simple-effects analysis subsequent to the ML group $\times$ task interaction, $F(1, 58) = 41.34$, $p < .05$, a supra-postural task effect was demonstrated, $F(1, 29) = 55.24$, $p < .05$, and $F(1, 29) = 5.96$, $p < .05$, by both CP patients and TD participants, respectively. Like AP sample entropy, both groups produced a lower sample entropy (more complex spatiotemporal profile) during tube task performance than in the absence of concurrent activity (CP $M = 0.138 \pm 0.091$ bits, TD $M = 0.044 \pm 0.023$ bits). Group differences were significant at each level of Task in simple-effects analyses. ML sample entropy was comparatively higher (less complex) in CP patients relative to TD participants in the No-Task condition, $F(1, 58) = 29.54$, $p < .05$, but lower (more complex) during tube task performance, $F(1, 58) = 39.68$, $p < .05$. This interaction is also illustrated in Figure 16.
A significant task main effect was also noted, wherein during tube task performance sample entropy was lower (more complex) relative to the No-Task condition, \( F(1, 58) = 61.15, p < .05. \)

*Locus of Attention*

The influence of locus of attention as a moderator of the task effect was examined by submitting the data to a \( 2 \times 2 \) (group \(
\times\) locus) mixed-design ANOVA. In the AP COP time series, a significant interaction between group and
locus of attention emerged in the analysis of COP SD, \( F(1, 58) = 15.59, p < .05 \). Simple-effects analysis indicated that only the TD participants exhibited a significant change in COP variability as a function of where attention was directed, \( F(1, 29) = 39.69, p < .05 \) (see Figure 17); the magnitude of COP variability was lower when TD participants focused on the effects of their movement instead of the movement itself.

![Figure 17](image_url)

*Figure 17.* Significant AP group × locus of attention interaction for COP standard deviation (± SE).

During internal attention trials, participants generated COP time series with a higher AP sample entropy (less complexity) than they did during external attention trials \( F(1, 58) = 25.08, p < .05 \). No effects of locus of attention on ML postural sway were noted.

**Analysis of Error**

Performance on the tube task was evaluated in terms of the number of audible chimes in each measurement period. A \( 2 \times 2 \) (group × difficulty) ANOVA on error in each of the tube conditions revealed that locus of attention was
significantly associated with the number of errors committed. A significant group × locus of attention interaction was observed, $F(1, 58) = 5.05, p < .05$. This interaction is pictured in Figure 18. Simple-effects analysis revealed that locus significantly affected the number of errors that TD participants made, $F(1, 29) = 18.45, p < .05$, but had no influence on CP performance. Significant group differences were noted during both internal and external conditions, $F(1, 58) = 26.02, p < .05$ and $F(1, 58) = 59.24, p < .05$, respectively. A main effect of group showed that CP patients produced more errors on the tube task than TD children, $F(1, 58) = 55.578, p < .05$.

![Figure 18. Significant group × locus of attention interaction for task performance error (± SE).](image)

The relationship between task performance and postural stability was assessed by examining correlation z-scores with all measures in which significant tube-task effects were detected (see Table 3). Complimentary to findings for the steadiness task, during performance of the tube task the
relationship between error and sample entropy was reciprocal. For both AP and ML COP time series, superior task performance (a lower number of errors) was associated with increases in the sample entropy measure (a decrease in COP complexity). Additionally, in both the AP and ML COP time series, as maxline increased (mathematical stability), so did the number of errors committed during the tube task.
CHAPTER 4

Discussion

The purpose of this study was to determine the effects of CP, supra-postural task performance, and moderators of supra-postural tasks on postural stability and postural sway dynamics. In general, the results support a priori hypotheses regarding the changing nature of postural sway and sway dynamics in the face of disease and supra-postural tasks. The significance of these results, implications for CP, and future directions are considered in the following sections.

Postural Sway Variability

I predicted that individuals with CP would exhibit greater COP variability than TD children. That prediction was confirmed in baseline measures obtained during quiet, unperturbed stance. COP standard deviation was greater for CP patients than controls in both the AP and ML directions.

Group × Supra-Postural Task interactions in the steadiness task demonstrated a characteristic group difference (CP > TD) in the No-Task condition. During performance of the steadiness task, children with CP demonstrated expected decreases in sway variability, but TD children actually demonstrated increases in sway variability. Subsequently, during task performance, CP patients exhibited lower AP and ML sway variability than TD children. During the tube task, this difference between groups was marginally significant; in both the tube task (AP and ML) and the steadiness task (AP),
children with CP did in fact demonstrate significantly less sway variability than TD children during supra-postural task performance.

The identical pattern of results in both tasks buttresses the finding that CP patients demonstrate flexibility in the postural control system when it is constrained by concurrent activity. I predicted that individuals with CP would exhibit greater COP variability than TD children. That prediction was confirmed in baseline measures obtained during quiet, unperturbed stance. COP standard deviation was greater for CP patients than controls in both the AP and ML directions. However, the reversal in stability during task performance was unexpected. It may be that these two groups used different postural control strategies in order to facilitate task performance. For example, if CP children have difficulty dissociating corrections of the upper extremity from movement of the trunk, in order to successfully perform these tasks whole body movement would need to be minimized. TD children, in contrast, may have dissociated movement in the upper extremity and movement of the torso, which may have eliminated the need to reduce postural sway variability. In order to test this hypothesis it would be necessary to track the kinematics of the trunk and arm, which was not possible using the instrumentation in the present study. Even if this had occurred for the TD children, it is unclear why sway would have increased significantly (rather than remained constant) in the no-task condition. Another alternative is that for TD children the supra-postural steadiness task served as a distractor, diverting away attention from postural control, and thereby resulting in degraded postural performance. However such a result might be
expected to have occurred (and perhaps have been stronger) for the CP children, who in addition to exhibiting motor impairments tend to exhibit cognitive impairments as well.

Analysis of supra-postural task performance (i.e., error rates) lends some support to this interpretation. Despite increases in sway variability during the steadiness and tube tasks, TD children were able to outperform children with CP. Analysis of error revealed a main effect of group, indicating that TD children committed fewer errors during task performance. Thus TD children were solving the challenge posed by the supra-postural task, though presumably through a mechanism other than postural stabilization. This interpretation must be qualified, however, because a task performance criterion was established in the steadiness task. All participants were required to make three or fewer errors on each trial, effectively restricting the range of possible responses (errors committed) and potentially biasing statistical analyses.

**Spatiotemporal Profile of the COP**

The results of this study were generally consistent with the hypothesis that COP time series of individuals with CP would exhibit a loss of complexity in the form of increased regularity of spatiotemporal patterns of the COP (Goldberger, 1996, 1997; Goldberger, Peng, & Lipsitz, 2002; Goldberger, Rigney, & West, 1990; West & Goldberger, 1987). I observed greater % determinism, maxline, and sample entropy in the AP and ML COP time series of CP patients in the baseline comparisons. The spatiotemporal profile for CP participants was characterized by stereotypical regularity (cf. Goldberger, 1997). Collectively,
these findings indicate that the COP time series of CP patients exhibited high
degrees of rigidity, stereotypy, and regularity during non-perturbed standing.

However, this conclusion was contradicted by two measures, RQA
entropy and trend. To the extent that these measures validly index complexity in
the spatiotemporal profile of the COP, the RQA entropy and trend results in the
present study appear to challenge the assertion that the COP profiles of children
with CP deviate from a pattern of “health.” For example, in baseline conditions,
children with CP demonstrated larger absolute values of trend. This is an
indicator of drift in the COP time series; nonstationarity is a fundamental aspect
of postural control in a healthy system (Dijkstra, 1998; Isableau, Ohlmann,
Cremieux, & Amblard, 1997; Riley, Balasubramaniam, & Turvey, 1999;
Zatsiorsky & Duarte, 1998). These apparently contradictory results are
discussed in greater detail in a later section that describes what these various
measures actually quantify in a time series.

Analysis of the spatiotemporal profile during supra-postural task
performance generally supported the hypothesis that supra-postural task
conditions would constrain the postural control system and reduce differences
between CP and TD children. The hypothesis that supra-postural task
performance fosters a behavioral context in which participants with CP might be
encouraged to demonstrate a “healthier” COP profile was also generally
supported. Both children with CP and TD children demonstrated an increase in
complexity during the steadiness and tube tasks, according to the sample
entropy measure. Although the group difference was not significant, children
with CP actually exhibited lower mean values of AP and ML sample entropy than TD children during performance of the tube task, implying nominally greater complexity in their spatiotemporal profile.

Again, the claims about the effects of supra-postural task performance on the spatiotemporal profile of the COP could be questioned because children with CP committed more errors than TD children. However, correlation analyses demonstrated that superior performance was associated with decreased determinism (steadiness task) and decreased sample entropy (both tasks). Both of these trends were illustrated not just in TD participants but also in CP patients during supra-postural task performance. Moreover, simple-effects analysis of error in the tube task indicated that the locus of attention had no bearing on the number of errors that CP patients committed or on sway variability. This is in sharp contrast to TD participants, who exhibited both a decrease in sway variability and an increase in the number of errors committed in the internal focus conditions. Comparatively speaking, the ability to maintain a constant level of error across these conditions of tube-task performance may reflect a degree of relative task success for the CP patients given that their performance was not supported by reduced COP variability across locus of attention conditions.

**Supra-Postural Task Moderators**

Predictions regarding moderating effects of task difficulty were not fully supported. To the extent that these supra-postural tasks present a context in which the postural control system can be functionally constrained, I anticipated that a difficult task (steadiness task) and an external locus of attention (tube task)
should foster a sway profile in CP patients that is “healthy” (e.g., less movement variability, greater complexity) and analogous to the TD spatiotemporal profile. This hypothesis was partly supported by the finding that in difficult steadiness task conditions, maxline decreased in both children with CP and TD children. Similarly, although postural activity became more complex (increased sample entropy) in TD children when performing the tube task in the external locus of attention condition, the effect was not observed in children with CP.

**Entropy, Sample Entropy, and Trend**

The effects of group, supra-postural task performance, and supra-postural task manipulations on RQA entropy and sample entropy were seemingly contradictory. Sample entropy measures reflected the predicted loss of complexity associated with CP and a restoring of complexity during supra-postural task performance. RQA entropy typically demonstrated an opposite pattern. For example, in the steadiness task and tube task, main effects of RQA entropy indicated that the deterministic structure of postural sway was more complex in CP patients than in TD children.

One possible explanation for this discrepancy is that these two tools index complexity in different ways. RQA entropy is a measure of the complexity of the deterministic structure of a time series (Webber & Zbilut, 1994, 1996); it is essentially a measure of the regularity of diagonal line lengths in a recurrence plot (neighborly data points that repeat themselves over the time series). This contrasts with the characterization of complexity provided by sample entropy. Sample entropy explores the conditional probability that a signal will repeat itself.
for a certain number of points, within a pre-determined tolerance range. It characterizes the deterministic as well as the stochastic features of the time series rather than just the deterministic structure of the time series.

It could be that what is quantified by RQA entropy is not an appropriate sense of “complexity.” As Goldberger et al. (2002, p. 24) pointed out, “increased irregularity does not imply increased physiologic complexity.” Recurrence entropy was recently at odds with a collection of other dynamic measures supporting a loss of complexity in recent work with Parkinson’s disease (see Schmit et al., 2006). These findings cast doubt on the utility of RQA entropy as a measure of complexity with which to evaluate the hypothesis that physiological complexity decreases with disease.

CP patients reliably demonstrated greater trend magnitude than TD participants. This conceptually also seems to be at odds with the loss of complexity hypothesis. Nonstationarity is an expectation in a healthy postural control system; the COP exhibits properties characteristic of fractal Brownian motion (Collins & De Luca, 1993, 1995; Riley, Balasubramaniam, Mitra, & Turvey, 1998; Riley, Mitra, Stoffregen, & Turvey, 1997, Riley, Wong, Mitra, & Turvey, 1997). However, nonstationarity may reflect a strategy in an unstable (e.g. pathological) system. Children with CP may be demonstrating an approach to postural control that involves “running with” rather than resisting the dynamics of the system (e.g., not countering tendencies to behave in a particular way until a constraint threatens task performance; see Riley et al., 1999a; Treffner &
Kelso, 1997). These data may be an illustration of change in nonstationarity that accompanies populations with movement pathologies.

Alternatively, examination of the trend values may indicate that both CP and TD participants demonstrated stationarity of the COP time series if they are deemed to be within the proximity of 0% local recurrence (% recurrence is an output variable from RQA that was not considered in the current study; see Riley et al., 1999a; Webber & Zbilut, 1994, 1996). Webber, Schmidt, and Walsh (1995) state that by definition trend values were considered equivalent to zero if they fell within a narrow band between ±10% local recurrence. In a second example, Webber (2005) categorized trend as reflecting system stationarity if values fall between ±5 units of zero. In the present study, main effects of trend were detected in the steadiness and tube task in both the AP and ML time series. Examination of the mean values of trend indicated, however, that the largest mean trend magnitude observed in this study was < 4 units. According to this interpretation of the trend measure, CP patients did in fact demonstrate a stationarity that would be expected in a disease state and in accordance with the loss of complexity hypothesis. TD children also exhibited COP stationarity, however; this could be because young children do not demonstrate the same COP complex, nonstationary COP dynamics as adults.

**Implications for CP**

Postural instability is symptomatic of CP, particularly in patients demonstrating ataxia and cerebellar involvement. When balance becomes an issue for patients with CP, fall-related injuries, restriction of gait patterns, and
decreased mobility are common. These issues (particularly falling) represent major health care concerns in the United States and have negative psychological counterparts, such as fear of falling, which can result in a substantial decrease in the amount of a person’s functional activity (Adkin, Frank, & Jog, 2003; Stolze, Klebe, Zechlin, Baecker, Friege, & Deuschl, 2004). Moreover, as evidenced by this work, balance control is fundamental to the control of other behaviors (Gibson, 1966; Riccio, 1993; Riccio & Stoffregen, 1988), including locomotion, manual manipulation, and social interaction (Shockley, Santana, & Fowler, 2003). Thus, when balance control is impaired, the impairment may spill over to other behaviors that require a stable postural background for their performance. Consequently, a more complete understanding of conditions in daily life that intensify that instability is fundamentally important.

Additionally, the detection of postural instability in children with CP has historically been crude. Clinical tests and measures of balance typically include one-legged stance trials and self-report of falls. Although these measures may provide gross information about instability (e.g., presence or absence thereof), they cannot be used to quantify the degree of instability with which a child with CP may contend. More objective methods used to gauge the severity of motor dysfunction in CP emphasize patterns of abnormal muscle tone, the delay/absence of righting, equilibrium, and protective reactions, and the range or quality of the movement repertoire, but are not proxies for postural stability. Further, studies that have employed objective tests and measures of instability (e.g. static and dynamic posturography) historically have been conducted using
artificial perturbations or grossly simplified task environments, and lack those constraints on the postural control system that alter the pattern of postural stability that will emerge. In order to adequately evaluate and make generalizations regarding the status of the postural control system, it must be studied during concurrent functional activity. Balance cannot be separated from the actions of which it is an integral component or from the environment in which it is performed (Carr & Shepherd, 2001).

This study also illustrates the importance of treating instability within a framework of functional behavior. CP patients demonstrate aberrant physiology, including inappropriate sequencing of muscle control, poor anticipatory regulation, and destabilizing synergistic or antagonistic activity (Nashner et al., 1983. The functional implications of these departures from normal are instability and disordered movement in daily activity. Evaluating and treating these impairments in a non-behavioral context does not allow critical interplay between the postural control system and the requirements of concurrent activity; improvements in muscle activation and sequencing fostered in the absence of typical concurrent, goal-oriented behaviors may not generalize to enhanced postural stability in a functional context. Consequently, postural control may continue to be compromised in the child’s everyday activity. Moreover, altering the functioning of the musculoskeletal system may present new challenges to the CP patient who has adapted compensatory strategies in order to maintain postural control.
Cerebral palsy is a changeable condition (Bobath, 1971) insofar as maturational and adaptive processes may alter the clinical picture of the child over time (Kusban & Leviton, 1994). In fact, recent theories of motor development emphasize that motor behavior or developing behaviors are not the unfolding of predetermined patterns in the central nervous system (Kelso, 1995; Thelen & Smith, 1994). Woollacott, Hutchinson, Kartin, Price, and Shumway-Cook (2003) proffer support for this in a study demonstrating that reactive balance control can be improved in school-age children with CP.

These considerations make efforts to understand motor deficiencies and how best to address them of practical and clinical significance. Functional therapy programs are of particular relevance in the context of this research study. A functional therapy approach is anchored on the principle that motor behavior is a consequence of the dynamic interaction between subsystems in a task-specific context. Subsequently, a key distinction in functional therapy approaches is the conceptual shift from focusing on normality to focusing on functionality (Ketelaar, Vermeer, Hart, van Petegem-van Beek, & Helders, 2001). Unlike traditional approaches to treatment (e.g., Neurodevelopmental Treatment, an approach that emphasizes normal movement patterns in normal postures; Bobath, 1969), functional therapy programs address movement patterns in intervention but only within the context of a functional task behavior and the environment in which it is occurring. Children in functional therapy are encouraged to self-initiate activity in an environment with naturally occurring constraints (Latash, 1996; Wimmers, 1992). In a functional therapy evaluation, the therapist analyzes the subsystems
that constrain performance of a task. Perhaps of greater clinical significance, they also must analyze which constraining subsystems can be changed. A recent study by Ketelaar and colleagues (2001) compared the motor abilities of children with CP who were receiving functional physical therapy to a reference group whose therapeutic interventions focused on the normalization of movement. They concluded that although there were no differences in improved gross motor ability between approaches, the application of a functional therapy program for CP resulted in positive effects on the child's capability and independent performance of daily functional activity.

Future Directions

The results of this work motivate new research questions to be pursued in future investigations. Although clear instances of a supra-postural task effect were demonstrated, it may be of interest to examine the influence of everyday supra-postural activities (e.g., holding a toothbrush, handwriting) on COP variability and dynamics, instead of developing a task intended to “foster” a functional context. Prospective supra-postural work should clearly operationalize improvement in task performance and continue to explore the moderating effects of other variables on supra-postural task effects.

Static posturography and spatiotemporal dynamics measures could be used in future studies to determine whether treatments like selective dorsal rhizotomies, botox regimens, pharmacological interventions, and orthopedic surgeries (e.g., heel cord release, hamstring lengthenings) result in the complex and irregular COP time series patterns that more closely resemble the profile of a
healthy control participant. Although many of these approaches to clinical management of CP have been investigated with respect to increases in range of motion, decreases in spasticity, or improvements in tone, their effects on postural stability and sway dynamics in CP have not been examined.

Bilateral training, a recent rehabilitation approach, has been associated with decreases in muscle impairments and improved performance of discrete unilateral and bilateral movement in the involved limb of individuals status post-CVA (Whitall, McCombe-Waller, Silver, & Macko, 2000). This approach may also have utility in the CP community; bilateral practice may facilitate coactivation and interhemispheric activation for asymmetric movements to develop, which could elicit functional improvements on the more affected side of CP patients with hemiparesis. These improvements are hypothesized to translate into post-intervention reductions in COP variability or changes in the dynamic patterns of the COP.

In the last decade, properties of sway dynamics have been explored in gait. The coordination of the many subsystems involved in the control of gait can be examined in the scaling properties of time series and the ways in which these subsystems adapt to changing environmental and physiological conditions (West, 2006). These scaling relations index complexity in the dynamics of gait. Studies have shown that gait complexity changes with disease. Gait research on Huntington’s disease demonstrated a reduction in the scaling exponent that characterizes stride rate variability (Hausdorff, Mitchell, Firtion, Peng, Cudkiowicz, Wei, & Goldberger, 1997). Perhaps more importantly, Hausdorff
and colleagues noted that the stride rate variability index decreases with increases in disease severity (as measured by the Unified Huntington’s Disease Rating Scale). If this trend generalizes to other populations, it would demonstrate the quantitative utility of non-linear approaches as indicators of level of recovery or of rehabilitation progress.

Although gait research has contributed to the recent flurry of support for dynamical disease, the applicability of these findings could be enhanced by examining gait in a functional context (e.g., constraining gait and subsequently the postural control system by having participants engage simultaneously in a “supra-gait tasks”). Examples of more functional gait contexts might include ambulation while concurrently carrying a load, engaging in cognitive activity, or maneuvering in an environment with obstacles.

**Conclusion**

The effects of balance impairment can be dramatic. Presently the understanding of postural instability in CP is, at best, modest. Although an extensive amount of prior research on postural control with this population has been conducted, many of the findings may not generalize beyond laboratory tasks because postural stability was assessed in many prior studies without constraining the postural control system in representative ways. In contrast, the present study provided a functional and objective evaluation of balance control in CP and revealed new information about the mechanisms of postural control that have not previously been considered.
The present results indicate that the postural stability of CP patients is both qualitatively and quantitatively different than control participants. An assumption in many studies of postural control is that the SD of the COP is a straightforward index of the quality of postural control—greater sway variability signifies less effective postural control (e.g., reduced postural stability). However, a number of researchers have cautioned that this assumption should not be made without further consideration of the dynamic patterns of the COP (Newell et al., 1993; Newell & Slifkin, 1998; Riccio, 1993; Riley, 2001; Riley & Turvey, 2002; Slifkin & Newell, 1999; van Emmerik & van Wegen, 2000, 2002). This research suggests that both kinds of indices will help to generate a profile of postural stability in CP patients. The variability increases observed in this study indicate that magnitudes of movement increase in CP, and the dynamic measures indicate that these increases are accompanied by a loss of complex, irregular variability that characterizes postural sway in healthy individuals.

Finally, the finding that CP participants demonstrated supra-postural task effects is both novel and promising. The functional contexts introduced in this study appear to have facilitated a coordination between the postural demands of a supra-postural task and corresponding postural demands of upright stance. Although not all measures included in this study reflected a statistically significant supra-postural task effect in children with CP (at a simple effects level of analysis), many did or minimally demonstrated trends in directions consistent with supra-postural effects. The findings in this research arguably have achieved a status of clinical significance, to the extent that clinical significance moves a
person outside the range of a dysfunctional population or within the range of the functional population (Jacobson, Follette, & Revenstorf, 1984). Accordingly, the assertion that poor postural control in CP is the catalyst for later motor deficiencies is challenged and instead suggests that dynamic aspects of the postural control system are preserved, allowing children with CP to function in ways that do not differ significantly from TD children when the situation demands it.
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APPENDIX A

Recurrence Quantification Analysis

In recent years there has been increased recognition that most physiological systems are complex, nonlinear, nonstationary, and noisy (e.g., Bassingthwaighte, Liebovitch, & West, 1994; Glass & Mackey, 1988; Goldberger, 1997; Murray, 1993; Riley & Turvey, 2002). In the field of postural control, this recognition has resulted in models of postural control and analytic techniques derived from stochastic physics and nonlinear dynamics (e.g., Collins & De Luca, 1993; (Collins, De Luca, Burrows, & Lipsitz, 1995; Dijkstra, 2000; Duarte & Zatsiorsky, 2000; Newell et al., 1993; Newell, Slobounov, Slobounova, & Molenaar, 1997; Peterka, 2000; Riley, 2001; Riley, Balasubramaniam, Mitra, & Turvey, 1998; Riley et al., 1999a; Riley & Clark, 2003; Rosenblum, Firsov, Kuuz, & Pompe, 1998; Rougier, 1998). Recurrence quantification analysis (RQA) is an example of one technique that has demonstrated utility in postural control (Webber & Zbilut, 1994, 1996, 2005; for applications to postural sway, see Pellecchia & Shockley, 2005; Riley et al., 1999a;). RQA was applied in the present study to the COP time series obtained from CP patients and TD children in order to quantify the spatiotemporal dynamics of postural sway.

RQA is a quantitative extension of the graphical method of recurrence plots introduced by Eckmann et al. (1987). Recurrence plots were originally designed to locate recurrent patterns (hidden rhythms) and nonstationarity (drift) in a time series. Recurrence plots (and RQA) do not impose constraints on data set size, stationarity or statistical distribution, and are effective even in the
presence of noise and underlying state changes. Those characteristics make the technique ideal for study of physiological data (Webber & Zbilut, 1994).

A recurrence plot is a topologically equivalent recreation of a univariate time series thought to be part of a larger, $n$-dimensional, nonlinear system. Thus, the first step in generating a recurrence plot is to recreate the $n$-dimensional phase space of the system dynamics. An $n$-dimensional space is reconstructed from a measured, univariate time series using the method of delays (see, e.g., Sauer, Yorke, & Casdagli, 1991). The method of delays uses time-delayed copies of the measured time series as surrogate variables to stand in place of the other unmeasured (and usually unknown) system variables. Phase space reconstruction is an application of the embedding theorem, which states that the observed time series (which is a one-dimensional projection of the underlying system dynamics from the true, multi-dimensional phase space of a nonlinear system) preserves certain invariant properties of the system dynamics, and those properties can be measured in the reconstructed phase space (Grassberger & Procaccia, 1983; Takens, 1981). The set of all data vectors that are embedded in the reconstructed phase space constitutes a trajectory through the reconstructed phase space. Invariant properties of the original dynamics are preserved in that trajectory.

The method of delays requires choosing a time delay, $\gamma$, to create the time-lagged copies of the measured signal that are used as surrogate dimensions of the reconstructed space. Phase space reconstruction also requires choosing an embedding dimension, $d_e$, that is sufficient to “unfold” the $n$-
dimensional dynamics of the measured system (i.e., $d_e$ must be of a dimension greater than $n$). There are principled methods for choosing $\gamma$ and $d_e$ (e.g., Abarbanel, 1996). For instance, $\gamma$ may be chosen based on the autocorrelation function (Weber, 2001) or the average mutual information function (Fraser & Swinney, 1986) of the measured time series, and a technique termed false nearest neighbors analysis may be used to determine $d_e$. Additional techniques used to determine these values for the present data will be described later in the appendix.

Once values of $\gamma$ and $d_e$ have been selected and phase space reconstruction is completed, a characteristic of the data set called recurrence, or “neighborliness” (proximity in the reconstructed phase space) is defined by counting the number of data points within a sphere of some chosen radius, $r$, when the sphere is centered around a given data point. The Euclidean distance in the reconstructed phase space between a given point $i$ and every other point $j = 1$ to $N$ (where $N$ is the length of the trajectory in reconstructed phase space) is calculated. If the distance is less than or equal to $r$, the points $(i, j)$ are considered recurrent. The distance calculations and determination of recurrence is computed for all $i = 1$ to $N$ (i.e., each data point is compared to every other data point). The degree and nature of the recurrence in time series are specified in a recurrence plot (Riley et al., 1999a), where each darkened $(i, j)$ coordinate represents a recurrent point in the reconstructed phase space. Recurrence represents an instance of auto-correlation in the data, and neighborliness in reconstructed phase space means the trajectory repeats itself over time.
RQA is a set of objective, quantitative measures that describe the signal depicted in the recurrence plot; these measures include % recurrence, % determinism, maxline, entropy, and trend. Percent recurrence quantifies the percentage of the plot occupied by recurrent points. It is calculated by taking the number of recurrent points and dividing it by the total number of \((i, j)\) coordinates in a triangular half of the plot (because the plot is symmetrical about the main diagonal, all calculations are focused on just one of the two triangular areas). The distinction between points that are isolated and those that are organized in diagonal patterns is quantified by % determinism, which is the percentage of recurrent points that fall along upward diagonal line segments. Maxline is the length of the longest diagonal line parallel to the main diagonal, excluding the main diagonal. Maxline is inversely proportional to the largest positive Lyapunov exponent, which is, roughly speaking, a measure of the mathematical stability of the time series. High values of maxline indicate greater stability in the mathematical sense of decreased sensitivity to a change in initial conditions; this is not equivalent to “postural stability.” Entropy is purported to be a measure of complexity of the deterministic structure of the time series. It is computed as the Shannon entropy of a histogram of line segment lengths (the number of observed upward diagonal lines of different lengths are counted and distributed over integer bins of a histogram, where each bin represents a different line length),

\[
E = - \sum P_b \log_2(P_b)
\]  

(1)
where \( P_b \) indicates bin probabilities of all nonzero bins greater than or equal to the number of recurrent points defining a line (Weber & Zbilut, 1994). Trend is a measure of the paling of the recurrence plot away from the main diagonal. It is computed by finding the slope of the line of best for % recurrence as a function of distance from the main diagonal. Non-zero trend is an indication of drift in the system. Values of trend close to zero indicate stationarity. According to Webber, values are considered equivalent to zero if they fell within a narrow band between ±10% local recurrence (Webber et al., 1995).

Together, visual inspection of the recurrence plot and RQA provide a robust means of studying the spatiotemporal dynamics of a time series. The primary drawback of the technique concerns the difficulty of reconstructing the \( n \)-dimensional phase space. Selecting appropriate values of the input parameters (embedding dimension, delay, radius) demands a thorough understanding of the system under scrutiny.

In order to determine appropriate input parameters for time lag, embedding dimension, and radius, the response of RQA output measures over systematic changes in the input parameters was determined (Zbilut & Webber, 1992). RQA measures were computed for a range of typical postural sway parameter settings (cf. Riley et al., 1999a). From this range, a setting was chosen that yielded smooth changes in the RQA output measures over changes in input parameters (Riley et al., 1999a). In addition to smooth % recurrence responses, the radius parameter should be set to a value so that identified recurrence is local in the reconstructed phase space, rather than global (Riley et
al., 1999a). Additionally, the size of the radius should not result in saturation of % determinism (values near the floor at 0% or ceiling at 100%).

Based on the surface plots and these guidelines, both AP and ML COP time series were embedded in a space of $d_e = 13$, using the measured COP signal and time-lagged copies of that signal with a delay $\gamma = 4$ as coordinates of the reconstructed phase space. Smooth responses of % recurrence to changes in input parameters was observed in that range of parameters and, the overall goal of achieving local recurrence (overall mean % recurrence = 0.95 in Task I; overall mean % recurrence = 0.88 in Task I) was achieved with the selection of a radius of 8% of the mean Euclidean distance separating points in the reconstructed phase space. The number of successive points required to identify a parallel line segment was set to 2. Four of the RQA measures were then computed (% recurrence was not considered in the present study), averaged across trials per condition for each participant and submitted to ANOVAs with foot position (baseline), SPT effects (Tasks I and II), task difficulty (Task I), locus of attention (Task II), and group as independent factors.

In order to confirm the appropriate choice of parameter settings and to rule out the possibility of artifactual results, the RQA results attained were compared to those obtained from randomly shuffled data (samples were randomly re-ordered to create new time series) under the same input parameters (Theiler, Eubank, Longtin, Galdrikian, & Farmer, 1992; Webber & Zbilut, 1994, 1998). When shuffled, any structure found in the reconstructed phase space should be destroyed, which would indicate that the originally observed structure was
dependent upon the original sequential order of the data points and was not a statistical artifact. Randomization of the present data resulted in substantial drops in each of the RQA measures (i.e., randomized determinism for all sampled trials was less than 1% in 5 data records). The outcome of this procedure supports the conclusion that the results obtained under the present parameterization reflect the true properties of the temporal evolution of COP and that the COP dynamics contain a degree of deterministic structure (Riley et al., 1999a).
APPENDIX B
Sample Entropy

Sample entropy is a newer analytical approach used to index a system that is both stochastic and nonlinear. To date, there are few postural control investigations that have employed sample entropy as a descriptor of the spatiotemporal profile of postural sway. However, based on the recent position that static stance contains stochastic as well as deterministic components (Collins & De Luca, 1993; Newell et al., 1997; Riley et al., 1999; Frank et al., 2001), sample entropy has recently been applied to movement disordered COP trajectories in stroke patients (Roerdink et al., 2006) and in children with CP (Donker et al., 2008). The utility of sample entropy has been demonstrated in cardiology as an indicator of a reduction in the nonlinear characteristics of cardiac rhythms (e.g., Dawes, Moulden, Sheil, & Redman, 1996; Goldberger, Mietus, Rigney, Wood, & Fortney, 1994; Javorka et al. 2002; Lewis & Short, 2007; Merati et al., 2006; Platys & Gal, 2006). Sample entropy was applied in the present study to the COP time series obtained from CP patients and TD controls in order to quantify the complexity of postural sway.

Sample entropy is an extension of approximate entropy (Pincus, 1991). Approximate entropy was designed to index change in underlying physiological control processes. It is the negative natural logarithm of the conditional probability that a dataset of length $N$, having repeated itself within a tolerance $r$ for $m$ points, will also repeat itself for $m + 1$ points (c.f. Lake et al., 2002). This approach indexes the probability of repeated template sequences in the data. If $B$ is the number of matches in a dataset and $A$ is the subset of matches for
length $m + 1$ points, the conditional probability is expressed as $A/B$; approximate entropy is the average of the negative natural logarithm of $A/B$ for each template.

Because neither $A$ nor $B$ can be zero, the conditional probabilities must be corrected so that a template can match itself. This correction biases the conditional probability (and subsequently biases approximate entropy) when the number of matches in the dataset are small, and with the result that entropy estimates are lower than predicted values. These shortcomings spurred the development of sample entropy (Richman & Moorman, 2000).

Sample entropy differs from approximate entropy in two specific ways. The first is that it does not allow self-matches. Theoretically, this change was justified on grounds that entropy is a measure of the rate of information production and, in this context, comparing data with themselves has no meaning (Richman & Moorman, 2000). Sample entropy also deviates from approximate entropy by avoiding the template approach; $A$ and $B$ are permitted to accrue for all templates (Lake et al., 2002). Instead, sample entropy calculates the negative logarithm of a conditional probability associated with the entire time series. In situations where no matches occur, $B = 0$, indicating that no regularity was detected.

Sample entropy also demonstrates relative consistency; using parameters $m$ and $r$, if a COP time series of a TD participant yields a lower sample entropy than the COP time series of a CP patient, this trend will not be affected by changing the parameter values. It is relative consistency that permits the inference that data did not arise from a random process. Moreover, like RQA,
sample entropy does not impose constraints on data set size, stationarity or statistical distribution, and has demonstrated sensitivity to the detection of underlying state changes. These characteristics are desirable in order for a technique to be useful for studying physiological data (Webber & Zbilut, 1994).

Selection of parameter settings for a sample entropy analysis are critical. The approach is limited in this way; although guidelines for maximizing these values exist, parameter selection is not a precise science. The parameters $m$ and $r$ represent the match size and tolerance within which matches will be searched. Generally, existing rules have led to the use of values of $r$ between 0.1 and 0.25 and values of $m$ between 1 and 2 for datasets with 100 to 5,000 data points (Groome, Mooney, Holland, Smith, Atterbury, & Loizou, 1999; Palazzolog, Estafanous, & Murray, 1998).

The accuracy and estimation of sample entropy improve as the number of matches increase. Accordingly, a smaller value of $m$ (short template) and a large $r$ (wide tolerance) should generate optimal sample entropy estimates (the highest number of matches). However, the discriminative capacity of sample entropy declines; as $r$ grows, it approaches a conditional probability of 1, and yields a sample entropy estimate of 0. Additionally, underlying physical processes are optimally apparent at different levels of $m$. If the value of $m$ is too low, these processes may go undetected (Lake et al., 2002). Selecting appropriate values of the input parameters $m$ and $r$ demands a thorough understanding of the system under scrutiny.
Once values of $m$ and $r$ have been selected, the sample entropy analysis can be completed. A smaller sample entropy value reflects a high likelihood that sets of matching data in the COP time series will be followed by another match (within the pre-determined distance, $r$); a larger COP sample entropy value reflects highly irregular data, wherein matching set of points are likely followed by samples of different values (If $-\ln(B/A) = 1$, $\text{SEn} = 0$; if $-\ln(B/A) = 0$, $\text{SEn} \to \infty$).

Based on the history of parameter settings in postural control research (e.g., Donker et al., 2008), both the AP and ML COP time series were analyzed using a match length $m = 3$ and a tolerance $r = 0.2$ in the present study. Sample entropy estimates were averaged across trials per condition for each participant and submitted to ANOVA with group and the various repeated measures (foot position, task vs. no task, task moderators) as independent factors.