GREATER POSTURAL INSTABILITY AFTER TAKING A STEP IN CHILDREN WITH CEREBRAL PALSY

By

KATELYN SUE CAMPBELL

(Under the Direction of Christopher M. Modlesky)

ABSTRACT

PURPOSE: The aim of this study was to determine if children with cerebral palsy (CP) exhibit deficits in postural recovery after taking a step. **METHODS:** Children with spastic hemiplegic CP (n = 9) and typically developing (TD) children (n = 14) were recruited. Step recovery was divided into dynamic and static phases using ground reaction force. Center of pressure measures were used to determine postural stability. **RESULTS:** After taking a step, children with CP compared to TD children spent ~50 % more time in the more unstable, dynamic phase of step recovery. While in the dynamic phase, center-of-pressure measures suggest the children with CP were less stable than the TD children, especially in the more affected limb (MAL). Although there was some residual instability during the static phase, the differences were less pronounced and limited to the less affected limb (LAL). **CONCLUSION:** Children with hemiplegic CP compared to TD children take more time to recover after taking a step and are more unstable during the recovery process, especially during the dynamic phase in the MAL.

INDEX WORDS: cerebral palsy, hemiplegic, step recovery, center of pressure, sample entropy, velocity

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CHAPTER 1

INTRODUCTION

Cerebral palsy (CP) is a permanent movement disorder affecting posture and muscle tone that is a result of disturbances in the infant or fetal brain (Bax et al., 2005; Rosenbaum et al., 2007). Approximately 3.0 to 3.6 per 1000 children have CP, making it one of the most common causes of motor disability in children (Arneson et al., 2009; Centers for Disease Control and Prevention, 2004; Christensen et al., 2014; Kirby et al., 2011; Yeargin-Allsopp et al., 2008).

Cerebral palsy can be classified by motor type: spastic, dyskinetic, hypotonic, or ataxic. Spasticity is the most prevalent (Arneson et al., 2009) and is often in combination with one of the other types (Paneth, 2008). Spasticity is characterized as a velocity-dependent, increased resistance to stretch (McIntyre, Morgan, Walker, & Novak, 2011) and reflexes which often make movements appear stiff or jerky (Cans et al., 2007). Cerebral palsy can also be classified by topography, or which areas of the body it affects. Hemiplegia involves only one side of the body. Typically, the upper limb is more affected than the lower limb. Diplegia involves both sides of the body, with the lower limbs being more affected than the upper limbs. Quadriplegia involves both sides of the body and both the upper and lower limbs. The trunk, mouth, and face are also commonly involved in quadriplegia (McIntyre et al., 2011). Because children with hemiplegic CP are more affected on one side of their body, they exhibit reduced synchronization (Domagalska-Szopa & Szopa, 2013, 2014), pathological asymmetry, and unequal weight distribution (Domagalska, Szopa, & Lembert, 2011), which could affect postural control.

Due to the marked impact balance and postural control deficits have on the physical activity of children with CP, it is important to employ simple approaches that can be used to understand the extent of the problem and identify effective treatments. The stepping movement, which is performed numerous times through the day and is essential for daily living, is a common mechanism to restore balance and postural control after a perturbation. Studies comparing older and younger adults have revealed that simply assessing the recovery from taking a single step may provide valuable insight into postural control (Johnson, Mihalko, & Newell, 2003; Kilby, Slobounov, & Newell, 2014)Older adults, who are known to have postural deficits and increased fall risk, take longer to recover from taking a step and are less stable when completing the step. However, no studies have used step recovery to assess dynamic postural control in children with CP.

In addition to understanding the time to recover from a step, evaluating center of pressure (COP) measurements during different phases of the step recovery process would provide greater insight in the dynamic and static postural control of children with CP. A method based on ground reaction force (GRF) has been shown to effectively separate dynamic and static phases of postural control that occur during sit to stand, another important movement needed for daily living (Pavao, Santos, Oliveira, & Rocha, 2015). Employing such a technique would allow assessment of the dynamic and static phases of step recovery in children with CP and typically developing (TD) children. This information would allow us to understand the level of compromise within the different phases of the step recovery process of children with CP. Therefore, using a method proposed by Pavao et al. (2015), the current study assessed the differences between children with CP and TD children during dynamic and static postural control.

Statement of the Problem

Balance and coordination are known to be negatively impacted in children with CP. Quiet stance is a common assessment of balance and is known to be valid and reliable (Pavao, dos Santos, Woollacott, & Rocha, 2013). However, few studies have assessed postural control during step recovery, none of which were with CP, and no studies have assessed COP variables during the dynamic and static phases independently. Assessing recovery from taking a step could prove invaluable to researchers and clinicians because it may help them understand the level of deficits in postural control in children with CP. Moreover, it may uncover potential targets for assessing the effectiveness of treatments.

Specific Aim

Aim: The aim of this study was to determine if children with CP compared to their TD peers exhibit deficits in postural control during different phases of recovery from taking a step.

Hypotheses

Hypothesis 1: Children with CP compared to TD children will spend more time in the dynamic phase after taking a step.

Hypothesis 2: Children with CP compared to TD children will exhibit greater postural instability after taking a step. A more pronounced level of instability will be observed during the dynamic phase, when the stepping limb comes in contact with the floor, than during the static phase, when GRF has stabilized.

Significance of the Study

Children with CP have poor balance, placing them at high risk for falls and injury. The results of this study will have a positive impact on the methodology used to assess treatments as well as a better understanding of COP variables of the more (MAL) and less affected limb (LAL) of children with CP during the dynamic phase and the static phase of recovering after taking a step.

CHAPTER 2

LITERATURE REVIEW

Cerebral Palsy

Cerebral palsy is one of the most common causes of motor disability in children, with a prevalence of approximately 3.0 to 3.6 per 1000 children (Arneson et al., 2009; Centers for Disease Control and Prevention, 2004; Christensen et al., 2014; Kirby et al., 2011; Yeargin-Allsopp et al., 2008). It is a group of permanent disorders caused by disturbances in the infant or fetal brain that affect movement, posture, and muscle tone, often resulting in limitations in activity (Bax et al., 2005; Rosenbaum et al., 2007). These disorders are often accompanied by sensation, perception, cognition, communication, and behavior disturbances as well as other comorbidities such as epilepsy (Bax et al., 2005; Rosenbaum et al., 2007). Cerebral palsy is often diagnosed within the first few years of life with developmental delays becoming apparent within that time.

Although the initial disturbances to the brain are non-progressive, development of secondary conditions that affect function may occur over time (National Guideline Alliance (Great Britain), 2017). Children with CP typically have one or more of the following motor type classifications: spasticitic, dyskinesic, hypotonic, or ataxic (Paneth, 2008). Unsurprisingly, most combinations include spasticity (Paneth, 2008), as spastic CP is by far the most prevalent (Arneson et al., 2009; Christensen et al., 2014; Kirby et al., 2011; Paneth, 2008; Yeargin-Allsopp et al., 2008). Spasticity is caused by damage to the motor cortex and is characterized as a velocity-dependent, increased resistance to stretch due to increased muscle tone (McIntyre et al.,

2011; Paneth, 2008) and reflexes (Cans et al., 2007) which often makes movements appear stiff or jerky. When the muscles of children with this type of CP are moved, a spastic catch can be felt after the onset of movement (Cans et al., 2007). In the lower limbs, spasticity often causes internal rotation and adduction of the hips which can lead to the flexed posture and pigeon-toed gait commonly seen in CP (Paneth, 2008).

In addition to motor type classification, children with CP can also be classified by topography which includes: hemiplegia, diplegia, and quadriplegia. Hemiplegia involves only one side of the body, with the upper limb typically more affected than the lower. Diplegia involves both sides of the body, with the lower limbs being more affected than the upper limbs. Quadriplegia involves both sides of the body and both upper and lower limbs; often affecting the trunk, mouth, and face as well (McIntyre et al., 2011). Because of these topographies, children with CP, especially those with hemiplegia, may have a more and less affected limb causing reduced synchronization and differences in weight-bearing between the limbs (Domagalska-Szopa & Szopa, 2013, 2014).

Motor Function (GMFCS)

Motor function deficits in children with CP include delay of motor development, slower gait speed, greater physiological cost, lower endurance during walking, and abnormal movement pattern (Bobath & Bobath, 1975). Postural control has a direct relationship with the level of functionality and dependence on a caregiver in children with CP (Pavao, Nunes, Santos, & Rocha, 2014). The impact of CP on daily life is dependent upon severity which is classified using the Gross Motor Function Classification System (GMFCS). The GMFCS has been observed to be a valid and reliable tool for prognosis (Bodkin, Robinson, & Perales, 2003;

Palisano et al., 1997). The GMFCS ranges from Level I (least severe) to Level 5 (most severe). Level I indicates that the child can walk and climb stairs independently and can perform gross motor skills, but speed, balance, and coordination are reduced. Level II indicates that the child can walk independently, with limitations on uneven surfaces and in confined spaces, and climb stairs with the assistance of a hand railing. The ability to perform gross motor skills is drastically reduced. Level III indicates the ability to walk with the assistance of a mobility device and climb stairs using a hand railing. If the upper limb is not highly affected, they can manually propel a wheelchair. Individuals classified as Level IV rely more on wheeled mobility via a powered wheelchair. Level V individuals have limited motor function in all areas with limitations in sitting and standing, and little to no means of independent mobility. Some children classified as Level V can reach independent mobility through highly modified powered wheelchairs (Palisano et al., 1997). The majority of CP cases are classified as Level I and II (Himmelmann, Beckung, Hagberg, & Uvebrant, 2006).

Postural Control

Because the majority of a human's body mass is located far from the ground, we are naturally an unstable system that requires the postural control system to act continuously to maintain stability (D. A. Winter, 1995). Postural control is typically assessed using COP measurements during static standing, though it can also be assessed during static sitting or dynamic functional activities (Pavao et al., 2013). Tools used to assess static standing posture can include force platforms, electromyography, infrared emitters, and magnetic tracking (Pavao et al., 2013).

Center of pressure is the location of the vertical GRF vector found by taking a weighted average of all of the pressures exerted over the surface in contact with the ground (D. A. Winter, 1995). Center of pressure provides a representation of how the ankle muscles are maintaining stability. While standing feet side by side, movement in the anterioposterior (AP) direction is controlled primarily using an ankle strategy which involves the plantarflexors and dorsiflexors; whereas movement in the mediolateral (ML) direction is under the control of a hip load/unload strategy using the hip abductors and adductors (D. A. Winter, 1995; D. A. Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998).

The inverted pendulum model states that the center of mass is controlled by the COP, where the difference of the COP and center of mass is directly proportional to the horizontal acceleration of the body (D. A. Winter, 1995; D. A. Winter et al., 1998). The center of mass accelerates in the direction opposite of the location of the COP during gait (D. A. Winter et al., 1998). For instance, if the COP is located in front of the center of mass, the center of mass will be accelerated backward and vice versa. If COP is located to the right, center of mass accelerates to the left. The movement of COP regulates the center of mass by imposing torques to restore stability of the system (D. A. Winter et al., 1998). These torques are determined by joint stiffness by means of muscle tone controlled by the central nervous system (D. A. Winter et al., 1998). In other words, COP is the neuromuscular response of the body to correct imbalances in the center of mass (D.A. Winter, 1990).

Quiet Standing in Children with Cerebral Palsy

Standing requires the continual re-establishment of equilibrium, defined as the balance of forces and moments acting on the body (Iqbal, 2011), by maintaining the center of mass within

the base of support which requires continual feedback from multiple systems including the visual and somatosensory systems. Maintaining this equilibrium can prove challenging for children with CP, as standing is the position most intensely susceptible to destabilizing forces (Pavao et al., 2014). Children with CP are unable to coordinate the activation of postural muscles in the correct sequence with co-activation of muscles sometimes occurring (Brogren, Hadders-Algra, & Forssberg, 1998; Nashner, Shumway-Cook, & Marin, 1983; Woollacott et al., 1998) due to interactions between the sensory system, central nervous system, and musculoskeletal system being affected (Woollacott & Shumway-Cook, 2005). Musculoskeletal constraints may include a crouched posture and a reduced range of motion, which could contribute to balance problems (Woollacott et al., 1998). In addition to this change in the order of muscle recruitment, loss of interarticular coordination is a common neuromotor deficit seen in children with CP (Nashner et al., 1983).

Nearly all musculoskeletal disorders, including CP, are associated with poor balance and coordination; however, the central nervous system may adapt to these deficits by compensating with another system (D. A. Winter, 1995). Improvements in postural control in children with CP are vital, as postural control is an integral part of all motor abilities and its improvement could lead to improvements in function for the child (Ferdjallah, Harris, Smith, & Wertsch, 2002). Therefore, clinical assessments of postural control in children with CP could prove valuable to researchers and clinicians.

Domagalska-Szopa and Szopa (2013, 2014) studied weight-bearing between the MAL and LAL of children with CP and described the progravitational and antigravitational postural patterns associated with hemiplegic CP. A progravitational postural pattern describes children that typically overload the MAL while an antigravitational postural pattern describes children

with a tendency to overload the LAL, therefore under loading the MAL (Domagalska-Szopa & Szopa, 2013, 2014). In a later study, the authors observed poorer postural stability in children with CP that favored the antigravitational postural pattern (Szopa & Domagalska-Szopa, 2015). The authors suggested that the decreased postural stability was probably due to the increased weight bearing asymmetry, pelvic hike on the MAL, and excessive plantar flexion observed in the group with the antigravitational postural pattern (Szopa & Domagalska-Szopa, 2015).

Children with CP exhibit greater (Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008; Rose et al., 2002) and more regular sway (Donker et al., 2008), as symbolized by increased mean sway amplitude, than TD children, suggesting reduced postural stability during quiet standing. Sway path length is also reduced in children with CP, suggesting less twisting and turning during quiet standing (Donker et al., 2008). Children with CP have been shown to have lower sample entropy values (Donker et al., 2008), which is a measure of randomness. An increased regularity in COP trajectories is a trademark of poor postural control. This increased regularity in COP trajectories is consistent with findings from research done in stroke patients (Roerdink et al., 2006), patients with Parkinson's disease (Schmit et al., 2006), and athletes with concussions (Cavanaugh, Guskiewicz, & Stergiou, 2005).

Higher mean velocities of oscillation have been observed in children with CP while standing and negatively correlate with dependence on a caregiver (Pavao et al., 2014). Velocity of oscillation is a primary predictor of stability in postural control. Velocities of oscillation inversely correlate with body control during standing suggesting increased velocities reflect reduced postural control (Pavao et al., 2014). With the majority of functional self-care tasks performed while standing (i.e. brushing teeth, combing hair, bathing, and dressing) (Pavao et al., 2014), reduced postural control may significantly impact functional ability and dependence on a

caregiver. An increased dependence on a caregiver could negatively impact social interactions with people outside of their family and caregiver (Pavao et al., 2014).

Ankle and hip control synergies are altered in children with CP (Ferdjallah et al., 2002) primarily due to reduced range of motion and contractures of the hip, knee, and ankle muscles (Domagalska et al., 2011). Because of this alteration in ankle and hip control synergies, children with CP may prefer limb protraction/retraction contribution compared to a TD children, as it requires less muscular effort than ankle control. This idea was supported by Ferdjallah et al. (2002), who observed increased limb protraction/retraction contribution in the AP direction in children with CP, likely due to poor ankle control. In addition, Pavao et al. (2014) observed that children with CP, 7 hemiplegic and 3 diplegic, exhibit larger ML displacements during quiet standing suggesting the use of a hip strategy instead of the ankle strategy seen in TD children, further insinuating poor ankle control and ability to activate the ankle muscles in children with CP. Rojas et al. (2013) observed larger ML displacement in diplegic compared to hemiplegic children. This larger ML displacement is associated with increased dependence on a caregiver (Pavao et al., 2014); whereas AP displacement, often thought essential for maintaining postural control during standing, does not significantly correlate with dependence on a caregiver, suggesting that a higher dependence on the hip strategy to adapt may be an indicator of lower functional ability (Pavao et al., 2014). Maki, Holliday, and Topper (1991) reported similar findings in an elderly population with increased ML sway being the best predictor of fall risk.

Rose et al. (2002) reported that children with diplegic CP had decreased postural stability during the eyes closed condition compared to the eyes-open condition. Similarly, TD children also had decreased stability during the eyes-closed condition; therefore, decreased postural stability during eyes-closed is not unique to the CP disorder. There were no significant

differences between CP and TD children during the eyes-closed condition, suggesting that children with CP typically have a normal dependence on visual information to maintain stability (Rose et al., 2002). The observations of Rose et al. (2002) suggest that if children with CP are compensating for musculoskeletal and neuromotor dysfunction, they are not doing so with the ocular system. This observation appears to be contradicted by Ferdjallah et al. (2002) who reported that the elimination of visual information increased hip and ankle balance strategies in children with diplegic CP, suggesting that children with CP may compensate for their postural deficits with visual information. Because of these contradictory findings, more research should be done on COP measures in the absence of visual information in children with CP. Furthermore, the relationship between postural stability and vision should be examined in children with other types of CP.

Step Recovery in Children with Cerebral Palsy

The goal during quiet stance is to maintain postural stability while keeping the center of mass within the base of support. On the other hand, the goal during stepping is to maintain dynamic stability, while moving the center of mass outside of the base of support, to prevent falling. While recovering from a step, the center of mass must return inside of the base of support and regain static stability through the absorption of mechanical energy by the plantar flexors (D. A. Winter, 1995). Stabilization after stepping may be more difficult for children with CP than for TD children. The central nervous system, which is damaged in children with CP, needs to predict the future position of the center of mass (D. A. Winter, 1995). Like many elderly patients, children with CP may overshoot or undershoot the final center of mass position while attempting to regain stability (D. A. Winter, 1995).

Notable studies assessed step recovery in older adults. Johnson et al. (2003) assessed time to recovery and Kilby et al. (2014) assessed the recovery of postural stability from taking a step in an aging population. Compared to young adults, older adults took longer to recover from a step (Johnson et al., 2003), were slower to step, had decreased initial stability, and a decreased stabilization rate (Kilby et al., 2014). However, there were no differences between groups in the level of recovered postural stability (Kilby et al., 2014).

Though no other studies specifically addressed step recovery, Nashner et al. (1983) showed that children with CP display difficulties in the timing of their muscle responses including delayed ankle contraction, proximal-to-distal muscle response sequence, and co-contraction of the agonist and antagonist muscles. These atypical responses could lead to a reduced ability to recover postural stability. The crouched posture typically observed in children with CP may also contribute to a decreased ability to recover balance, signified by a longer time to recover and increased sway (Woollacott & Shumway-Cook, 2005). To test this theory, Burtner, Qualls, and Woollacott (1998) had TD children stand in a crouched posture and then measured their neuromuscular responses to slipping. The TD children demonstrated increased co-contraction of agonist and antagonist muscles and a more proximal-to-distal muscle response pattern, suggesting that the balance of children with CP may be greatly affected by their musculoskeletal alignment (Burtner et al., 1998; Woollacott et al., 1998).

No studies have assessed how children with CP recover from taking a step and how leading with the MAL or LAL may affect the step recovery process. A similar task done in research that could provide insight into the recovery from taking a step includes planned gait termination, though gait termination typically involves multiple steps and repeatedly moving the center of mass outside of the base of support. Because step recovery is gait initiation followed by

immediate planned gait termination, it is likely that the center of mass does not go outside of the base of support to the same degree. Many gait termination studies focused on the trajectory of the center of mass instead of COP measurements. Center of mass-COP inclination angles are defined as the angles formed by the intersection of the line connecting the COP and center of mass and a vertical line extending from the COP (Feng, Pierce, Do, & Aiona, 2014). Feng et al. (2014) observed smaller peak ML and posterior center of mass-COP inclination angles in the children with hemiplegic CP than in TD children when the MAL trailed, but not when the MAL lead the step. The difference in peak posterior inclination angles of the MAL and LAL during gait could translate to differences in COP measurements between the MAL and LAL while recovering from a step. Center of pressure measurements may change depending on whether the MAL or LAL is the stepping.

Because step recovery is dynamic at the onset of the task and static at the end, it could prove beneficial to assess this task in two parts. Though no one has done this in step recovery, a similar method has been done in children with CP during sit to stand. Pavao et al. (2015) assessed postural control during the dynamic (during sit to stand movement) and static (during static standing position) phases of sit to stand. The sit-to-stand movement was divided into 2 dynamic phases (preparation and rising) and 1 static phase (stabilization). The preparation phase began when vertical GRF decreased by more than 2.5% of the weight of the feet on the platform and ended when peak vertical GRF was reached. The rising phase began at peak vertical GRF and ended when vertical GRF reached body weight. The stabilization phase began when vertical GRF reached body weight and ended when vertical GRF oscillation reached approximately 2.5% of the body weight. Relative to TD children, children with CP exhibited higher AP and ML COP displacement amplitude, COP oscillation area, and mean oscillation velocity during the

preparation phase (first dynamic phase), but there were no significant differences in the other two phases. The observations indicate that children with CP compared to TD children exhibit greater postural instability during the preparation phase of the sit-to-stand movement and led the authors to conclude that interventions for children with CP should focus on this phase.

Summary

This review of literature demonstrates that CP in children is associated with balance deficits, such as poor postural control and reduced stability (Woollacott & Shumway-Cook, 2005). Although many studies have assessed COP measurements in children with CP during quiet stance, few studies have assessed COP during step recovery, none of which included individuals with CP. Whether children with CP, like older adults, have difficulty recovering postural stability after taking a step is unknown. If a deficit is present, it is likely more pronounced during the dynamic phase, when recovery is beginning, than during the static phase, when recovery is ending. However, studies are needed to test this idea.

CHAPTER 3

GREATER POSTURAL INSTABILITY AFTER TAKING A STEP IN CHILDREN WITH CEREBRAL PALSY

Introduction

Cerebral palsy (CP) is group of permanent disorders caused by disturbances in the infant or fetal brain (Bax et al., 2005; Rosenbaum et al., 2007) with a prevalence of approximately 3.0 to 3.6 per 1000 children, making CP one of the most common causes of motor disability in children (Arneson et al., 2009; Centers for Disease Control and Prevention, 2004; Christensen et al., 2014; Kirby et al., 2011; Yeargin-Allsopp et al., 2008). Because delays in development become apparent within the first few years of life, most diagnoses are within that time. Cerebral palsy affects movement, posture, and muscle tone with disturbances to sensation, perception, cognition, communication, and behavior (Bax et al., 2005; Rosenbaum et al., 2007). Due to the effects of the disorder, CP often results in low levels of physical activity. Hemiplegic CP is the most common form of the disorder. One side of the body in children with hemiplegic CP is primarily affected (McIntyre et al., 2011), causing a reduced synchronization (Domagalska-Szopa & Szopa, 2013, 2014), pathological asymmetry, and unequal weight distribution during standing (Domagalska et al., 2011).

Due to the disturbances in the brain, interactions between the sensory system, central nervous system, and musculoskeletal system are impaired in individuals with CP (Brogren et al., 1998; Nashner et al., 1983; Wolff et al., 1998) causing poor coordination of the activation of postural muscles and co-activation of the agonist and antagonist muscles (Woollacott & Shumway-Cook, 2005). Because of this, children with CP often have deficits in balance and

coordination affecting physical activity and functional ability (Ferdjallah et al., 2002); therefore, employing approaches to better understand the problem and identify treatments is pivotal.

The stepping movement, which is performed numerous times through the day and is essential for daily living, is a common mechanism to restore balance and postural control after a perturbation. Hence, studying the ability to recover from taking a step may provide valuable insight into postural control of children with CP. Older adults, who are known to have postural deficits and an increased fall risk, take longer to recover from step and are less stable during the step recovery process. However, recovery and stability during a step has not been assessed in children with CP.

If children with CP take longer to recover from taking a step and if they are less stable during the recovery compared to TD children, it is plausible that the instability is more pronounced during the dynamic phase of the process. A method by Pavao et al. (2015) based on GRF has been shown to effectively separate the dynamic and static phases of the sit to stand movement. Using this method to assess step recovery could also provide insight into where within the task is most affected by the disorder, which could become a target for intervention. A test assessing COP measurements within the dynamic and static phases of the step recovery task in children with CP, could provide invaluable information about postural control in children with CP during a task that is essential for daily living and performed numerous times throughout the day. Therefore, the aim of this study was to determine if children with hemiplegic CP compared to their TD peers exhibit deficits in postural control during different phases of recovery from taking a step.

Methods

Participants

Ambulatory children with spastic hemiplegic CP and TD children age 5 to 11 years old were recruited for this study. Children with CP were recruited from the Children's Healthcare of Atlanta, public schools throughout the state of Georgia, and pediatric rehabilitation offices throughout the southeast region of the United States as part of a randomized controlled trial examining the effect of a high-frequency, low-magnitude vibration intervention on muscle, physical activity, and balance in children with CP. Typically developing children who were similar in sex, race, and age to the children with CP were recruited from Athens and Atlanta Georgia, and surrounding communities. Recruitment was conducted through the use of flyers, postcards, and word of mouth.

Parents or guardians provided informed consent forms before the participation of their child in the study. Exclusion criteria included prior fracture in both femurs or tibias, currently taking bisphosphonates, unable to stand independently, orthopedic surgery within the last six months, children with pure athetoid CP, baclofen pump in the abdomen, and botulinum toxin treatment within the last year.

Anthropometrics

Participants' height and weight were measured while the children were wearing minimal clothing and without shoes or braces. Height was taken while standing using a stadiometer to the nearest 0.1 cm. Body mass was measured using a digital scale (Detecto 6550, Cardinal Scale, Webb City, MO) to the nearest 0.1 kg.

Sexual Maturation

Sexual maturity for each participant was assessed by their parent using the Tanner staging technique (Tanner, 1962). Signs of pubic hair and breast development were assessed in girls and pubic hair and testicular/penis development were assessed in boys. Ratings ranged from I to V, with I indicating no signs of sexual development and V indicating full development.

Gross Motor Function

Gross motor function was assessed by a healthcare professional using the GMFCS. The classification system ranges from I to V. A classification of GMFCS I and II are independently ambulatory, but have a reduced gait speed; GMFCS III achieve mobility through the use of assistive walking devices; and GMFCS IV and V achieve mobility through the use of a wheelchair (Palisano et al., 1997). This study included children classified as GMFCS I or II.

Step Recovery

Force platform data were collected using two adjacent strain gauge force platforms (Bertec, Columbus, OH, 100 Hz) that were the same level as the ground. Participants were instructed to stand quietly, with one foot on each platform for 30s with their eyes open. Participants stood quietly with their hands by their sides and focused on an "X" that was placed on the wall at eye level 4.5m in front of them. Three successful trials were collected and the first 5s of each trial were cut and the remaining 25s were analyzed.

After quiet stance testing was complete, participants were asked to step forward onto the force platforms with one foot on each platform and then stand quietly with their hands by their sides focusing on the "X" for 20s after the step. Participants were instructed to take a normal

step. Three trials were completed with the children with CP leading with their MAL and the TD children leading with their nondominant limb.

Data were assessed beginning at initial contact with the force platform for each foot. All data were processed using a custom Matlab script (R2018b, Mathworks, Inc., Natick, MA). Step recovery data was divided into two phases deemed the “Dynamic Phase” and “Static Phase”. A GRF peak to trough difference was calculated during quiet stance and an average was taken between three trials. The acceptable static range during step recovery was then determined using this average peak to trough difference plus and minus 2 standard deviations for each limb. The beginning of the static phase was defined as the moment when the GRF peak to trough difference returned to the range determined for each participant in quiet stance for at least 3s. The beginning of those 3s was considered the start of the static phase. The dynamic phase was from initial contact to the start of the static phase and the static phase consisted of the 5s immediately succeeding the dynamic phase, to minimize the potential effect of boredom. Figure 1 shows GRF during quiet stance and the two phases of step recovery.

Frequency analyses were run to determine cutoff frequencies. A 5 Hz 4th order zero-lag Butterworth lowpass filter was used to filter quiet stance data and step recovery data to find the static phase and to match the quiet stance data they were being compared to. However, after the locations of each stage was found using the 5 Hz step recovery data, raw step recovery data were filtered using an 8 Hz 4th order zero-lag Butterworth lowpass filter. Ground reaction force and linear (i.e., sway distance and sway velocity) and nonlinear (i.e., sample entropy (SampEn)) COP variables were calculated in both the AP and ML directions for each limb during quiet stance, the dynamic phase of step recovery, and the first 5s of the static phase of step recovery. Linear COP

measures were calculated according to Prieto, Myklebust, Hoffmann, Lovett, and Myklebust (1996). Data from the three trials were averaged.

Statistical Analysis

Statistical tests were performed using IBM SPSS Statistics 25 (IBM Corp, Armonk, NY). Normality was assessed using skewness and kurtosis. Values less than 2 in both skewness and kurtosis were considered normally distributed. Paired sample t-tests, Pearson's correlations, scatter plots, and Bland-Altman plots were used to determine if there were differences in GRF in the static phase after taking a step and GRF in quiet stance, which would indicate whether if the static phase was accurately determined. Independent samples t-tests and Mann-Whitney U tests were used to determine if there were group differences in postural stability during the dynamic or static phases of step recovery, as reflected by differences in COP variables between children with CP and TD children. Alpha level was set at 0.05 and all tests were 2-tailed. The magnitude of the effects was determined using Cohen's d (d = mean difference between groups/pooled SD), with 0.2, 0.5, and 0.8 representing small, moderate, and large effect sizes, respectively (Cohen, 1988).

Results

Nine children with hemiplegic CP and 14 TD children participated in the study. Their physical characteristics are reported in Table 1. Children with CP had lower height percentile than TD children (d = 1.655, $p < 0.001$), but no other differences in physical characteristics were observed ($p > 0.05$).

The GRF during quiet stance and the static phase of step recovery were not significantly different in either limb in either group (d range = 0.030 to 0.202; $p > 0.05$). They were also

strongly related in related in the MAL ($r = 0.91$, $p < 0.001$) and LAL ($r = 0.93$, $p < 0.001$) of children with CP and the nondominant ($r = 0.98$, $p < 0.001$) and dominant ($r = 0.97$, $p < 0.001$) limbs of TD children, and demonstrated strong agreement, as indicated by the scatter plots and Bland-Altman plots presented in Figure 2.

Figure 3 demonstrates a longer dynamic phase in the MAL (i.e., stepping) (45%; $d = 1.021$, $p = 0.026$) and the LAL (i.e., trailing) (53 %; $d = 1.035$, $p = 0.025$) of children with CP compared to TD children. Group comparisons of COP data related to the dynamic phase of step recovery test are presented in Figure 4. Compared to TD, children with CP exhibited lower ML SampEn in the MAL ($d = 1.121$, $p = 0.017$). Children with CP also had higher AP and ML sway distance in the MAL ($d = 1.393$, $p = 0.005$ and $d = 1.213$, $p < 0.001$, respectively), and ML sway distance in the LAL ($d = 1.388$, $p < 0.001$). In addition, children with CP had higher AP and ML sway velocity in the MAL ($d = 1.045$, $p = 0.033$ and $d = 0.965$, $p = 0.007$, respectively), and higher AP sway velocity in the LAL ($d = 0.913$, $p = 0.023$).

Group comparisons of COP data related to the static phase of step recovery test are presented in Figure 5. Compared to TD children, children with CP exhibited higher ML sway distance in the MAL, but the difference was not statistically significant ($d = 1.051$, $p = 0.088$). Children with CP exhibited significantly higher AP and ML sway distance in the LAL ($d = 1.244$, $p = 0.041$ and $d = 1.609$, $p = 0.013$, respectively). Children with CP exhibited higher AP sway velocity in the MAL, but the difference was not statistically significant ($d = 0.947$, $p = 0.077$).

Discussion

This is the first study to assess the recovery of postural stability after taking a step in children with CP. The primary finding was that during the dynamic phase, the period between the foot making contact with the force platform and GRF of the limb reaching a level similar to quiet stance, the children with hemiplegic CP compared to TD children had almost 50 % lower SampEn in the ML direction, and 20 to 341 % higher sway distance and sway velocity in the AP and ML directions. In addition, children with hemiplegic CP spent ~ 30 % longer in the dynamic phase. After the static phase was reached, children with hemiplegic CP had elevated AP and ML sway distance in the LAL; however, the magnitude of the elevation was smaller than observed in the dynamic phase. The results of the study indicate that children with CP exhibit considerable postural instability even with a small activity, such as taking a step, especially when taking a step with the MAL. Most of this instability is present during the dynamic phase immediately after the foot makes contact with the floor. The results of the study are important because children with CP fall more than TD children, putting them at greater risk for injuries, such as a fracture.

Previous studies have assessed time to recovery (Johnson et al., 2003), initial instability, level of recovered stability, and stabilization rate of COP and center of mass sway velocity, and virtual time to contact in an elderly population during step recovery (Kilby et al., 2014). A previous study has also assessed COP variables during the different phases of sit to stand in children with CP (Pavao et al., 2015). However, until the present study, the different phases of the step recovery process had not been evaluated in any population. The assessment of the different phases of the step recovery process in children with CP allowed us to determine where the most pronounced deficits were present.

Differences were observed between children with CP and TD children during the dynamic phase primarily in the stepping, or more affected, limb. Compared to TD children, children with CP had lower SampEn in the ML direction in the MAL suggesting an increased regularity in COP trajectories. This decreased SampEn is a trademark of poor postural control and has been observed previously in children with CP (Donker et al., 2008), stroke patients (Roerdink et al., 2006), patients with Parkinson's disease (Schmit et al., 2006), and athletes with concussions (Cavanaugh et al., 2005) during quiet stance. Decreased ML SampEn in the MAL and no difference in the LAL during step recovery suggest that children with CP have less complex, and therefore less effective, physiological control in the MAL and typical control in the LAL.

Increased sway velocity in both directions was also observed in the MAL of children with CP. This is consistent with observations during quiet stance (Pavao et al., 2014) and the first dynamic phase of sit to stand (Pavao et al., 2015). Velocity is a primary predictor of stability in postural control (Pavao et al., 2014). An increased sway velocity indicates reduced stability in children with CP during the dynamic phase of step recovery. Children with CP had an increased time in the dynamic phase in both limbs, further suggesting an increased instability during dynamic movements especially in the MAL.

The use of a semi-dynamic balance test, such as step recovery, in populations with musculoskeletal disorders like CP could be beneficial to researchers and clinicians when assessing the effectiveness of treatments. The results from the present study indicate that the step recovery test provides a robust assessment of postural stability in children with CP. In addition to detecting group differences in COP measures between children with CP and TD children, it allowed us to uncover the more pronounced deficit in the dynamic than the static phase of the

step recovery process. Further research should assess the differences in COP measurements between children with CP and TD children while the LAL is the stepping limb, in children with diplegic CP, and in the static phase in more detail.

The present study has strengths that should be highlighted. First, a method to assess COP variables in both the dynamic and static phases of the step recovery process was presented. The assessment of these two phases independently allowed for a better understanding of where during step recovery process children with CP differ from TD children. Second, only children with the hemiplegic form of CP were included in the study. It is plausible that inclusion of other types of CP would have dampened the results and reduced the likelihood of observing statistically significant results.

The present study also has limitations that need to be discussed. First, the sample size was small. However, despite this limitation, group differences were detected in several measures of postural stability indicting that the effects were large. Second, only children with hemiplegic CP were included in the study. However, this enabled a more focused study and laid the foundation for future studies involving children with other types of CP. Third, due to age and attention span, younger children were not included in the study. Lastly, the step recovery test is limited to children with CP who are ambulatory.

In conclusion, the findings suggest that children with hemiplegic CP relative to TD children spend more time during the dynamic phase of step recovery and exhibit considerable postural instability after taking a step. The greatest instability occurs during the dynamic phase of the step recovery movement. Future studies are needed to determine if this postural instability predicts their risk for falls and participation in physical activity.

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Figure Legends

Figure 1. Procedure used to assess step recovery. (Top) An acceptable ground reaction force (GRF) fluctuation range was determined during 3 trials of quiet stance. (Bottom) The ground reaction force (GRF) fluctuation range determined during quiet stance was used to determine the dynamic (A) and static (B) phases of step recovery

Figure 2. Pearson's correlations and Bland-Altman plots assessing differences in ground reaction force (GRF) during quiet stance and the static phase of step recovery of the more affected (MAL) and less affected limbs (LAL) in children with cerebral palsy (CP) and typically developing (TD) children.

Figure 3. Time the more affected (MAL) and less affected limbs (LAL) spent in the dynamic phase of step recovery in children with cerebral palsy (CP) and typically developing (TD) children. Values are means ± SE.

Figure 4. Sample entropy (SampEn; A), sway distance (B), and sway velocity (C) in the anteriorposterior (AP) and mediolateral (ML) directions in the more affected (MAL) and less affected limbs (LAL) of children with cerebral palsy (CP) and typically developing (TD) children during the dynamic phase of step recovery. Values are means ± SE.

Figure 5. Sample entropy (SampEn; A), sway distance (B), and sway velocity (C) in the anteriorposterior (AP) and mediolateral (ML) directions in the more affected (MAL) and less

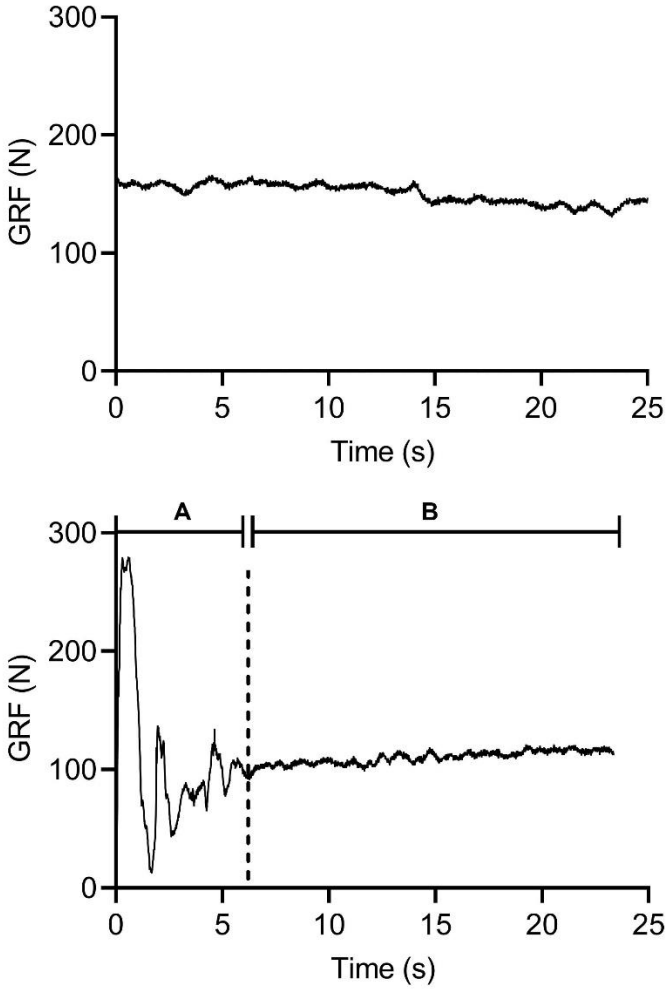
affected limbs (LAL) of children with cerebral palsy (CP) and typically developing (TD) children during the static phase of step recovery. Values are means ± SE.

Table 1. Physical characteristics of children with cerebral palsy (CP) and typically developing (TD) children

	CP (n = 9)	TD (n = 14)
Age (y)	8.9 ± 1.7	8.6 ± 2.0
Tanner stage (I/II/III/IV/V)		
Pubic hair	8/1/0/0/0	13/0/0/1/0
Breast/testicular	6/3/0/0/0	13/1/0/0/0
Height (m)	1.27 ± 0.100	1.32 ± 0.142
Height (%)	21.2 ± 13.7*	61.0 ± 30.7
Body mass (kg)	26.5 ± 5.1	30.5 ± 11.5
Body mass (%)	36.6 ± 25.0	54.8 ± 32.6
BMI (kg/m^2)	16.4 ± 2.1	16.8 ± 3.3
BMI (%)	46.9 ± 33.7	49.0 ± 36.1
GMFCS (I/II)	8/1	

Values are mean ± SD; % for height, body mass, and BMI reflect the percentile relative to age- and sex-based norms; GMFCS = gross motor function classification system. *Group difference, $p < 0.05$

Figure 1.


300
200
100
0
GRF (N)
0
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10
15
20
25
Time (s)
A
B
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GRF (N)
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Time (s)

Figure 2.

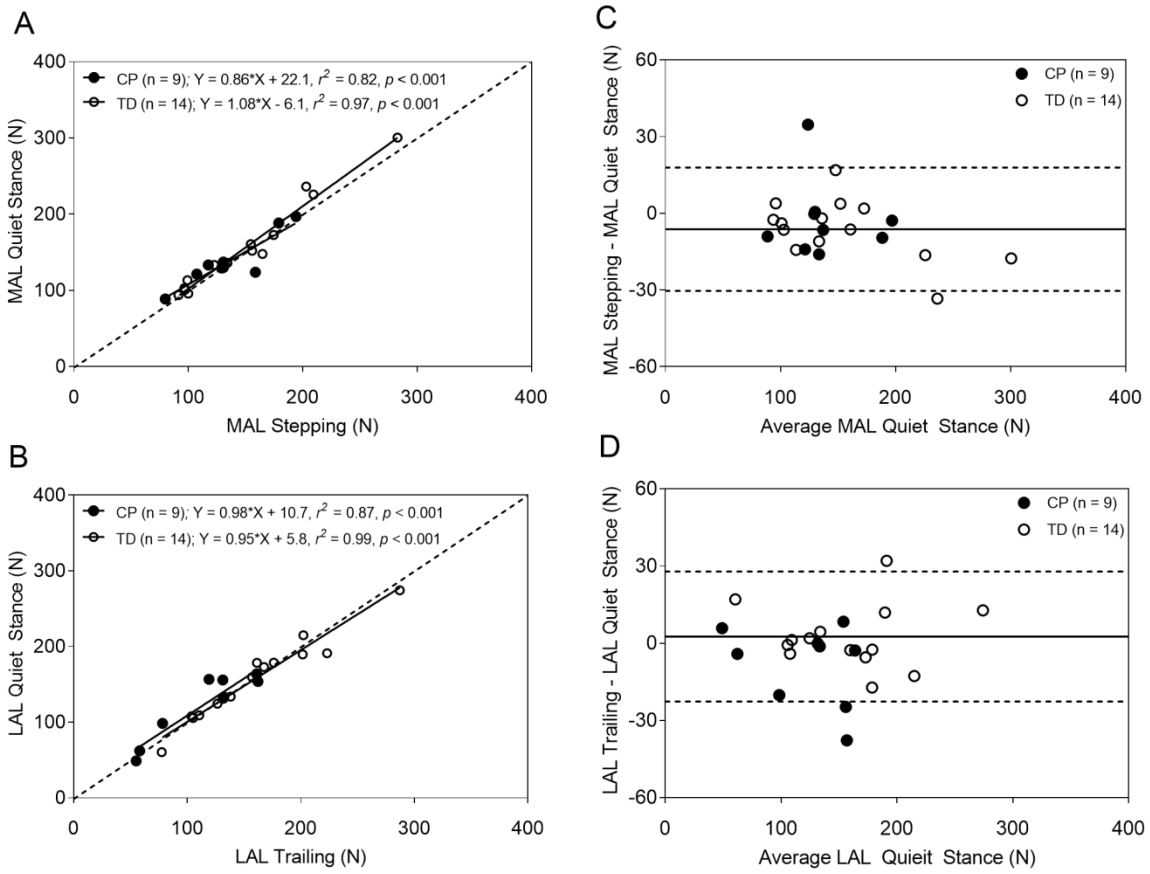

A
CP (n = 9); Y = 0.86*X + 22.1, r^2 = 0.82, p < 0.001
TD (n = 14); Y = 1.08*X - 6.1, r^2 = 0.97, p < 0.001
MAL Quiet Stance (N)
MAL Stepping (N)
B
CP (n = 9); Y = 0.98*X + 10.7, r^2 = 0.87, p < 0.001
TD (n = 14); Y = 0.95*X + 5.8, r^2 = 0.99, p < 0.001
LAL Quiet Stance (N)
LAL Trailing (N)
C
CP (n = 9)
TD (n = 14)
MAL Stepping - MAL Quiet Stance (N)
Average MAL Quiet Stance (N)
D
CP (n = 9)
TD (n = 14)
LAL Trailing - LAL Quiet Stance (N)
Average LAL Quieit Stance (N)

Figure 3.

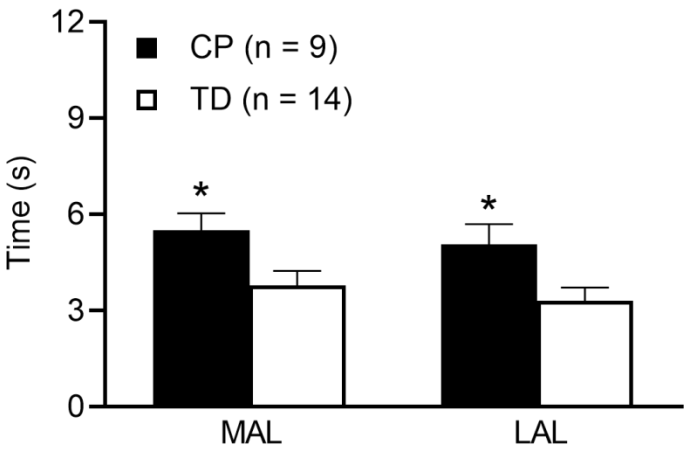


Figure 4.

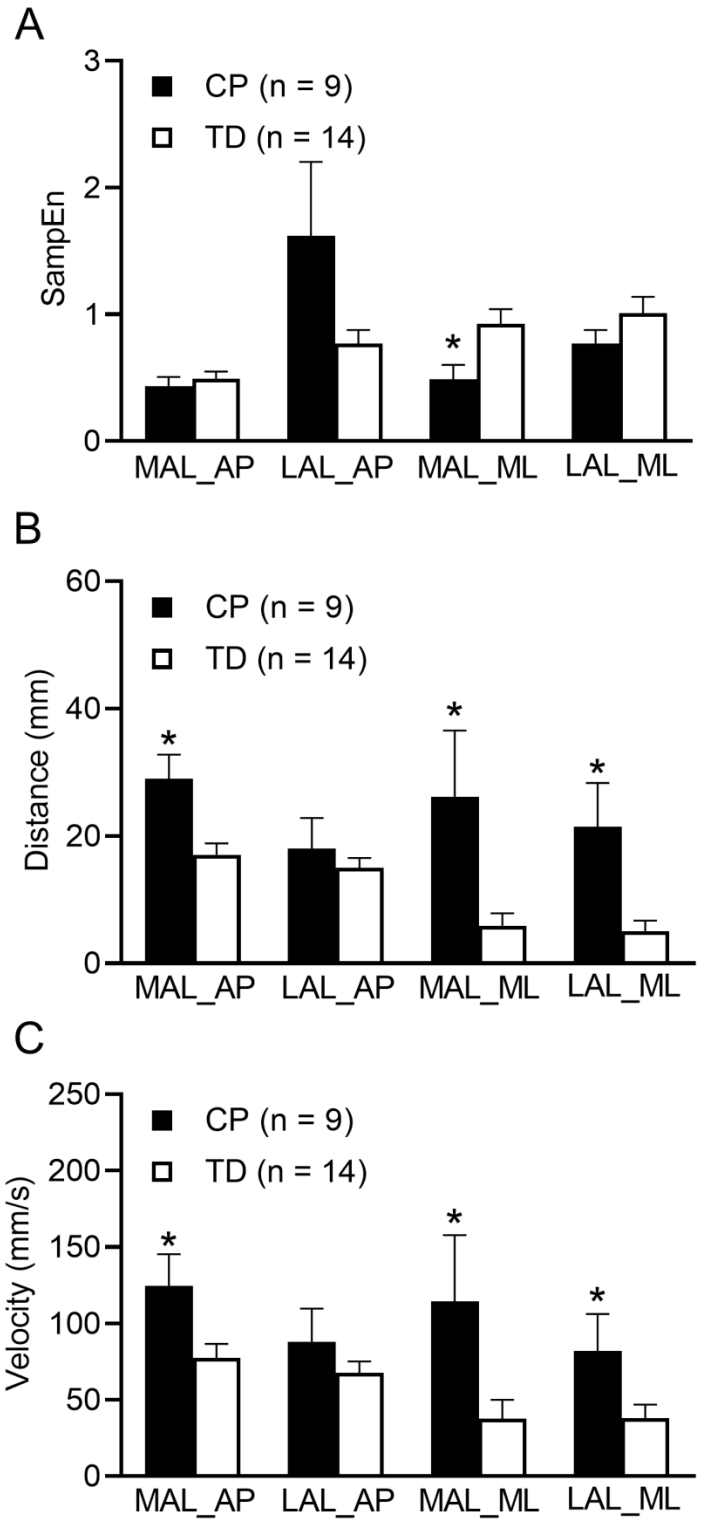
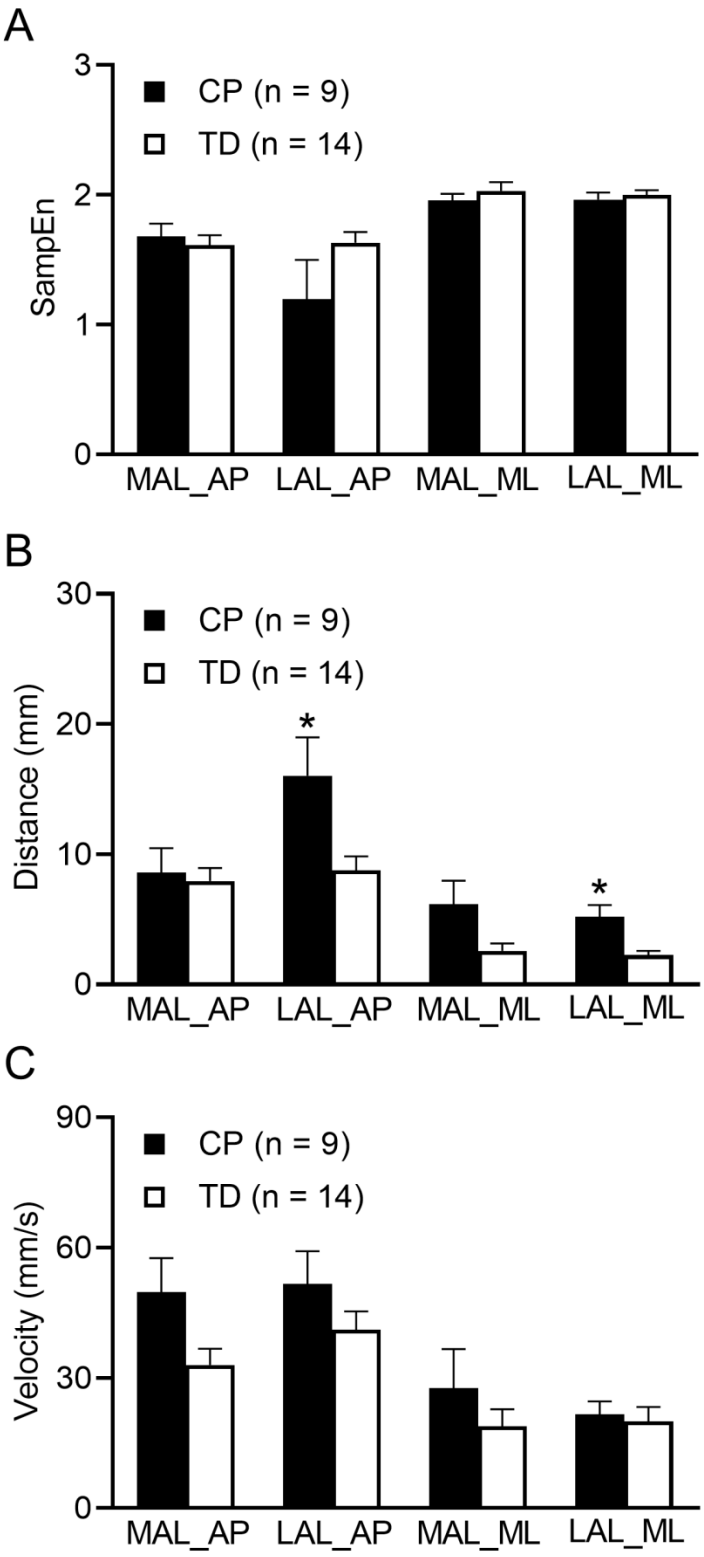

A
CP (n = 9)
TD (n = 14)
SampEn
3
2
1
0
*
MAL_AP
LAL_AP
MAL_ML
LAL_ML
B
CP (n = 9)
TD (n = 14)
Distance (mm)
60
40
20
0
*
*
*
MAL_AP
LAL_AP
MAL_ML
LAL_ML
C
CP (n = 9)
TD (n = 14)
Velocity (mm/s)
250
200
150
100
50
0
*
*
*
MAL_AP
LAL_AP
MAL_ML
LAL_ML

Figure 5.


A
SampEn
3
2
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CP (n = 9)
TD (n = 14)
MAL_AP
LAL_AP
MAL_ML
LAL_ML
B
Distance (mm)
30
20
10
0
*
*
C
Velocity (mm/s)
90
60
30
0

CHAPTER 4

CONCLUSIONS AND SUMMARY

The objective of this study was to determine if children with hemiplegic CP compared to their TD peers exhibit deficits in postural control during different phases of recovery from taking a step. Force platforms were used to assess COP during quiet stance and step recovery. Step recovery was divided into dynamic and static phases. Step recovery was deemed static when GRF reached the same fluctuation range observed during quiet stance. The study determined that dividing step recovery into phases was a valid assessment as indicated by excellent agreement in GRF between quiet stance and the static phase of step recovery. After the method was validated, it was used to assess postural stability in children with hemiplegic CP.

Significant differences were observed between children with CP and TD children during the dynamic phase of step recovery, especially in the MAL. Children with CP compared to TD children exhibited lower ML SampEn in the MAL during the dynamic phase of step recovery. This lower ML SampEn indicates more regularity within the system and suggests less effective control and postural stability in the MAL during dynamic tasks. No differences were observed in the LAL indicating typical control and postural stability in that limb.

Higher sway velocity in both directions was also observed during the dynamic phase of step recovery in the MAL of children with CP compared to TD. Similar to lower SampEn, higher sway velocity indicates reduced stability in children with CP. Children with CP also spent more time adjusting during and after a step than TD children, as indicated by increased time in the dynamic phase in the MAL and LAL. An increased time to adjust further suggests an increased

instability during dynamic movements especially in the MAL of children with CP. Some residual instability was observed during the static phase, but the differences were less pronounced and limited to the LAL.

In conclusion, children with hemiplegic CP exhibit considerable postural instability after taking a step, with most deviations from TD children occurring in the dynamic phase. In addition, children with CP spend more time in the dynamic phase than TD children. The observed results are important because they provide a more focused intervention target for researchers and may have uncovered a treatment target for clinicians interested in improving postural stability in children with hemiplegic CP. Further studies should assess differences between children with CP and TD children in the static phase, while the LAL is the stepping limb, and in children with diplegic CP.

REFERENCES

1. Arneson, C. L., Durkin, M. S., Benedict, R. E., Kirby, R. S., Yeargin-Allsopp, M., Van Naarden Braun, K., & Doernberg, N. S. (2009). Prevalence of cerebral palsy: Autism and Developmental Disabilities Monitoring Network, three sites, United States, 2004. *Disabil Health J, 2*(1), 45-48. doi:10.1016/j.dhjo.2008.08.001
2. Bax, M., Goldstein, M., Rosenbaum, P., Leviton, A., Paneth, N., Dan, B., . . . Executive Committee for the Definition of Cerebral, P. (2005). Proposed definition and classification of cerebral palsy, April 2005. *Dev Med Child Neurol, 47*(8), 571-576. doi:10.1017/s001216220500112x
3. Bobath, B., & Bobath, K. (1975). *Motor development in the different types of cerebral palsy*. London: W. Heinemann Medical Books.
4. Bodkin, A. W., Robinson, C., & Perales, F. P. (2003). Reliability and validity of the gross motor function classification system for cerebral palsy. *Pediatr Phys Ther, 15*(4), 247-252. doi:10.1097/01.PEP.0000096384.19136.02
5. Brogren, E., Hadders-Algra, M., & Forssberg, H. (1998). Postural control in sitting children with cerebral palsy. *Neurosci Biobehav Rev, 22*(4), 591-596. doi:10.1016/s0149-7634(97)00049-3
6. Burtner, P. A., Qualls, C., & Woollacott, M. H. (1998). Muscle activation characteristics of stance balance control in children with spastic cerebral palsy. *Gait Posture, 8*(3), 163-174. doi:10.1016/s0966-6362(98)00032-0

7. Cans, C., Dolk, H., Platt, M. J., Colver, A., Prasauskiene, A., Krageloh-Mann, I., & Group, S. C. (2007). Recommendations from the SCPE collaborative group for defining and classifying cerebral palsy. *Dev Med Child Neurol Suppl, 109*, 35-38. doi:10.1111/j.1469-8749.2007.tb12626.x
8. Cavanaugh, J. T., Guskiewicz, K. M., & Stergiou, N. (2005). A nonlinear dynamic approach for evaluating postural control: new directions for the management of sport-related cerebral concussion. *Sports Med, 35*(11), 935-950. doi:10.2165/00007256-200535110-00002
9. Centers for Disease Control and Prevention. (2004). Economic costs associated with mental retardation, cerebral palsy, hearing loss, and vision impairment--United States, 2003. *MMWR Morb Mortal Wkly Rep, 53*(3), 57-59. doi:10.1016/S1479-3547(03)03011-2
10. Christensen, D., Van Naarden Braun, K., Doernberg, N. S., Maenner, M. J., Arneson, C. L., Durkin, M. S., . . . Yeargin-Allsopp, M. (2014). Prevalence of cerebral palsy, co-occurring autism spectrum disorders, and motor functioning - Autism and Developmental Disabilities Monitoring Network, USA, 2008. *Dev Med Child Neurol, 56*(1), 59-65. doi:10.1111/dmcn.12268
11. Cohen, J. (1988). *Statistical power for the behavioral sciences* (2nd edn ed.). Hillsdale, NJ: Lawrence ErlBaum Associates.
12. Domagalska-Szopa, M., & Szopa, A. (2013). Body posture asymmetry differences between children with mild scoliosis and children with unilateral cerebral palsy. *Biomed Res Int, 2013*, 1-7. doi:10.1155/2013/462094

13. Domagalska-Szopa, M., & Szopa, A. (2014). Postural pattern recognition in children with unilateral cerebral palsy. *Ther Clin Risk Manag, 10*, 113-120. doi:10.2147/TCRM.S58186
14. Domagalska, M. E., Szopa, A. J., & Lembert, D. T. (2011). A descriptive analysis of abnormal postural patterns in children with hemiplegic cerebral palsy. *Med Sci Monit, 17*(2), CR110-116. doi:10.12659/msm.881396
15. Donker, S. F., Ledebt, A., Roerdink, M., Savelsbergh, G. J., & Beek, P. J. (2008). Children with cerebral palsy exhibit greater and more regular postural sway than typically developing children. *Exp Brain Res, 184*(3), 363-370. doi:10.1007/s00221-007-1105-y
16. Feng, J., Pierce, R., Do, K. P., & Aiona, M. (2014). Motion of the center of mass in children with spastic hemiplegia: balance, energy transfer, and work performed by the affected leg vs. the unaffected leg. *Gait Posture, 39*(1), 570-576. doi:10.1016/j.gaitpost.2013.09.009
17. Ferdjallah, M., Harris, G. F., Smith, P., & Wertsch, J. J. (2002). Analysis of postural control synergies during quiet standing in healthy children and children with cerebral palsy. *Clin Biomech (Bristol, Avon), 17*(3), 203-210. doi:10.1016/s0268-0033(01)00121-8
18. Himmelmann, K., Beckung, E., Hagberg, G., & Uvebrant, P. (2006). Gross and fine motor function and accompanying impairments in cerebral palsy. *Dev Med Child Neurol, 48*(6), 417-423. doi:10.1017/S0012162206000922
19. Iqbal, K. (2011). Mechanisms and models of postural stability and control. *Annu Int Conf IEEE Eng Med Biol Soc, 2011*, 7837-7840. doi:10.1109/IEMBS.2011.6091931

20. Johnson, C. B., Mihalko, S. L., & Newell, K. M. (2003). Aging and the time needed to reacquire postural stability. *J Aging Phys Act, 11*, 459-469. doi:doi.org/10.1123/japa.11.4.459

21. Kilby, M. C., Slobounov, S. M., & Newell, K. M. (2014). Aging and the recovery of postural stability from taking a step. *Gait Posture, 40*(4), 701-706. doi:10.1016/j.gaitpost.2014.08.002

22. Kirby, R. S., Wingate, M. S., Van Naarden Braun, K., Doernberg, N. S., Arneson, C. L., Benedict, R. E., . . . Yeargin-Allsopp, M. (2011). Prevalence and functioning of children with cerebral palsy in four areas of the United States in 2006: a report from the Autism and Developmental Disabilities Monitoring Network. *Res Dev Disabil, 32*(2), 462-469. doi:10.1016/j.ridd.2010.12.042

23. Maki, B. E., Holliday, P. J., & Topper, A. K. (1991). Fear of falling and postural performance in the elderly. *J Gerontol, 46*(4), M123-131. doi:10.1093/geronj/46.4.m123

24. McIntyre, S., Morgan, C., Walker, K., & Novak, I. (2011). Cerebral palsy--don't delay. *Dev Disabil Res Rev, 17*(2), 114-129. doi:10.1002/ddrr.1106

25. Nashner, L. M., Shumway-Cook, A., & Marin, O. (1983). Stance posture control in select groups of children with cerebral palsy: deficits in sensory organization and muscular coordination. *Exp Brain Res, 49*(3), 393-409. doi:10.1007/BF00238781

26. National Guideline Alliance (Great Britain). (2017). In *Cerebral palsy in under 25s: assessment and management*. London: National Institute for Health and Care Excellence (UK).

27. Palisano, R., Rosenbaum, P., Walter, S., Russell, D., Wood, E., & Galuppi, B. (1997). Development and reliability of a system to classify gross motor function in children with

cerebral palsy. *Dev Med Child Neurol, 39*(4), 214-223. doi:10.1111/j.1469-8749.1997.tb07414.x

28. Paneth, N. (2008). Establishing the diagnosis of cerebral palsy. *Clin Obstet Gynecol, 51*(4), 742-748. doi:10.1097/GRF.0b013e318187081a
29. Pavao, S. L., dos Santos, A. N., Woollacott, M. H., & Rocha, N. A. (2013). Assessment of postural control in children with cerebral palsy: a review. *Res Dev Disabil, 34*(5), 1367-1375. doi:10.1016/j.ridd.2013.01.034
30. Pavao, S. L., Nunes, G. S., Santos, A. N., & Rocha, N. A. (2014). Relationship between static postural control and the level of functional abilities in children with cerebral palsy. *Braz J Phys Ther, 18*(4), 300-307. doi:10.1590/bjpt-rbf.2014.0056
31. Pavao, S. L., Santos, A. N., Oliveira, A. B., & Rocha, N. A. (2015). Postural control during sit-to-stand movement and its relationship with upright position in children with hemiplegic spastic cerebral palsy and in typically developing children. *Braz J Phys Ther, 19*(1), 18-25. doi:10.1590/bjpt-rbf.2014.0069
32. Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., & Myklebust, B. M. (1996). Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng, 43*(9), 956-966. doi:10.1109/10.532130
33. Roerdink, M., De Haart, M., Daffertshofer, A., Donker, S. F., Geurts, A. C., & Beek, P. J. (2006). Dynamical structure of center-of-pressure trajectories in patients recovering from stroke. *Exp Brain Res, 174*(2), 256-269. doi:10.1007/s00221-006-0441-7
34. Rojas, V. G., Rebolledo, G. M., Munoz, E. G., Cortes, N. I., Gaete, C. B., & Delgado, C. M. (2013). Differences in standing balance between patients with diplegic and

hemiplegic cerebral palsy. *Neural Regen Res, 8*(26), 2478-2483. doi:10.3969/j.issn.1673-5374.2013.26.009

35. Rose, J., Wolff, D. R., Jones, V. K., Bloch, D. A., Oehlert, J. W., & Gamble, J. G. (2002). Postural balance in children with cerebral palsy. *Dev Med Child Neurol, 44*(1), 58-63. doi:10.1017/s0012162201001669
36. Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., Bax, M., Damiano, D., . . . Jacobsson, B. (2007). A report: the definition and classification of cerebral palsy April 2006. *Dev Med Child Neurol Suppl, 109*, 8-14. doi:10.1111/j.1469-8749.2007.tb12610.x
37. Schmit, J. M., Riley, M. A., Dalvi, A., Sahay, A., Shear, P. K., Shockley, K. D., & Pun, R. Y. (2006). Deterministic center of pressure patterns characterize postural instability in Parkinson's disease. *Exp Brain Res, 168*(3), 357-367. doi:10.1007/s00221-005-0094-y
38. Szopa, A., & Domagalska-Szopa, M. (2015). Postural stability in children with hemiplegia estimated for three postural conditions: standing, sitting and kneeling. *Res Dev Disabil, 39*, 67-75. doi:10.1016/j.ridd.2015.01.001
39. Tanner, J. M. (1962). *Growth at adolescence, with a general consideration of the effects of hereditary and environmental factors upon growth and maturation from birth to maturity* (2d ed.). Oxford,: Blackwell Scientific Publications.
40. Winter, D. A. (1990). *Biomechanics and motor control of human movement* (2nd ed.). New York: Wiley.
41. Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & Posture, 3*(4), 193-214. doi:10.1016/0966-6362(96)82849-9

42. Winter, D. A., Patla, A. E., Prince, F., Ishac, M., & Gielo-Perczak, K. (1998). Stiffness control of balance in quiet standing. *J Neurophysiol, 80*(3), 1211-1221. doi:10.1152/jn.1998.80.3.1211

43. Wolff, D. R., Rose, J., Jones, V. K., Bloch, D. A., Oehlert, J. W., & Gamble, J. G. (1998). Postural balance measurements for children and adolescents. *J Orthop Res, 16*(2), 271-275. doi:10.1002/jor.1100160215

44. Woollacott, M. H., Burtner, P., Jensen, J., Jasiewicz, J., Roncesvalles, N., & Sveistrup, H. (1998). Development of postural responses during standing in healthy children and children with spastic diplegia. *Neurosci Biobehav Rev, 22*(4), 583-589. doi:10.1016/s0149-7634(97)00048-1

45. Woollacott, M. H., & Shumway-Cook, A. (2005). Postural dysfunction during standing and walking in children with cerebral palsy: what are the underlying problems and what new therapies might improve balance? *Neural Plast, 12*(2-3), 211-219; discussion 263-272. doi:10.1155/NP.2005.211

46. Yeargin-Allsopp, M., Van Naarden Braun, K., Doernberg, N. S., Benedict, R. E., Kirby, R. S., & Durkin, M. S. (2008). Prevalence of cerebral palsy in 8-year-old children in three areas of the United States in 2002: a multisite collaboration. *Pediatrics, 121*(3), 547-554. doi:10.1542/peds.2007-1270

APPENDIX

Table 2. Comparison of ground reaction force (GRF) during quiet stance and the static phase of step recovery

	Limb	Quiet Stance (N)	Step Recovery (N)	*d*	*p*
CP (n = 9)	MAL	138.9 ± 33.7	136.3 ± 35.7	0.074	0.626
	LAL	122.9 ± 43.0	114.4 ± 40.9	0.202	0.139
TD (n = 14)	MAL	157.1 ± 59.4	149.0 ± 55.5	0.141	0.076
	LAL	158.3 ± 52.8	159.9 ± 56.2	0.030	0.451

Values are reported as means ± SD. MAL = more affected limb; LAL = less affected limb.

Table 3. Center of pressure (COP) variables during the dynamic phase after taking a step with the more affect limb (MAL)

	CP (n = 9)	TD (n = 14)	*d*	*p*
MAL				
Time Dynamic (s)	5.5 ± 1.6	3.8 ± 1.7	1.021	0.026
AP SampEn	0.43 ± 0.21	0.49 ± 0.22	0.267	0.539
ML SampEn	0.49 ± 0.34	0.93 ± 0.43	1.121	0.017
AP Distance (mm)	29.0 ± 11.5	17.0 ± 6.7	1.393	0.005
ML Distance (mm)	26.1 ± 31.3	5.9 ± 7.2	1.213	0.000
AP Velocity (mm/s)	124.7 ± 61.8	77.5 ± 34.4	1.045	0.033
ML Velocity (mm/s)	114.2 ± 130.8	37.8 ± 46.0	0.965	0.007
LAL				
Time Dynamic (s)	5.1 ± 1.9	3.3 ± 1.6	1.035	0.025
AP SampEn	1.62 ± 1.76	0.77 ± 0.41	0.909	0.926
ML SampEn	0.77 ± 0.31	1.01 ± 0.48	0.573	0.204
AP Distance (mm)	18.0 ± 14.3	15.0 ± 5.8	0.336	0.516
ML Distance (mm)	21.4 ± 20.7	5.1 ± 6.1	1.388	0.000
AP Velocity (mm/s)	88.0 ± 65.0	67.7 ± 28.5	0.476	0.403
ML Velocity (mm/s)	82.1 ± 72.1	38.0 ± 33.1	0.913	0.023

Values are reported as mean ± SD. Children with cerebral palsy (CP) different from typically developing (TD) children. LAL = less affected limb.

Table 4. Center of pressure (COP) variables during the static phase after taking a step with the more affected limb (MAL)

	CP (n = 9)	TD (n = 14)	*d*	*p*
MAL				
AP SampEn	1.68 ± 0.30	1.61 ± 0.29	0.233	0.590
ML SampEn	1.96 ± 0.15	2.03 ± 0.26	0.340	0.446
AP Distance (mm)	8.61 ± 5.60	7.96 ± 3.65	0.146	0.740
ML Distance (mm)	6.17 ± 5.41	2.58 ± 2.13	1.051	0.088
AP Velocity (mm/s)	49.77 ± 23.46	32.97 ± 14.06	0.947	0.077
ML Velocity (mm/s)	27.70 ± 26.85	18.84 ± 14.95	0.452	0.403
LAL				
AP SampEn	1.19 ± 0.91	1.63 ± 0.31	0.805	0.198
ML SampEn	1.96 ± 0.16	2.00 ± 0.15	0.220	0.613
AP Distance (mm)	16.05 ± 8.77	8.78 ± 3.96	1.244	0.041
ML Distance (mm)	5.19 ± 2.75	2.26 ± 1.23	1.609	0.013
AP Velocity (mm/s)	51.61 ± 22.75	41.14 ± 15.57	0.570	0.203
ML Velocity (mm/s)	21.60 ± 8.88	20.03 ± 12.37	0.142	0.336

Values are reported as mean ± SD. Children with cerebral palsy (CP) different from typically developing (TD) children. LAL = less affected limb.