Summer 8-11-2020

The Effects of the Addition of a Single Session of Whole-Body Vibration to a Bout of Treadmill Walking on Gait and Lower Extremity Spasticity in Ambulatory Children with Cerebral Palsy

Gena Henderson

ACCEPTANCE

This dissertation, THE EFFECTS OF THE ADDITION OF A SINGLE SESSION OF WHOLE-BODY VIBRATION TO A BOUT OF TREADMILL WALKING ON GAIT AND SPASTICITY IN AMBULATORY CHILDREN WITH CEREBRAL PALSY, by GENA MARIE HENDERSON, was prepared under the direction of the candidate's Dissertation Advisory Committee. It is accepted by the committee members in partial fulfillment of the requirements for the degree, Doctor of Philosophy, in the College of Education & Human Development, Georgia State University.

The Dissertation Advisory Committee and the student's Department Chairperson, as representatives of the faculty, certify that this dissertation has met all standards of excellence and scholarship as determined by the faculty.

____
Jianhua (Jerry) Wu, Ph.D.
Committee Chair

____
Yu-ping Chen, PT, Sc.D.
Committee Member

____
Leslie Brandon, Ph.D.
Committee Member

____
Feng Yang, Ph.D.
Committee Member

____
Date

____
Jacalyn Lund, Ph.D.
Chairperson, Department of Kinesiology & Health

____
Paul A. Alberto, Ph.D.
Dean, College of Education & Human Development

AUTHOR'S STATEMENT

By presenting this dissertation as a partial fulfillment of the requirements for the advanced degree from Georgia State University, I agree that the library of Georgia State University shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to quote, to copy from, or to publish this dissertation may be granted by the professor under whose direction it was written, by the College of Education & Human Development's Director of Graduate Studies, or by me. Such quoting, copying, or publishing must be solely for scholarly purposes and will not involve potential financial gain. It is understood that any copying from or publication of this dissertation which involves potential financial gain will not be allowed without my written permission.

____

Gena Marie Henderson

NOTICE TO BORROWERS

All dissertations deposited in the Georgia State University library must be used in accordance with the stipulations prescribed by the author in the preceding statement. The author of this dissertation is:

Gena Marie Henderson
Department of Kinesiology & Health
College of Education & Human Development
Georgia State University

The director of this dissertation is:

Jianhua (Jerry) Wu, PhD
Department of Kinesiology & Health
College of Education & Human Development
Georgia State University
Atlanta, GA 30303

CURRICULUM VITAE

Gena M Henderson, PT, DPT, PCS

ADDRESS: 125 Decatur Street
Atlanta, GA 30303

EDUCATION:

PhD	2020	Georgia State University Department of Kinesiology & Health
DPT	2008	Belmont University School of Physical Therapy
BS	2002	Mississippi College Biology

PROFESSIONAL EXPERIENCE:

2020-present	Owner/Physical Therapist Inclusive Pediatric Therapy
2014-2019	Staff Physical Therapist Sunshine Pediatric Therapy
2014-2015	Physical Therapist II Children's Healthcare of Atlanta
2008-2013	Physical Therapist III Monroe Carell Jr Children's Hospital at Vanderbilt

PRESENTATIONS AND PUBLICATIONS:

Henderson, G. M., Ferreira, D., Wu, J. *The Effects of Direction and Speed on Treadmill Walking in Typically Developing Children.*
Manuscript in revision with Gait & Posture (June 2020)

Liang, H., **Henderson, G. M.**, Wu, J. *Neuromuscular response to a single session of whole-body vibration in children with cerebral palsy: A pilot study.*
Manuscript in revision with Clinical Biomechanics (June 2020)

Henderson, G. M., Beerse, M., Liang, H., Ferreira, D., Wu, J. (2019, October) Improvement in Overground Walking After Treadmill-Based Gait Training in a Child with Agenesis of the Corpus Callosum. Physical Therapy, 100 (1) 157-167. *https://doi.org/10.1093/ptj/pzz144.*

Henderson, G. M., Ferreira, D., Wu, J. (2019, June). *The effects of direction and speed on treadmill walking in typically developing children.* North American Society for the Psychology of Sport and Physical Activity Annual Conference, Baltimore, MD.

Beerse, M., **Henderson, G. M.**, Liang, H., Ferreira, D., Wu, J. (2019, February). Variability of spatiotemporal gait parameters in children with and without Down syndrome during treadmill walking. *Gait & Posture 68*, 2017-212.

Henderson, G. M., Beerse, M., Wu, J. (2018, February). *Changes in gait kinematics after treadmill training in a child with agenesis of the corpus callosum: A case study.* American Physical Therapy Association Combined Sections Meeting, New Orleans, LA.

Henderson, G. M., Beerse, M., Wu, J. (2017, October). *Changes in gait parameters following treadmill training in a child with agenesis of the corpus callosum: A case study.* American Congress of Rehabilitation Medicine Annual Conference, Atlanta, GA.

Wu, J., **Henderson, G. M.**, Beerse, M. (2017, June). *Spatiotemporal gait parameters in children with fragile X syndrome compared to children with and without Down syndrome: Case studies.* Southeastern Pediatric Research Conference, Atlanta, GA.

Henderson, G. M., Beerse, M., Ajisafe, T., Wu, J. (2016, November). *Variability of Foot Rotation Angle During Treadmill Walking in Children with and Without Down Syndrome.* American Physical Therapy Association's Section on Pediatrics Annual Conference, Keystone, CO.

Beerse, M., **Henderson, G. M.**, Ajisafe, T., Wu, J. (2016, August. *Spatiotemporal Pattern of Treadmill Walking in Children with and Without Down Syndrome.* American Society of Biomechanics Meeting, Raleigh, NC.

Maitre, N., **Henderson, G. M.**, Gogliotti, S., Pearson, J., Simmons, A., Wang, L., Slaughter, J. C., Key, A. (2014, June). Feasibility of Event-related Potential Methodology to Evaluate Changes in Cortical Processing After Rehabilitation in Children with Cerebral Palsy: A Pilot Study. *J Clin Exp Neuropsychol 23,* 1-11.

PROFESSIONAL SOCIETIES AND ORGANIZATIONS

2005-present	American Physical Therapy Association
2007-present	Academy of Pediatric Physical Therapy
2016-present	Academy of Physical Therapy Education
2016-present	American Physical Therapy Association Section on Research
2017-present	American Physical Therapy Association Biomechanics Special Interest Group

THE EFFECTS OF THE ADDITION OF A SINGLE SESSION OF WHOLE-BODY VIBRATION TO A BOUT OF TREADMILL WALKING ON GAIT AND SPASTICITY IN AMBULATORY CHILDREN WITH CEREBRAL PALSY

by

GENA HENDERSON

Under the Direction of Jianhua (Jerry) Wu, PhD

ABSTRACT

Single bouts of whole-body vibration (WBV) have been shown to reduce spasticity and increase active range of motion (ROM) in adults and children with cerebral palsy (CP). The effects, while transient, may provide a time window for participating in another intervention. Treadmill training is a common intervention that allows for the massed practice of walking in a controlled environment. I hypothesized that the use of WBV as a preparatory tool prior to treadmill walking may represent a more effective paradigm than using treadmill walking in isolation. This study aimed to investigate the acute effects of the addition of WBV to treadmill walking on muscle spasticity and overground walking of ambulatory children with CP. Nine children (3M/6F) with CP aged 6-17 years, Gross Motor Function Classification System (GMFCS) levels I-III participated in this study. Subjects' lower extremity spasticity and overground walking were evaluated before and after two interventions: 10 minutes of treadmill walking alone, and 12 minutes of WBV (20Hz, 2mm) followed by 10 minutes of treadmill walking.

Some subjects showed improvements after the combined intervention. However, several subjects also demonstrated improvements following the treadmill walking alone. Changes in lower extremity spasticity and overground walking parameters demonstrated high inter-subject variability. Interestingly, the inter-subject variability of response was not correlated with age, motor ability, or baseline spasticity. It was concluded that WBV may be a promising modality to reduce spasticity and improve motor function in children with CP. However, future studies are warranted to further investigate potential factors associated with the variability of response to the modality of WBV and treadmill walking more thoroughly.

INDEX WORDS: whole body vibration, treadmill training, gait, spasticity, cerebral palsy

THE EFFECTS OF THE ADDITION OF A SINGLE SESSION OF WHOLE-BODY VIBRATION TO A BOUT OF TREADMILL WALKING ON GAIT AND SPASTICITY IN AMBULATORY CHILDREN WITH CEREBRAL PALSY

by

GENA HENDERSON

A Dissertation

Presented in Partial Fulfillment of Requirements for the

Degree of

Doctor of Philosophy

in

Kinesiology

in

Kinesiology & Health

in

the College of Education & Human Development
Georgia State University

Atlanta, GA
2020

DEDICATION

To Steve Henderson, who continued to unconditionally love and support me even after he finally understood just how long this dissertation was going to take to complete.

To Corrine Vitek, who was always ready with a shoulder to cry on, a word of advice, or a much-needed distraction – and somehow always knew which one I needed, even when I didn't.

To my parents, Jerry and Sherry Priest, who worried about what this process would do to me but never stopped telling me to follow my dreams with my whole heart.

To all my friends and family, who cheered me on through this whole process.

This is for you.

ACKNOWLEDGMENTS

I would like to thank the following people, without whom the completion of this dissertation would not have been possible:

My advisor, Dr. Jerry Wu, for the guidance, mentorship, support, and infinite patience he has extended to me for the past five years.

My colleagues Diego Ferreira, Virginia Liang, Matt Beerse, and Han Kim, for their assistance with data collection and, more importantly, for their unending support and encouragement during this process.

My dear friends Dr. Ashley Schilling and Dr. Rachel Zoeller, without whose brilliant clinical minds and timely advice I would never have come this far.

All my co-workers and students at The Ellis School of Atlanta for keeping my head in the clinic and reminding me that being a clinician doesn't take time away from my research – it makes me better at it.

My committee, Dr. Yu-ping Chen, Dr. Feng Yang, and Dr. Leslie Brandon, for their insightful critiques and comments that greatly improved the quality of this manuscript.

And finally, to all the children and families who took time from their busy schedules to come and participate in this study – thank you from the bottom of my heart for your contributions to this work, because without you all it would not have been possible.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

6-MWT	6-minute walk test
CCI	Co-activation index
CDC	Centers for Disease Control and Prevention
CP	Cerebral palsy
EMG	Electromyography
GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
MAS	Modified Ashworth Scale
MVIC	Maximal voluntary isometric contraction
MTS	Modified Tardieu Scale
PBWS	Partial body-weight support
QOL	Quality of life
RI	Relaxation index
ROM	Range of motion
RMS	Root mean square
TUG	Timed Up and Go
TT	Treadmill training
WBV	Whole-body vibration

1 A REVIEW OF LITERATURE ON INTERVENTIONS TO ADDRESS LOWER EXTREMITY SPASTICITY AND WALKING ABILITY IN CHILDREN WITH CEREBRAL PALSY

Cerebral palsy (CP) is defined as “a group of permanent disorders of the development of movement and posture, causing activity limitations that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain” (Rosenbaum et al., 2007). It is the most common motor disability in childhood, with an occurrence of between 1.5 and 4 per 1,000 live births worldwide. The most common presentation of CP is spastic CP, representing approximately 80% of individuals; this form of CP is characterized by a form of hypertonia known as spasticity. Hypertonia is typically defined simply as increased muscle tone. In the context of neuromotor disease, it is best described as an increase in “the readiness with which the nervous system activates the muscle in response to stimuli” (Masi & Hannon, 2008). The presence of spasticity in CP frequently correlates with the presence of various impairments, such as muscle weakness, increased contracture development, and stereotypical gait abnormalities. Spasticity has long been considered to be the cause of these impairments in many children with CP, even though a causal relationship is not well-supported in the literature (Pandyan et al., 2005).

Although many children with CP demonstrate concurrent deficits in cognition, communication, and various sensory modalities (Palisano, Orlin, & Schreiber, 2017), motor deficits are the defining feature of this condition. Walking is frequently compromised in children with CP, although the degree of limitation can vary (Moreau et al., 2016). The functional walking abilities of children with CP are classified as one of five levels using the Gross Motor Function Classification System (GMFCS), a measure in which lower scores reflect higher motor abilities

(Palisano, Rosenbaum, Bartlett, & Livingston, 2008). Children at levels I, II, and III are all able to walk with assistive devices if necessary in a community setting, but still often require intervention to address gait abnormalities (Palisano et al., 2017). Abnormal gait and increased lower extremity spasticity have been associated with decreased participation in age-appropriate activities and social roles (Omura, Fuentes, & Bjornson, 2018), Therefore, improving ambulation abilities and decreasing the detrimental effects of spasticity typically emerge as critical goals of therapeutic intervention for children with CP.

Whole-body vibration (WBV) is a treatment technique that is rapidly gaining popularity; its use in the rehabilitation of a variety of populations, including children with neuromotor disorders, has continued to increase in recent years. Studies looking at the transient, acute effects of WBV on individuals with CP have found improvements in spasticity, dynamic and active range of motion (ROM), postural control, gait parameters, and functional measures of gait such as the Timed Up and Go (TUG) and 6-minute walk test (6-MWT) (Ahlborg, Andersson, & Julin, 2006; Cheng, Ju, Chen, Chuang, & Cheng, 2015; Cheng, Yu, Wong, Tsai, & Ju, 2015; Duquette, Guiliano, & Starmer, 2015; Ibrahim, Eid, & Moawd, 2014; Krause et al., 2017; Park, Park, Choi, Cho, & Rha, 2017; Sa-Caputo et al., 2016; Yabumoto et al., 2015). These transient effects have been reported to last from thirty minutes (Cheng, Ju, et al., 2015) up to two hours (Park et al., 2017). Studies looking at longer protocols have reported lasting effects up to three days post-cessation of treatment (Cheng, Yu, et al., 2015), although longer-term follow-up studies are still lacking.

The transient effects on spasticity are of particular interest, which is suspected to be due to a combination of the vibration reducing the sensitivity of the hyper-excitable stretch reflex and a promotion of increased reciprocal inhibition (Krause et al., 2017). It is theorized that this decrease in spasticity is responsible for some of the improvements in active and dynamic ROM, as well as some improved gait parameters, that are observed following vibration (Krause et al., 2017), given that correlations between spasticity and gait parameters have been shown to exist in this population (Choi, Park, Park, & Rha, 2018; Lotfian et al., 2016). Multiple authors have suggested that this may make WBV a promising therapeutic modality that will allow children with CP to participate more fully in exercise and functional activities immediately following vibration (Cheng, Ju, et al., 2015; Krause et al., 2017; Park et al., 2017).

Treadmill training (TT) is one of the most commonly utilized rehabilitation techniques in pediatric rehabilitation. Independent ambulation is often an important goal for many families seeking physical therapy but is nearly always delayed in children with CP (Palisano et al., 2017). Motor learning theory recognizes practice as the most important factor when learning or refining a new skill (Shumway-Cook & Woollacott, 2012). Indeed, typically developing children take over 2,000 steps per hour when learning to walk (Adolph et al., 2012)! Thus, to improve the gait patterns of children with CP, it stands to reason that they must complete substantial amounts of practice in order to be successful. The treadmill provides an efficient means to accomplish this, as the moving belt facilitates repetitive stepping in a controlled and consistent environment. In addition to providing an opportunity to practice stepping, the parameters of treadmill walking can be altered to accomplish specific goals (Damiano & DeJong, 2009). For instance, walking backward may facilitate an increased step length during forward walking (Abdel-Aziem & El-Basatiny, 2017; Kim, Ryu, Je, Jeong, & Kim, 2013), and utilizing partial body-weight support (PBWS) may increase a child's tolerance for TT, allowing for improvements in endurance (Visser, Westman, Otieno, & Kenyon, 2017). Additionally, my pilot work has demonstrated that setting a faster pace on the treadmill promotes increased dynamic ROM at the ankle in typically developing children. Thus, modulating the conditions under which a child performs treadmill walking can allow for significant amounts of practice of a new motor pattern in a controlled environment. This concept provides the basic framework for TT rehabilitation techniques, which have been frequently shown to be safe and feasible for children with CP (Damiano & DeJong, 2009; Mutlu, Krosschell, & Spira, 2009; Zwicker & Mayson, 2010).

A limitation of TT, and indeed all forms of gait training, is that it can be challenging for therapists to ensure that the training is being completed with proper form. If a child performs significant repetitions using poor form, motor learning theory states that they are merely reinforcing these poor motor patterns. Thus, to maximize the benefits of TT, stepping should be performed with as typical a pattern as possible. Since WBV has been shown to transiently decrease spasticity and normalize some gait parameters such as stride length, it stands to reason that following bouts of WBV immediately with a single treadmill walking intervention session could best utilize the transient effects of WBV to increase the effectiveness of TT. However, to date, the efficacy of this combination has not been investigated in the literature.

Guiding Question

This study aims to compare the effectiveness of two interventions (a single session of treadmill walking only, and a single session of WBV followed by a single session of treadmill walking) on acutely improving the gait pattern and lower extremity spasticity of ambulatory children with spastic CP between the ages of 6 and 17.

The central research question is:

Is a single session of WBV followed by a single bout of treadmill walking more effective than a single bout of treadmill walking alone in acutely decreasing lower extremity spasticity and improving overground gait patterns in children with CP?

Review

Cerebral palsy: overview and clinical presentation

Currently, CP is defined as "a group of permanent disorders of the development of movement and posture, causing activity limitations that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain" (Rosenbaum et al., 2007). It is the most common motor disability in childhood, with an occurrence of between 1.5 and 4 per 1,000 live births worldwide. The most common presentation of CP is spastic CP, representing approximately 80% of individuals (CDC, 2018); this form of CP is characterized by a form of hypertonia known as spasticity and typically results from an injury to the periventricular white matter during gestation (Zhou, Butler, & Rose, 2017). CP can also be classified as dyskinetic, which presents with dystonic or choreoathetoid movements and is usually the result of damage to the basal ganglia, or ataxic, which presents with ataxia and is usually the result of damage to the cerebellum (Zhou et al., 2017).

The clinical presentation of children with CP can vary wildly, depending on both the nature of their injury and its severity, but several impairments tend to be consistent across this population. Gross motor development is typically delayed, and children demonstrate difficulty with both mobility, such as crawling, creeping, and walking, and with transitional movements, such as moving in and out of sitting and standing (Palisano et al., 2017). Balance and postural control are often impaired (Woollacott & Shumway-Cook, 2005), and both muscle strength (Wiley & Damiano, 1998) and joint ROM are decreased. Additionally, these children often demonstrate decreased muscle bulk, decreased ability to perform maximal muscle contractions (Elder et al., 2003), impaired rapid force generation (Moreau, Falvo, & Damiano, 2012), and poor selective motor control (Rose, 2009), defined as the ability to purposefully isolate and activate a specific muscle without involuntary associated movements.

Due to the significant variability in clinical presentation, children with CP are often further classified by subtype and area of involvement. Subtypes includes spastic, dyskinetic, and ataxic, as previously described, and mixed, in which characteristics of two or more subtypes are jointly present. Areas of involvement can include (a) hemiplegia, in which only the right or left side of the body is affected, (b) diplegia, in which the lower limbs only are affected, or (c) quadriplegia, in which all four limbs are affected (Palisano et al., 2017). Additionally, children with CP can be classified using the Gross Motor Function Classification System (GMFCS), a measure that has been validated in children up to 18 years of age (Palisano et al., 2008), which stratifies children with CP based on their gross motor function. Children who are Level I on the GMFCS are independently ambulatory and can run, hop, and climb stairs unassisted, while children at Level II require the use of a handrail for stair negotiation and may choose to use an assistive device (such as canes, crutches, or a walker) when ambulating for community mobility. Children who are Level III ambulate using an assistive device as their primary means of mobility, although they may choose to utilize wheeled mobility in the community. At Level IV, children use wheeled mobility in most settings, although they may ambulate recreationally using specialized equipment, and at Level V, children are dependent on caregivers for all mobility, maintenance of postural control, and self-care (Palisano et al., 2000).

Nearly 60% of children with CP walk independently with or without assistive devices (CDC, 2018). However, abnormalities of gait represent a significant issue for most of this population (Gage, 2009; Woollacott & Shumway-Cook, 2005). Additionally, gait disorders in CP are often progressive as children move into adolescence and young adulthood, despite the presence of a non-progressive brain lesion (Palisano et al., 2017). This suggests that, although different insults to the brain produce stereotypically different gait patterns, secondary impairments also play a significant role in the presentation of gait in children with CP. Additionally, there is significant variability in the clinical progression, even within GMFCS levels, suggesting that functional capacity can be affected by external factors, including therapeutic intervention (Hanna et al., 2009).

Spasticity, its assessment, and its role in gait abnormalities

Spasticity is generally recognized as the defining clinical feature for most children with CP. However, the exact definition of spasticity, and its role in the clinical presentation of these children, continues to be a subject of debate in the literature (Desloovere et al., 2006; Malhotra, Pandyan, Day, Jones, & Hermens, 2009). The traditional definition of spasticity, put forth by James Lance, states that it is “a motor disorder characterized by a velocity dependent increase in the tonic stretch reflex (muscle tone) with exaggerated tendon jerks, resulting from hyper excitability of the stretch reflex, as one component of the upper motor neuron syndrome” (Pandyan et al., 2005). In accordance with this view, spasticity has been generally assessed by observing the response to a rapid, passive movement by an examiner; the elicitation of increased muscle tone with high velocity movement is considered a positive sign that spasticity is present. More recently, this definition of spasticity has been questioned. We now recognize that what we tend to classify as spasticity is actually a combination of (1) passive stiffness derived from the viscoelastic properties of spastic tissues, (2) hyperreflexia of the stretch reflex, and (3) poor descending cortical control of the stretch reflex (Palisano et al., 2017; Pandyan et al., 2005).

Spastic muscle demonstrates inherently different morphology than typical muscle. Most notably, the muscles are smaller and demonstrate decreased longitudinal growth. As children grow and their bones lengthen, typical muscle will expand longitudinally through the addition of more sarcomeres in series. Spastic muscle, in contrast, adapts to the need for growth by lengthening existing sarcomeres. This is detrimental in two important ways: first, that the over-lengthened sarcomeres are no longer able to generate force as efficiently, owing to their sub-optimal length-tension relationship, and second, that the muscle is more prone to strain, which often leads to increased amounts of fibrotic tissue within the muscle (Palisano et al., 2017). This infiltration of non-contractile fibrous tissue into the muscle also has significant detrimental effects on force production. Overall, spastic muscle has an inherently increased passive stiffness due to these adaptations.

The stretch reflex is a simple monosynaptic reflex that is activated when a muscle is quickly increased in length. When muscle spindles detect a rapid lengthening, impulses travel along Ia afferent fibers to the spinal cord, where they synapse onto an α-motor neuron which causes the stretched muscle to contract to prevent overlengthening and injury (Enoka, 2015). This stretch reflex is considered to be hyperactive in spastic muscle, meaning that it demonstrates an exaggerated response to stimuli that would not provide the reflex in typical muscle. Pandyan et al. (2005) suggests that this should be the result of either one or both of the following mechanisms: an increase in the response of the stretch reflex itself, such as would occur with α-motor neuron hyperexcitability or decreased Ia presynaptic inhibition, or a decreased threshold in the muscle spindles themselves, resulting in the reflex being activated at lower levels of stimulus. Although a hyperexcitability of the stretch reflex is documented in some individuals diagnosed with spasticity, the evidence does not support this as the sole defining feature of spastic muscle (Pandyan et al., 2005).

Finally, individuals with upper motor neuron lesions are known to have damage to their descending extrapyramidal tracts, which are thought to be associated with increases in muscle tone (Gage, 2009). Mechanisms such as impaired reciprocal inhibition or impaired presynaptic inhibition are thought to also contribute to the clinical presentation of spasticity (Crenna, 1998; Palisano et al., 2017). In summary, far from being a simple hyperexcitability of the stretch reflex, what we refer to clinically as spasticity is a complex interaction of changes in muscle architecture and neural control.

Clinical spasticity in CP frequently correlates with the presence of various impairments, such as muscle weakness and the development of contracture, and gait abnormalities (Choi et al., 2018; Lotfian et al., 2016). These impairments have traditionally been attributed to the presence of spasticity, even though it is not entirely clear which aspects of spasticity, if any, are contributing to them (Pandyan et al., 2005). Despite the lack of a proven causal relationship, most medical interventions for individuals with spasticity are narrowly focused on decreasing the hyperactivity of the stretch reflex response, with the assumption that this will lead to improvements in function and participation. Injection of botulinum toxin type A , a neurotoxin that causes transient chemical denervation of a target muscle, has been found to successfully improve the gait kinematics and kinetics of individuals with spastic CP when combined with regular physical therapy (Boyd, Pliatsios, Starr, Wolfe, & Graham, 2000). Alternately, a 10-year follow-up study on children with spastic CP who underwent selective dorsal rhizotomy, a surgical procedure that involves pruning afferent fibers from the muscle spindles to decrease the magnitude of a hyperactive stretch reflex, found that lasting improvements in spasticity were not correlated with improved function or decreased rate of contracture development. This supports that findings of Crenna (1998), who noted that decreasing hyperreflexia does not consistently lead to improved functional movement, and Ross and Engsberg (2007), who found that spasticity was minimally correlated with both gait patterns and overall gross motor function; they found that muscle strength was a far better predictor in children with spastic diplegia.

More nuanced views about the role of spasticity in gait abnormalities have arisen in recent years. Poor selective motor control, decreased strength, abnormal muscle morphology, and abnormal motor recruitment strategies may all play a role in producing these abnormal gait patterns (Gage, 2009; Palisano et al., 2017). This suggests that determining the underlying mechanism responsible for a given gait deviation is critical to developing an appropriate intervention.

Unfortunately, assessment of spasticity itself is a complicated process. The most common clinical measures of spasticity are the Modified Ashworth Scale (MAS) (Bohannon & Smith, 1987) and the Modified Tardieu Scale (MTS) (R. N. Boyd & Graham, 1999). Both of these assessments involve rating the spasticity of a muscle based on passive, high velocity movements by an examiner; the MAS simply assigns a single numerical score based on the severity of the spastic "catch," while the MTS subjectively categorizes the spastic "catch" and also notes the angle at which the reaction occurs (called the R1 angle). As has already been established, spasticity is far more complex than a simple overactive stretch reflex, and yet, the most commonly utilized clinical measures only take this aspect into account.

Damiano et al. (2002) compared the MAS with an instrumented assessment that utilized surface electromyography (EMG) to assess the stretch reflex and a passive isokinetic device to determine the passive stiffness, resistance torque, and onset angle of muscular reaction during knee motion at different velocities. They found that measures of passive stiffness, defined as the rate of change of resistance torque during isokinetic assessments, rather than the angle of onset of a stretch response, were more correlated with the MAS. Germanotta et al. (2017) also showed poor correlation between instrumented measures of the stretch reflex and the MAS. This suggests that MAS scores may more accurately represent a measure of passive viscoelastic stiffness rather than the degree of abnormality of the stretch reflex. Since passive stiffness and the contribution of a hyperexcitable stretch reflex are not differentiated in the MAS, this suggests that the MAS has the potential to overestimate "spasticity" (when one defines spasticity solely as a hyperactive stretch reflex, as some clinicians still do) in the presence of significantly increased passive visco-elastic resistance to movement. Further, isokinetic measures of passive stiffness were more correlated than the angle of onset of the stretch response with two functional measures, the Gross Motor Function Measure (GMFM) and the Global Function Scale Score of the Pediatric Outcomes Data Collection Instrument (Damiano et al., 2002). Finally, instrumented measures of the stretch reflex response were highly correlated with the MAS at the extremes of the scale but showed a poor relationship mid-range (Damiano et al., 2002), and inter-rater reliability of the MAS has been found to be fair to poor (Numanoğlu, 2012). This suggests that the MAS is, at best, an inconsistent clinical tool and should not be used in isolation to describe spasticity.

The MTS has been shown to demonstrate better inter-rater reliability than the MAS (Numanoğlu, 2012). Many authors attribute this to its use of different velocities in testing, allowing for the distinction between resistance due to passive stiffness (assessment at a low velocity) and resistance due to a hyperactive stretch reflex (assessment at a high velocity). This gives the MTS the potential to differentiate the relative contributions of two different components of spasticity, which may allow for more nuanced clinical decision-making. Despite this, it still trails behind the MAS in terms of widespread use by clinicians and researchers.

Due to the difficulty in consistently quantifying spasticity with these existing clinical scales, several instrumented approaches utilizing kinematic, kinetic, and EMG data have been proposed in the literature. Biering-Sorensen, Nielsen, and Klinge (2006) recommended a combination of EMG assessment of the stretch-reflex threshold and kinematic evaluation to examine relationship between stretch velocity and evoked torque. Germanotta et al. (2017) utilized a robotic device called the PediAnkleBot to deliver a series of passive movements at varying angular velocities in conjunction with surface EMG to determine the tonic stretch reflex threshold (TSRT) of ankle musculature in children with spastic CP. Bar-On et al. (2013) proposed a similar integrated method which combined biomechanical and electromyographic data obtained during manual passive movement by an examiner; of note, the passive movements they used are very similar to the clinical performance of the MTS. This integrated measure utilized a combination of surface EMG and inertial measurement units to collect data while a joint was moved passively through its full ROM at different velocities: (a) low, in which the full range is completed in 5 seconds, and (b) high, in which the joint was taken through its full range as quickly as possible, faster than the limb would naturally drop under the effect of gravity. From this data, the maximum angular velocity and average root mean square envelope of EMG (RMS-EMG) activity (reported as a percentage of peak RMS-EMG activity obtained during a maximal voluntary isometric contraction (MVIC)) can be determined. Torque at the maximum angular velocity as well as work are then calculated for each movement velocity. Spasticity is then quantified in three ways: (a) change in the average RMS-EMG activity, (b) change in torque, and (c) change in work between the two movement velocities. Reliability and validity of this measure were established in children with spastic CP, with moderately high test-retest reliability and good discriminative validity in distinguishing those children with spastic muscles from their typically developing (TD) peers (Bar-On et al., 2013).

Notably, both authors note that their instrumented measures are only effective at quantifying spasticity at rest, and specifically recommend that these measurement techniques be reproduced during functional activities to ascertain how these spasticity-related parameters are correlated with changes in gait (Bar-On et al., 2013; Germanotta et al., 2017).

Whole-body vibration in individuals with cerebral palsy

Single bouts of whole-body vibration have been shown to positively affect spasticity and active ROM in multiple special populations, including adults with acute and chronic stroke, and adults and children with CP (Alashram, Padua, & Annino, 2019; Duquette et al., 2015; R. Ritzmann, Stark, & Krause, 2018; Sa-Caputo et al., 2016; Saquetto, Carvalho, Silva, Conceicao, & Gomes-Neto, 2015). These transient after-effects are reported to last between thirty minutes and two hours (Cheng, Ju, et al., 2015; Park et al., 2017; R. Ritzmann et al., 2018). While WBV has been shown in the literature to have positive effects on the motor function of individuals with neuromotor disorders, the precise mechanisms are still being investigated. However, WBV appears to act on the neuromotor systems of individuals with CP in two ways: (1) modulation of the hyper-excitable stretch reflex by decreasing the sensitivity of the muscle spindle, and (2) facilitation of reciprocal inhibition (Krause et al., 2017). These mechanisms are particularly interesting when considering the effects on children with CP; while many previous therapies focused on improving the function of individuals with spasticity have focused solely on decreasing the stretch reflex, there is little evidence to support that this particular aspect of spasticity is a key detriment to function. WBV appears to have beneficial effects on multiple facets of spasticity, potentially making it a more effective treatment modality. Additionally, WBV has the benefit of being a “passive” modality (Krause et al., 2017), meaning that children who lack motivation or attention, or who cannot fully participate in a task due to cognitive limitations, can still receive its full benefits.

Dickin, Faust, Wang, and Frame (2013) studied the acute effects of WBV on adults with CP. Frequencies were individualized for each subject, and ranged from 20-50 Hz, and an amplitude of 2 mm was used. The training consisted of 5 bouts of 60 seconds of vibration, after which the immediate effects were assessed. They found increased overground walking speed and stride length, as well as a significant improvement (approximately 20°) of dynamic ankle ROM during gait. The authors suggested that the vibration may have caused the muscle to lengthen and become more pliable, allowing for the increased ROM. Spasticity was not directly assessed, so it is difficult to make conclusions about its potential role in the increased ROM. However, repetitive passive and active ROM have been shown to decrease scores on the MAS in individuals with CP by improving the passive viscoelastic properties of the muscle (Chang et al., 2013; Willerslev-Olsen, Lorentzen, & Nielsen, 2014). As WBV provides substantial repetitions of a passive movement in a short period of time, it is feasible that it also is able to improve muscular passive stiffness.

Acute effects of WBV have also been assessed in children with CP. Cheng, Ju, et al. (2015) utilized a frequency of 20 Hz and an amplitude of 2 mm and provided twenty minutes of WBV training. They found improvements in active ROM about the knee and ankle, improved scores on the MAS and the Wartenburg pendulum test's relaxation index (RI), and improved performance on the 6-minute walking test (6-MWT) and the Timed Up-and-Go test (TUG). These improvements were still present thirty minutes after the cessation of the vibration training. The changes in the TUG were positively correlated with the changes in the RI, suggesting that the improvements in the gait task may have been the result of decreased spasticity. As the positive effects were shown to persist for at least thirty minutes, the authors suggested that the "acute effects might promote children's active participation in exercise" (Cheng, Ju, et al., 2015). Park et al. (2017) also investigated the acute effects in children with CP, also utilizing a frequency of 20 Hz and an amplitude of 2 mm for twenty minutes. Similar to Cheng, Ju, et al. (2015), they found improvements in the RI following WBV, which were still present two hours after cessation of vibration. H. Q. Liang (2018) found immediate improvements in spasticity and overground gait parameters following nine minutes of WBV at a frequency of 20 Hz and an amplitude of 2 mm. Han, Lee, and Yun (2019) also investigated acute changes in functional gait and balance following 3 minute bouts of WBV at a variety of frequencies. They found similar improvements in functional walking ability and postural control following WBV at 18 Hz but noted that these improvements were not present when frequencies of 12 Hz or 26 Hz were used. This suggests that the effectiveness of WBV may depend heavily on the parameters used during the training protocol.

Krause et al. (2017) also investigated the acute effects of WBV in children with CP, but utilized a much shorter duration of training, providing one minute of WBV at frequencies ranging between 16-25 Hz and amplitudes ranging between 1.5-3 mm. They were interested in the mechanism behind changes in active ROM and tested both the intensity of the calf stretch reflexes and the MVIC of several lower limb muscles. They found improved voluntary control about the knee joint, as well as decreased intensity of the stretch reflex in the soleus. Interestingly, significant changes were not seen in the intensity of the stretch reflex of the gastrocnemius or in the active ROM of the ankle joint, despite the closer proximity of the ankle joint to the vibration plate. Further, the reported standard deviations of the group level responses are quite high, and the inter-subject responses to WBV were highly variable. This could be a function of the differing frequencies used (which were individualized to each subject) or possibly represent a non-homogenous response to WBV in this population with highly heterogeneous clinical presentations.

Variability of response aside, Krause et al. (2017) suggest that the improvements seen are the result of suppressing hyper-active stretch reflexes, allowing for improved voluntary control. They also view WBV as a modality that can facilitate active participation in therapy, stating that "by demonstrating improved voluntary movement execution after WBV, the time frame immediately after WBV may be used for targeted movement therapy: subjects might actually take advantage of increased supraspinal input by means of greater voluntary motor control" (Krause et al., 2017). As poor voluntary motor control and the interference of a hyperactive stretch reflex can both limit active participation in therapeutic activities, these findings suggest that WBV used as a modality at the beginning of a therapy session could improve quality of movement during subsequent interventions. For gait training in particular, it is crucial that the movement patterns being repeated mimic typical gait as closely as possible; repetitive stepping with poor form will only reinforce poor movement patterns. Thus, utilizing WBV prior to such an intervention may allow for effective practice of more normalized gait patterns, which in turn has the potential to improve carryover of these patterns.

Regarding long-term WBV training, Ibrahim et al. (2014) investigated the long-term effects of WBV training in children with spastic CP. A control group received typical physical therapy treatment only, while the experimental group also received nine minutes of WBV training at frequencies ranging from 12-18 Hz and amplitudes ranging from 4-6 mm. Strength, spasticity, functional gait parameters, and gross motor development were assessed before and after WBV training three times per week for twelve weeks. Significant improvements in knee extensor strength and spasticity, walking speed, and higher-level gross motor function were noted only in the WBV group. No additional follow-ups were performed, so it is unclear exactly how long the effects persisted following this twelve-week protocol.

Cheng, Yu, et al. (2015) also investigated the effects of a prolonged treatment protocol that involved completing sessions of WBV three times per week for eight weeks. The sessions lasted for ten minutes at a frequency of 20 Hz and an amplitude of 2 mm. They found improvements in MAS scores and 6-MWT scores immediately following the last session as well as three days later.

Additionally, Yabumoto et al. (2015) investigated functional walking ability, spasticity, and gross motor function before and after a 5-week WBV training protocol in an 8-year-old boy with spastic diplegia. WBV consisted of 5-6 minutes twice per week at a frequency of 30 Hz and an amplitude of 1-3 mm. Following training, the subject demonstrated improved walking speed and stride length, improved gross motor function, and improved R1 ROM into ankle dorsiflexion. Again, however, no follow-up visits were reported so it remains unknown how long these improvements persisted.

These studies, taken together, suggests that prolonged WBV training can produce more lasting effects than a single session. However, additional follow-up studies investigating how long the effects last after completion of longer training protocols are necessary.

Finally, four systematic reviews have been completed on the effects of WBV on individuals with CP (Duquette et al., 2015; R. Ritzmann et al., 2018; Sa-Caputo et al., 2016; Saquetto et al., 2015). Three reviews included only five or six articles, which speaks to the overall scarcity of English-language literature on this topic; the most recent review, which included articles in both English and German, included 32 studies. Overall these reviews and meta-analyses confirmed that WBV seems to have mildly positive effects on muscle strength, gait parameters (including walking speed and stride length), dynamic ROM at the ankle and knee, and gross motor function. Findings on spasticity were slightly more mixed, with Duquette et al. (2015) and R. Ritzmann et al. (2018) concluding that WBV had positive effects while Sa-Caputo et al. (2016) found the evidence to be inconclusive. One notable limitation to the existing research on WBV protocols is the lack of consistency with regards to frequency, amplitude, and duration (R. Ritzmann et al., 2018).

In general, WBV appears to be a promising intervention with the potential to have clinically significant positive effects on the spasticity and gait parameters of children with CP. However, more studies are needed both to confirm preliminary findings, to investigate ideal parameters and dosages, and to more closely study the mechanisms behind these findings.

Treadmill training in individuals with cerebral palsy

Treadmill training (TT) is a popular intervention technique in pediatric rehabilitation, and is commonly used for children with a wide variety of diagnoses, including CP. When learning or refining a motor skill, motor learning theory states that the most important factor is practice (Shumway-Cook & Woollacott, 2012). Typically developing children, for instance, perform enormous amounts of practice daily when learning to walk, taking over 2,000 steps per hour and traveling over two miles per day (Adolph, 2008; Adolph et al., 2012). Interestingly, it has been noted that individuals with neuromotor disorders, such as children with CP, tend to utilize atypical movement patterns that very closely resemble the immature patterns seen in early stages of development (Forssberg, 1999; Hadders-Algra, 2000; Lacquaniti, Ivanenko, & Zago, 2012). Given that the development of a mature gait pattern requires substantial levels of practice-based tuning of immature movement patterns, it stands to reason that providing children with neuromotor disorders with structured opportunities for practice can assist in improving their gait patterns. Further, it has been shown that the number of specific repetitions of a novel task is the most critical factor in teaching typical adults a novel gait pattern (Krishnan et al., 2019). This provides a framework for rehabilitation techniques focused on providing the necessary practice for individuals to successfully select and master more mature and efficient motor patterns.

A common challenge when performing repetitive gait training with children is completing sufficient practice, with appropriate form, in an efficient manner. Utilizing a treadmill is a common solution to this problem, as walking on a treadmill provides a repetitive stimulus for stepping, allowing for consistent, task-specific practice of ambulation. Further, systematic reviews have determined that TT was safe and well-tolerated for children with CP (Damiano & DeJong, 2009; Willoughby, Dodd, & Shields, 2009b; Zwicker & Mayson, 2010), and two meta-analyses have agreed that functional gait training, including TT, was the most effective way to improve walking ability and gait speed (Booth et al., 2018; Moreau et al., 2016).

An additional benefit of TT is that the parameters of treadmill walking (such as amount of body weight support, speed, direction, and grade) can be modulated to induce other improvements, such as increased muscle strength (Damiano & DeJong, 2009). Thus, controlling the conditions under which a child performs TT can allow for significant amounts of practice of a new motor pattern in a controlled environment. The benefits of TT with PBWS, walking backward, walking on an incline, and walking with an ankle load have all been explored in the literature in multiple special populations, including children with CP. However, the results have been inconclusive due to significant variation in both protocols and populations. For example, while TT has consistently been shown to accelerate the onset of walking in children with Down syndrome, its effectiveness in improving the gait pattern of children with CP or other neuromotor disorders is more uncertain (Damiano & DeJong, 2009; Valentin-Gudiol et al., 2017; Zwicker & Mayson, 2010).

Dodd and Foley (2007) utilized PBWS TT for children with CP at GMFCS levels III and IV, twice per week for six weeks, and found that the children increased their overground walking speed and distance at the end of the training period. El-Shamy (2017) utilized a similar protocol on children with CP at GMFCS levels I and II with an anti-gravity treadmill, and found similar improvements in gait speed and quality, as well as improvements in standing balance and fall risk. Kurz, Stuberg, and DeJong (2011) trained children with CP with PBWS twice per week for twelve weeks and found increases in overground walking speed as well as improved gait kinematics and improved scores on the GMFM dimension E, which measures walking, running, and jumping abilities. Kenyon, Westman, Hefferan, McCrary, and Baker (2017) and Visser et al. (2017) trained caregivers to complete a home-based PBWS TT program for twelve weeks, and found improved functional abilities, as measured by the Functional Assessment Questionnaire and the Canadian Occupational Performance Measure (Kenyon et al., 2017; Visser et al., 2017), as well as improved scores on the 6-MWT (Visser et al., 2017). Additionally, two systematic reviews showed that PBWS TT has promising positive effects, especially for children at GMFCS levels III and IV (Damiano & DeJong, 2009; Willoughby, Dodd, & Shields, 2009a).

TT that involves walking backward, on an incline, or with ankle load has also been shown to improve gait parameters in children with CP. Kim et al. (2013) found increased overground walking speed and increased step length following eight weeks of backward TT at three times per week. Abdel-Aziem and El-Basatiny (2017) found similar increases in walking speed and step length following backward TT, as well as improvements in GMFM dimension D and E scores, which measure standing, walking, running, and jumping skills. El-Basatiny and Abdel-Aziem (2015) found increased postural stability following twelve weeks of backward TT at three times per week. A systematic review by Elnahhas, Elshennawy, and Aly (2019) concluded that there was moderate evidence that backward walking on a treadmill was more effective than forward walking at improving gait parameters and walking speed.

With regard to incline, Willerslev-Olsen et al. (2014) studied a four-week home-based TT program that involved walking up an incline in children with CP and found decreased passive stiffness about the ankle as well as improved heel strike during overground walking. Lorentzen et al. (2017) found similar results in adults with CP who completed a six-week program of uphill TT for thirty minutes per day, as well as improvements in maximal walking speed. A daily, four-week home-based TT protocol that involved increases in both speed and incline found improved push-off and improved symmetry of gait (Lorentzen et al., 2020) as well as improved heel strike (Willerslev-Olsen et al., 2014; Willerslev-Olsen, Petersen, Farmer, & Nielsen, 2015) and decreased passive stiffness about the ankle joint (Willerslev-Olsen et al., 2014).

Further, Simao et al. (2019) found that adding an external ankle load to the involved lower limb of children with spastic hemiplegia could produce acute improvements in foot clearance during swing phase once the load was removed. Finally, my own pilot work in typically developing children has shown that walking forward on a treadmill at a fast pace, equivalent to 125% of preferred overground walking speed, results in significantly increased dynamic range of motion at the ankle during gait.

Many of the inconsistencies in the results of TT in the literature have been attributed to differences in both patient populations and protocols (Valentin-Gudiol et al., 2017; Zwicker & Mayson, 2010). Additionally, there is a lack of studies that attempt to mitigate the individual differences in children with CP by combining TT with interventions focused on, for instance, strengthening or spasticity reduction. Such combined interventions could represent an opportunity to perform TT on a more homogenous population by preparing for the training with interventions focused on decreasing impairment-level inconsistencies such as spasticity or voluntary muscle activation. Combined interventions also have the potential to ensure that the TT protocols are being performed with the best form possible, maximizing the benefits of these task-specific repetitions. In accordance with these principles, it is possible that the combination of WBV to decrease spasticity and allow for improved voluntary muscular control and TT to allow for the massed practice of improved gait patterns may represent a more effective treatment paradigm than either of these interventions in isolation.

In conclusion, the concept of preliminary spasticity management improving physical therapy outcomes is supported in the literature, with the combination of Botox-A injections and rehabilitation having been shown to improve the gait patterns and motor function of children with CP (Boyd et al., 2000; Fattal-Valevski, Domenievitz, Giladi, Wientroub, & Hayek, 2008).

However, BTX-A is invasive, and its effectiveness may decrease with repeated use (Fattal-Valevski et al., 2008). Thus, exploration of a non-invasive therapeutic paradigm which can be used to reduce spasticity and potentially augment rehabilitation outcomes in children with CP is indicated. Further, although multiple authors have suggested that WBV may have clinical utility as a spasticity-reducing preparatory modality (Cheng, Ju, et al., 2015; Krause et al., 2017), there has been no literature to date which investigates the relative effectiveness of specific rehabilitation interventions with and without the addition of WBV. This study, therefore, serves as an initial report of the effect that a single bout of WBV can have on both the performance of, and the acute outcomes associated with, one of the most common physical therapy interventions: gait training on a treadmill.

References

Abdel-Aziem, A. A., & El-Basatiny, H. M. (2017). Effectiveness of backward walking training on walking ability in children with hemiparetic cerebral palsy: a randomized controlled trial. *Clin Rehabil, 31*(6), 790-797. doi:10.1177/0269215516656468

Adolph, K. E. (2008). Motor and Physical Development: Locomotion. In M. M. Haith & J. B. Benson (Eds.), *Encyclopedia of infant and early childhood development* (pp. 359-373). San Diego, CA: Academic Press.

Adolph, K. E., Cole, W. G., Komati, M., Garciaguirre, J. S., Badaly, D., Lingeman, J. M., . . . Sotsky, R. B. (2012). How do you learn to walk? Thousands of steps and dozens of falls per day. *Psychol Sci, 23*(11), 1387-1394. doi:10.1177/0956797612446346

Ahlborg, L., Andersson, C., & Julin, P. (2006). Whole-body vibration training compared with resistance training: effect on spasticity, muscle strength and motor performance in adults with cerebral palsy. *J Rehabil Med, 38*(5), 302-308. doi:10.1080/16501970600680262

Alashram, A. R., Padua, E., & Annino, G. (2019). Effects of Whole-Body Vibration on Motor Impairments in Patients With Neurological Disorders: A Systematic Review. *Am J Phys Med Rehabil, 98*(12), 1084-1098. doi:10.1097/PHM.0000000000001252

Bar-On, L., Aertbelien, E., Wambacq, H., Severijns, D., Lambrecht, K., Dan, B., . . . Desloovere, K. (2013). A clinical measurement to quantify spasticity in children with cerebral palsy by integration of multidimensional signals. *Gait Posture, 38*(1), 141-147. doi:10.1016/j.gaitpost.2012.11.003

Biering-Sorensen, F., Nielsen, J. B., & Klinge, K. (2006). Spasticity-assessment: a review. *Spinal Cord, 44*(12), 708-722. doi:10.1038/sj.sc.3101928

Bohannon, R. W., & Smith, M. B. (1987). Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther, 67*(2), 206-207.

Booth, A. T. C., Buizer, A. I., Meyns, P., Oude Lansink, I. L. B., Steenbrink, F., & van der Krogt, M. M. (2018). The efficacy of functional gait training in children and young adults with cerebral palsy: a systematic review and meta-analysis. *Dev Med Child Neurol, 60*(9), 866-883. doi:10.1111/dmcn.13708

Boyd, Pliatsios, V., Starr, R., Wolfe, R., & Graham, H. K. (2000). Biomechanical transformation of the gastroc-soleus muscle with botulinum toxin A in children with cerebral palsy. *Dev Med Child Neurol, 42*(1), 32-41.

Boyd, R. N., & Graham, H. K. (1999). Objective measurement of clinical findings in the use of botulinum toxin type A for the management of children with cerebral palsy. *Eur J Neurol, 6*(S4), s23-s35. doi:doi:10.1111/j.1468-1331.1999.tb00031.x

CDC. (2018, March 9, 2018). Data & Statistics for Cerebral Palsy. Retrieved from https://www.cdc.gov/ncbddd/cp/data.html

Chang, Y. J., Liang, J. N., Hsu, M. J., Lien, H. Y., Fang, C. Y., & Lin, C. H. (2013). Effects of continuous passive motion on reversing the adapted spinal circuit in humans with chronic spinal cord injury. *Arch Phys Med Rehabil, 94*(5), 822-828. doi:10.1016/j.apmr.2012.11.035

Cheng, H. Y., Ju, Y. Y., Chen, C. L., Chuang, L. L., & Cheng, C. H. (2015). Effects of whole body vibration on spasticity and lower extremity function in children with cerebral palsy. *Hum Mov Sci, 39*, 65-72. doi:10.1016/j.humov.2014.11.003

Cheng, H. Y., Yu, Y. C., Wong, A. M., Tsai, Y. S., & Ju, Y. Y. (2015). Effects of an eight-week whole body vibration on lower extremity muscle tone and function in children with cerebral palsy. *Res Dev Disabil, 38*, 256-261. doi:10.1016/j.ridd.2014.12.017

Choi, J. Y., Park, E. S., Park, D., & Rha, D. W. (2018). Dynamic spasticity determines hamstring length and knee flexion angle during gait in children with spastic cerebral palsy. *Gait Posture, 64*, 255-259. doi:10.1016/j.gaitpost.2018.06.163

Crenna, P. (1998). Spasticity and 'spastic' gait in children with cerebral palsy. *Neurosci Biobehav Rev, 22*(4), 571-578.

Damiano, D. L., & DeJong, S. L. (2009). A systematic review of the effectiveness of treadmill training and body weight support in pediatric rehabilitation. *J Neurol Phys Ther, 33*(1), 27-44. doi:10.1097/NPT.0b013e31819800e2

Damiano, D. L., Quinlivan, J. M., Owen, B. F., Payne, P., Nelson, K. C., & Abel, M. F. (2002). What does the Ashworth scale really measure and are instrumented measures more valid and precise? *Dev Med Child Neurol, 44*(2), 112-118.

Desloovere, K., Molenaers, G., Feys, H., Huenaerts, C., Callewaert, B., & Van de Walle, P. (2006). Do dynamic and static clinical measurements correlate with gait analysis parameters in children with cerebral palsy? *Gait Posture, 24*(3), 302-313. doi:10.1016/j.gaitpost.2005.10.008

Dickin, D. C., Faust, K. A., Wang, H., & Frame, J. (2013). The acute effects of whole-body vibration on gait parameters in adults with cerebral palsy. *J Musculoskelet Neuronal Interact, 13*(1), 19-26.

Dodd, K. J., & Foley, S. (2007). Partial body-weight-supported treadmill training can improve walking in children with cerebral palsy: a clinical controlled trial. *Dev Med Child Neurol, 49*(2), 101-105. doi:10.1111/j.1469-8749.2007.00101.x

Duquette, S. A., Guiliano, A. M., & Starmer, D. J. (2015). Whole body vibration and cerebral palsy: a systematic review. *J Can Chiropr Assoc, 59*(3), 245-252.

El-Basatiny, H. M., & Abdel-Aziem, A. A. (2015). Effect of backward walking training on postural balance in children with hemiparetic cerebral palsy: a randomized controlled study. *Clin Rehabil, 29*(5), 457-467. doi:10.1177/0269215514547654

El-Shamy, S. M. (2017). Effects of Antigravity Treadmill Training on Gait, Balance, and Fall Risk in Children With Diplegic Cerebral Palsy. *Am J Phys Med Rehabil, 96*(11), 809-815. doi:10.1097/PHM.0000000000000752

Elder, G. C., Kirk, J., Stewart, G., Cook, K., Weir, D., Marshall, A., & Leahey, L. (2003). Contributing factors to muscle weakness in children with cerebral palsy. *Dev Med Child Neurol, 45*(8), 542-550.

Elnahhas, A. M., Elshennawy, S., & Aly, M. G. (2019). Effects of backward gait training on balance, gross motor function, and gait in children with cerebral palsy: a systematic review. *Clin Rehabil, 33*(1), 3-12. doi:10.1177/0269215518790053

Enoka, R. M. (2015). *Neuromechanics of human movement* (Fifth edition. ed.). Champaign, IL: Human Kinetics.

Fattal-Valevski, A., Domenievitz, D., Giladi, N., Wientroub, S., & Hayek, S. (2008). Long-term effect of repeated injections of botulinum toxin in children with cerebral palsy: a prospective study. *Journal of Children's Orthopaedics, 2*(1), 29-35. doi:10.1007/s11832-007-0075-8

Forssberg, H. (1999). Neural control of human motor development. *Current Opinion in Neurobiology, 9*, 676-682.

Gage, J. R. (2009). *The identification and treatment of gait problems in cerebral palsy* (2nd ed. ed.). London: Mac Keith Press.

Germanotta, M., Taborri, J., Rossi, S., Frascarelli, F., Palermo, E., Cappa, P., . . . Petrarca, M. (2017). Spasticity Measurement Based on Tonic Stretch Reflex Threshold in Children with Cerebral Palsy Using the PediAnklebot. *Front Hum Neurosci, 11*, 277. doi:10.3389/fnhum.2017.00277

Hadders-Algra, M. (2000). The Neuronal Group Selection Theory: a framework to explain variation in normal motor development. *Developmental Medicine & Child Neurology, 42*, 566-572.

Han, Y. G., Lee, S. W., & Yun, C. K. (2019). The immediate influence of various whole-body vibration frequency on balance and walking ability in children with cerebral palsy: a pilot study. *J Exerc Rehabil, 15*(4), 597-602. doi:10.12965/jer.1938318.159

Hanna, S. E., Rosenbaum, P. L., Bartlett, D. J., Palisano, R. J., Walter, S. D., Avery, L., & Russell, D. J. (2009). Stability and decline in gross motor function among children and youth with cerebral palsy aged 2 to 21 years. *Dev Med Child Neurol, 51*(4), 295-302.

Ibrahim, M. M., Eid, M. A., & Moawd, S. A. (2014). Effect of whole-body vibration on muscle strength, spasticity, and motor performance in spastic diplegic cerebral palsy children. *Egyptian Journal of Medical Human Genetics, 15*(2), 173-179. doi:10.1016/j.ejmhg.2014.02.007

Kenyon, L. K. P. D. P. P., Westman, M. P. D., Hefferan, A. P. D., McCrary, P. P. D., & Baker, B. J. P. P. N. (2017). A home-based body weight supported treadmill training program for children with cerebral palsy: A case series. *Physiother Theory Pract, 33*(7), 576-585. doi:10.1080/09593985.2017.1325956

Kim, S. G., Ryu, Y. U., Je, H. D., Jeong, J. H., & Kim, H. D. (2013). Backward walking treadmill therapy can improve walking ability in children with spastic cerebral palsy: a pilot study. *Int J Rehabil Res, 36*(3), 246-252. doi:10.1097/MRR.0b013e32835dd620

Krause, A., Schonau, E., Gollhofer, A., Duran, I., Ferrari-Malik, A., Freyler, K., & Ritzmann, R. (2017). Alleviation of Motor Impairments in Patients with Cerebral Palsy: Acute Effects of Whole-body Vibration on Stretch Reflex Response, Voluntary Muscle Activation and Mobility. *Front Neurol, 8*, 416. doi:10.3389/fneur.2017.00416

Krishnan, C., Dharia, A. K., Augenstein, T. E., Washabaugh, E. P., Reid, C. E., Brown, S. R., & Ranganathan, R. (2019). Learning new gait patterns is enhanced by specificity of training rather than progression of task difficulty. *J Biomech, 88*, 33-37. doi:10.1016/j.jbiomech.2019.03.014

Kurz, M. J., Stuberg, W., & DeJong, S. L. (2011). Body weight supported treadmill training improves the regularity of the stepping kinematics in children with cerebral palsy. *Dev Neurorehabil, 14*(2), 87-93. doi:10.3109/17518423.2011.552459

Lacquaniti, F., Ivanenko, Y. P., & Zago, M. (2012). Development of human locomotion. *Curr Opin Neurobiol, 22*(5), 822-828. doi:10.1016/j.conb.2012.03.012

Liang, H. Q. (2018). *Effect of Single-Session Whole-Body Vibration on Motor Function and Spasticity of Children with Cerebral Palsy*. Dissertation. Georgia State University. Atlanta, GA, USA.

Lorentzen, J., Frisk, R., Willerslev-Olsen, M., Bouyer, L., Farmer, S. F., & Nielsen, J. B. (2020). Gait training facilitates push-off and improves gait symmetry in children with cerebral palsy. *Hum Mov Sci, 69*, 102565. doi:10.1016/j.humov.2019.102565

Lorentzen, J., Kirk, H., Fernandez-Lago, H., Frisk, R., Scharff Nielsen, N., Jorsal, M., & Nielsen, J. B. (2017). Treadmill training with an incline reduces ankle joint stiffness and improves active range of movement during gait in adults with cerebral palsy. *Disabil Rehabil, 39*(10), 987-993. doi:10.1080/09638288.2016.1174745

Lotfian, M., Mirbagheri, M. M., Kharazi, M. R., Dadashi, F., Nourian, R., Irani, A., & Mirbagheri, A. (2016). Pendulum test measure correlates with gait parameters in children with cerebral palsy. *Conf Proc IEEE Eng Med Biol Soc, 2016*, 1708-1711. doi:10.1109/embc.2016.7591045

Malhotra, S., Pandyan, A. D., Day, C. R., Jones, P. W., & Hermens, H. (2009). Spasticity, an impairment that is poorly defined and poorly measured. *Clin Rehabil, 23*(7), 651-658. doi:10.1177/0269215508101747

Masi, A. T., & Hannon, J. C. (2008). Human resting muscle tone (HRMT): narrative introduction and modern concepts. *J Bodyw Mov Ther, 12*(4), 320-332. doi:10.1016/j.jbmt.2008.05.007

Moreau, N. G., Bodkin, A. W., Bjornson, K., Hobbs, A., Soileau, M., & Lahasky, K. (2016). Effectiveness of Rehabilitation Interventions to Improve Gait Speed in Children With Cerebral Palsy: Systematic Review and Meta-analysis. *Phys Ther, 96*(12), 1938-1954. doi:10.2522/ptj.20150401

Moreau, N. G., Falvo, M. J., & Damiano, D. L. (2012). Rapid force generation is impaired in cerebral palsy and is related to decreased muscle size and functional mobility. *Gait Posture, 35*(1), 154-158. doi:10.1016/j.gaitpost.2011.08.027

Mutlu, A., Krosschell, K., & Spira, D. G. (2009). Treadmill training with partial body-weight support in children with cerebral palsy: a systematic review. *Dev Med Child Neurol, 51*(4), 268-275. doi:10.1111/j.1469-8749.2008.03221.x

Numanoğlu, A. (2012). Intraobserver reliability of modified Ashworth scale and modified Tardieu scale in the assessment of spasticity in children with cerebral palsy. *Acta Orthopaedica et Traumatologica Turcica, 46*(3), 196-200. doi:10.3944/aott.2012.2697

Omura, J., Fuentes, M., & Bjornson, K. (2018). Participation in Daily Life: Influence on Quality of Life in Ambulatory Children with Cerebral Palsy. *PM R*. doi:10.1016/j.pmrj.2018.05.010

Palisano, R. J., Hanna, S. E., Rosenbaum, P. L., Russell, D. J., Walter, S. D., Wood, E. P., . . . Galuppi, B. E. (2000). Validation of a model of gross motor function for children with cerebral palsy. *Phys Ther*, *80*(10), 974-985.

Palisano, R. J., Orlin, M. N., & Schreiber, J. (2017). *Campbell's Physical Therapy for Children* (5th ed. ed.). St. Louis, MO: Elsevier Saunders.

Palisano, R. J., Rosenbaum, P., Bartlett, D., & Livingston, M. H. (2008). Content validity of the expanded and revised Gross Motor Function Classification System. *Dev Med Child Neurol, 50*(10), 744-750. doi:10.1111/j.1469-8749.2008.03089.x

Pandyan, A. D., Gregoric, M., Barnes, M. P., Wood, D., Wijck, F. V., Burridge, J., . . . Johnson, G. R. (2005). Spasticity: Clinical perceptions, neurological realities and meaningful measurement. *Disability and Rehabilitation, 27*(1-2), 2-6. doi:10.1080/09638280400014576

Park, C., Park, E. S., Choi, J. Y., Cho, Y., & Rha, D. W. (2017). Immediate Effect of a Single Session of Whole Body Vibration on Spasticity in Children With Cerebral Palsy. *Ann Rehabil Med, 41*(2), 273-278. doi:10.5535/arm.2017.41.2.273

Ritzmann, R., Stark, C., & Krause, A. (2018). Vibration therapy in patients with cerebral palsy: a systematic review. *Neuropsychiatr Dis Treat, 14*, 1607-1625. doi:10.2147/NDT.S152543

Rose, J. (2009). Selective motor control in spastic cerebral palsy. *Dev Med Child Neurol, 51*(8), 578-579. doi:10.1111/j.1469-8749.2009.03401.x

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.

Ross, S. A., & Engsberg, J. R. (2007). Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. *Arch Phys Med Rehabil, 88*(9), 1114-1120. doi:10.1016/j.apmr.2007.06.011

Sa-Caputo, D. C., Costa-Cavalcanti, R., Carvalho-Lima, R. P., Arnobio, A., Bernardo, R. M., Ronikeile-Costa, P., . . . Bernardo-Filho, M. (2016). Systematic review of whole body vibration exercises in the treatment of cerebral palsy: Brief report. *Dev Neurorehabil, 19*(5), 327-333. doi:10.3109/17518423.2014.994713

Saquetto, M., Carvalho, V., Silva, C., Conceicao, C., & Gomes-Neto, M. (2015). The effects of whole body vibration on mobility and balance in children with cerebral palsy: a systematic review with meta-analysis. *J Musculoskelet Neuronal Interact, 15*(2), 137-144.

Shumway-Cook, A., & Woollacott, M. H. (2012). *Motor control : translating research into clinical practice* (4. ed. ed.). Philadelphia: Wolters Kluwer Health, Lippincott Williams & Wilkins.

Simao, C. R., Regalado, I. C. R., Spaniol, A. P., Fonseca, D. O. S., Ribeiro, T. S., & Lindquist, A. R. (2019). Immediate effects of a single treadmill session with additional ankle loading on gait in children with hemiparetic cerebral palsy. *NeuroRehabilitation, 44*(1), 9-17. doi:10.3233/NRE-182516

Valentin-Gudiol, M., Mattern-Baxter, K., Girabent-Farres, M., Bagur-Calafat, C., Hadders-Algra, M., & Angulo-Barroso, R. M. (2017). Treadmill interventions in children under six years of age at risk of neuromotor delay. *Cochrane Database Syst Rev, 7*, Cd009242. doi:10.1002/14651858.CD009242.pub3

Visser, A., Westman, M., Otieno, S., & Kenyon, L. (2017). A Home-Based Body Weight-Supported Treadmill Program for Children With Cerebral Palsy: A Pilot Study. *Pediatr Phys Ther, 29*(3), 223-229. doi:10.1097/PEP.0000000000000406

Wiley, M. E., & Damiano, D. L. (1998). Lower-extremity strength profiles in spastic cerebral palsy. *Dev Med Child Neurol, 40*(2), 100-107.

Willerslev-Olsen, M., Lorentzen, J., & Nielsen, J. B. (2014). Gait training reduces ankle joint stiffness and facilitates heel strike in children with Cerebral Palsy. *NeuroRehabilitation, 35*(4), 643-655. doi:10.3233/NRE-141180

Willerslev-Olsen, M., Petersen, T. H., Farmer, S. F., & Nielsen, J. B. (2015). Gait training facilitates central drive to ankle dorsiflexors in children with cerebral palsy. *Brain, 138*(Pt 3), 589-603. doi:10.1093/brain/awu399

Willoughby, K. L., Dodd, K. J., & Shields, N. (2009a). A systematic review of the effectiveness of treadmill training for children with cerebral palsy. *Disability & Rehabilitation, 31*(24), 1971-1979. doi:10.3109/09638280902874204

Willoughby, K. L., Dodd, K. J., & Shields, N. (2009b). A systematic review of the effectiveness of treadmill training for children with cerebral palsy. *Disabil Rehabil, 31*(24), 1971-1979. doi:10.3109/09638280902874204

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

Yabumoto, T., Shin, S., Watanabe, T., Watanabe, Y., Naka, T., Oguri, K., & Matsuoka, T. (2015). Whole-body vibration training improves the walking ability of a moderately impaired child with cerebral palsy: a case study. *J Phys Ther Sci, 27*(9), 3023-3025. doi:10.1589/jpts.27.3023

Zhou, J., Butler, E. E., & Rose, J. (2017). Neurologic Correlates of Gait Abnormalities in Cerebral Palsy: Implications for Treatment. *Front Hum Neurosci, 11*, 103. doi:10.3389/fnhum.2017.00103

Zwicker, J. G., & Mayson, T. A. (2010). Effectiveness of treadmill training in children with motor impairments: an overview of systematic reviews. *Pediatric Physical Therapy, 22*(4), 361-377 317p. doi:10.1097/PEP.0b013e3181f92e54

FOREWORD

To compare the effects of a single bout of treadmill walking to a single combined bout of whole-body vibration and treadmill walking, data were collected at five time points: baseline (T1), following a bout of treadmill walking (T2), a second baseline following a 20-minute rest break (T3), following a session of whole-body vibration (T4), and following a second bout of treadmill walking (T5). To most effectively present the significant results, Chapter Two will focus on the changes in spasticity between two modalities (i.e., whole-body vibration vs. treadmill walking) seen in the first four time points, while Chapter Three will focus on the changes in overground gait seen across time points T1, T2, T3, T4, and T5.

2 COMPARING THE EFFECTS OF A SINGLE BOUT OF TREADMILL WALKING TO A SINGLE SESSION OF WHOLE-BODY VIBRATION ON LOWER EXTREMITY SPASTICITY IN AMBULATORY CHILDREN WITH CEREBRAL PALSY

Introduction

Cerebral palsy (CP) is the most common motor disability in childhood, with an occurrence of between 1.5 and 4 per 1,000 live births worldwide. The most common presentation of CP is spastic CP, representing approximately 80% of individuals; this form of CP is characterized by a form of hypertonia known as spasticity. Hypertonia is typically defined simply as increased muscle tone. In the context of neuromotor disease, it is best described as an increase in "the readiness with which the nervous system activates the muscle in response to stimuli" (Masi & Hannon, 2008). The presence of spasticity in CP frequently correlates with the presence of various impairments, such as muscle weakness, increased contracture development, and stereotypical gait abnormalities (Choi et al., 2018; Lotfian et al., 2016). Increased lower extremity spasticity has also been shown to be associated with decreased quality of life (Jaspers et al., 2013). Therefore, managing spasticity in an attempt to normalize movement patterns typically emerges as a goal of therapeutic intervention for children with CP and their families.

Quantifying spasticity to track improvement, however, is a complicated process. The most common clinical measures of spasticity are the Modified Ashworth Scale (MAS) (Bohannon & Smith, 1987) and the Modified Tardieu Scale (MTS) (R. N. Boyd & Graham, 1999). Both assessments involve subjectively rating the spasticity of a muscle following a passive, high velocity movement into a lengthened position. The MAS only assigns a single numerical score based on the severity of the spastic "catch," while the MTS assigns a numerical value to the spastic “catch,” notes the angle at which the spastic reaction occurs, and also notes the full passive range of motion (ROM) of the muscle when moved at a low velocity. The MTS has been shown to demonstrate better inter-rater reliability than the MAS (Numanoğlu, 2012). This may be due to its use of different velocities in testing, allowing for the distinction between resistance due to passive stiffness and resistance due to a hyperactive stretch reflex. This gives the MTS the potential to differentiate the relative contributions of these two different components, which may allow for more nuanced clinical decision-making. Despite this, it still trails behind the MAS in terms of widespread use by clinicians and researchers.

Due to the difficulty in quantifying spasticity with existing clinical scales, several instrumented approaches have been proposed in the literature. The Wartenburg pendulum test is a commonly used instrumented measure of spasticity that assesses spasticity and passive stiffness of the quadriceps. The subject sits quietly while kinematic and EMG data are collected as an examiner moves the knee passively into extension and then drops the lower leg, allowing the limb to oscillate until it comes to rest. This test has been reported to reliably distinguish the presence of quadriceps spasticity in individuals with CP, and can classify the levels of spasticity that are not apparent on the MAS (Greenan Fowler, Nwigwe, & Wong Ho, 2000). While it has not been compared directly to the MTS, the relative similarity of the MAS and MTS make it likely that the pendulum test may also be able to classify the levels of spasticity that the latter cannot. Thus, instrumented approaches like this may be able to distinguish changes in spasticity that are not detectable by standardized clinical measures, and therefore are a valuable tool for evaluating the effectiveness of interventions that reportedly affect spasticity.

Single bouts of whole-body vibration (WBV) have been reported to acutely decrease spasticity and improved isolated active ROM in children and adults with CP (Cheng, Ju, et al., 2015; Duquette et al., 2015; Krause et al., 2017; H. Q. Liang, 2018; Park et al., 2017; R. Ritzmann et al., 2018). These effects are transient, generally lasting between 30 minutes (Cheng, Ju, et al., 2015) and two hours (Park et al., 2017). Additionally, response to WBV is highly variable, with some children with CP demonstrating notable improvement and some failing to significantly respond to intervention at all (Krause et al., 2017; H. Liang, Henderson, & Wu, 2020). Despite these limitations, these acute effects still have clinical relevance. Cheng, Ju, et al. (2015) stated that these acute effects could "promote children's active participation in exercise," suggesting that WBV might be most effective as a preparatory modality, used to temporarily minimize spasticity and then combined with other rehabilitation techniques to maximize their potential benefits. However, some authors have posited that WBV functions in similar fashion to a traditional "warm-up" prior to exercise (Rittweger, 2010). Thus, it is important to quantify the acute effects of WBV and compare them with those of a more traditional "warm-up" modality to more accurately understand the neuromuscular mechanisms behind these improvements.

Treadmill training is a popular intervention technique in pediatric rehabilitation, and is commonly used for children with a wide variety of diagnoses, including CP. Systematic reviews have determined that participation in treadmill training was safe and well-tolerated for children with CP (Damiano & DeJong, 2009; Valentin-Gudiol et al., 2017; Willoughby et al., 2009b; Zwicker & Mayson, 2010), although specific benefits are less consistently documented and much more widely variable. With regards to spasticity, a weeks-long program of repetitive backward downhill treadmill walking has been shown to decrease subjective spasticity scores of the ankle plantarflexors on the MAS (Hosl, Bohm, Eck, Doderlein, & Arampatzis, 2018), but no other effects on lower extremity spasticity have been seen due to treadmill walking in individuals with CP (Zwicker & Mayson, 2010). Walking on a treadmill also represents a common "warm-up" modality used prior to higher-intensity exercise; warming up prior to exercise is recommended for individuals with CP (Verschuren, Peterson, Balemans, & Hurvitz, 2016) and may consist of 5-10 minutes of activity that encompasses low intensity walking or wheelchair propulsion ("Exercise principles and guidelines for persons with cerebral palsy and neuromuscular disorders," 1999). Thus, treadmill walking is a common, well-tolerated intervention in this population that often functions as both a "warm-up" and a treatment technique; it also has minimal known effects on spasticity, making it ideal to compare against WBV when investigating the acute neurophysiological mechanisms of the latter.

The purpose of this study, therefore, is to compare the acute effects of a single bout of treadmill walking to a single bout of WBV on the lower extremity spasticity of ambulatory children with CP. I hypothesize that a single bout of treadmill walking or WBV will produce different effects on lower extremity spasticity such that 1) a single bout of treadmill walking alone will produce no alterations in lower extremity spasticity, and that 2) a single bout of WBV will decrease lower extremity spasticity at the knee and ankle, as evidenced by an improvement in the R1 joint angle and an increase in the first flexion excursion, relaxation index, and number of oscillations of the lower limb during the pendulum test.

Methodology

Participants

I recruited 9 ambulatory children (3M/6F) with CP between the ages of 6-17 years. Mean (SD) height and mass were 133.4(18.8) cm and 32.1(15.2) kg (Table 2-1). Participants were required to have a medical diagnosis of CP and to be classified as a Level I, II, or III on the Gross Motor Function Classification System (GMFCS). Each subject's GMFCS level was confirmed by an experienced physical therapist prior to participation, either by administering the standardized questionnaire (Dietrich, Abercrombie, Fanning, & Bartlett, 2007) or confirming a parent-reported level using the GMFCS Expanded and Revised (Palisano, Rosenbaum, Bartlett, & Livingston, 2007). Exclusion criteria included a history of Botox injections to the lower extremities within the past three months, a history of musculoskeletal injury within the past six months, a history of lower extremity orthopedic surgery within the past six months, a history of significant uncontrolled cardiac abnormalities, a history of uncontrolled seizures, and any cognitive or behavioral issues that prevented the subject from safely following instructions while walking on the treadmill. This study was approved by the institutional review board at Georgia State university. Written parental permission was obtained from the parents or guardians of all the subjects and assent was obtained from all subjects prior to data collection.

Table 2-1 Descriptive data of all subjects

Subject	Gender	Age	Topography	GMFCS Level	Preferred Overground Speed (m/s)	Height (cm)	Body mass (kg)
CP01	F	11	L hemiplegia	I	1.39	152.0	49.2
CP02	F	7	diplegia	II	1.00	117.0	17.3
CP03	F	17	quadriplegia	III	0.82	158.0	55.4
CP04	M	13	quadriplegia	II	1.04	124.0	24.5
CP05	M	6	R hemiplegia	II	0.75	124.0	20.2
CP06	F	9	diplegia	II	0.54	116.0	19.8
CP07	M	6	quadriplegia	II	0.75	109.5	17.6

CP08	F	17	L hemiplegia	I	0.79	149.0	42.0
CP09	F	17	L hemiplegia	I	0.68	151.5	43.2
Mean (SD)	6 F 3 M	11.4 (4.7)	4 hemiplegia 2 diplegia 3 quadriplegia	3 I 5 II 1 III	0.90 (0.30)	133.4 (18.1)	32.1 (15.2)

Data collection

Anthropometric measures including height, body mass, and leg length were taken for each subject. Their skin was then marked with an eyebrow pencil to identify marker placement, and 16 reflective markers were placed on the lower body landmarks specified for the Plug-In Gait Lower Body model using double-sided tape; these landmarks include the anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), lateral thigh, lateral knee, lateral tibia, lateral malleolus, calcaneus, and second metatarsal bilaterally (Figure 2-1).

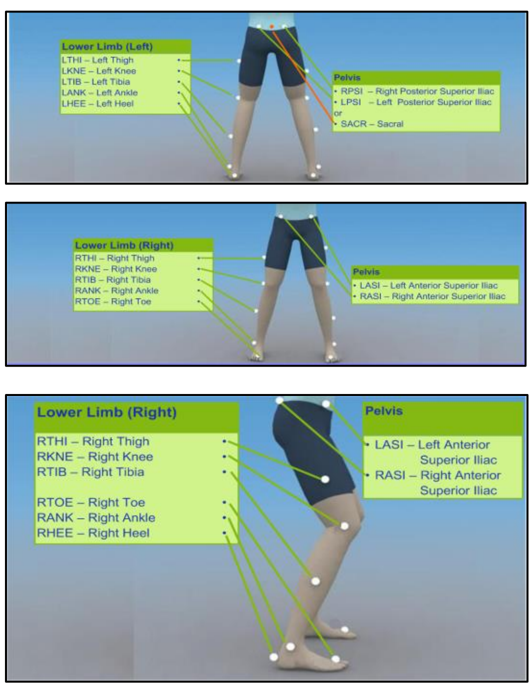


Figure 2-1 Marker placement for the Lower Body Plug-In Gait model

Following marker placement, the skin was gently abraded with an alcohol wipe and Trigno Wireless EMG sensors (Delsys, Natick, MA, USA) were adhered over the following muscles of the limb(s) being tested using double-sided tape: vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), and lateral gastrocnemius (LG). For individuals with hemiplegia, EMG data were only collected on the involved limb, while EMG data were collected bilaterally for individuals with diplegia or quadriplegia. Previous unpublished work in typically developing young adults has shown that vertical acceleration due to WBV is significantly reduced above the knee (Lelko, 2018), so the focus was limited to the muscles surrounding the knee and ankle joints only.After all markers and EMG sensors were secured, subjects completed three trials of walking along a 10-meter hallway at a comfortable pace. The timed trials were averaged to determine each subject's "self-selected" speed, which was utilized to calculate the speed of treadmill walking for each subject. The subject then moved to a plinth and performed three reps of a maximum voluntary isometric contraction (MVIC) of the quadriceps, hamstrings, tibialis anterior, and gastrocnemius for each limb being tested; manual resistance was applied to facilitate a maximum isometric contraction while EMG data were collected. Subject position and the application site of manual resistance were performed in accordance with Daniels and Worthingham's muscle testing parameters (Hislop, Avers, Brown, & Daniels, 2014). If the subject did not appear to utilize maximal effort for a trial, instructions were repeated, and additional trials collected until three successful trials were completed.

Next, spasticity and gait were assessed for the first of five times (Figure 2-2). The subject moved to a supine position on the plinth for assessment of spasticity of the gastrocnemius and hamstrings using the Modified Tardieu Scale (MTS).

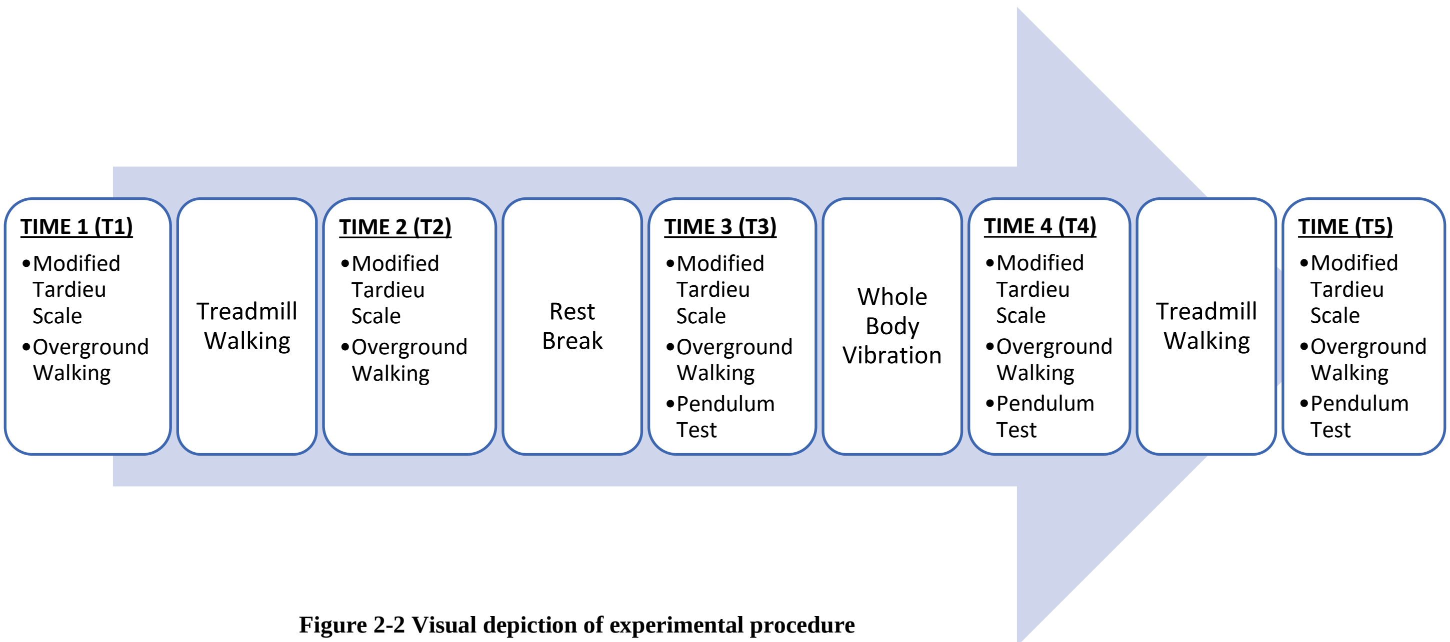


Figure 2-2 Visual depiction of experimental procedure

The MTS was performed by an experienced clinician in accordance with standardized procedures (R. N. Boyd & Graham, 1999). The subject remained positioned quietly in supine while the examiner moved the joint to be assessed. To assess spasticity of the gastrocnemius the knee was placed in full extension and the ankle moved into dorsiflexion, and to assess spasticity of the hamstrings the hip and knee were placed in 90° of flexion and the knee moved into extension. Joint angles were measured in accordance with standard goniometric principles (Norkin & White, 2016). The examiner moved the joint passively at two velocities, a high velocity (HV) to assess for the presence of a spastic “catch”, and a low velocity (LV) to assess muscle length. For the purposes of this study, LV was defined as completing the joint’s full available ROM in five seconds and HV was defined as completing the range as quickly as possible, faster than the limb would naturally drop under the effect of gravity. The examiner then graded the muscle reaction obtained during the HV movement on a six-point ordinal scale (R. N. Boyd & Graham, 1999) (Table 2-2).

Table 2-2 Scoring quality of muscle reaction using the Modified Tardieu Scale

SCORE	QUALITY OF MUSCLE REACTION
0	No resistance during passive movement
1	Slight resistance to passive movement with no clear “catch” at a precise angle
2	Clear “catch” at a precise angle, interrupting passive movement, followed by release
3	Clonus that fatigues in <10 seconds, occurring at a precise angle
4	Clonus that fatigues in >10 seconds, occurring at a precise angle
5	Immovable joint

The subject then completed five trials of overground walking at a self-selected pace along a 10m walkway through the camera field.

After completing these baseline assessments, the subject stepped onto a Zebris FDM-T instrumented treadmill (Zebris Medical GmbH, Isny, Germany). Soft mats were placed around the treadmill to prevent injury in case of a fall, and a researcher stood near the subject in order to assist if loss of balance occurred. The subjects also held onto an anterior support bar on the treadmill. Each subject completed ten minutes of forward treadmill walking at a speed equal to 125% of their self-selected overground speed obtained during the 10m walk test to provide a challenging walking task. My preliminary results from another study have shown that typically developing children demonstrate greater joint ROM and higher levels of muscle activation when walking on a treadmill at a faster speed (Henderson, Ferreira, & Wu, 2020). In the current study, three subjects were not able to maintain this pace and walked at slower speeds on the treadmill ranging from 96-104% of their self-selected pace, with speeds ranging from 0.63 – 1.12 m/s and a mean (SD) of 0.94 (0.3) m/s. The other six subjects were able to safely complete the full ten minutes of ambulation at 125% of their overground pace, with speeds ranging from 0.85 – 1.74 m/s and a mean (SD) of 1.08 (0.3) m/s.

During treadmill walking, two minutes of data were collected in the middle of the trial once the subject had visually appeared to reach steady-state walking; this included kinematic data from the Vicon motion capture system (Vicon, Denver, CO), the kinetic data from the instrumented treadmill belt, and EMG data from all surface EMG electrodes (Delsys, Natick, MA). After completing ten minutes of treadmill walking, the subject immediately repeated assessments of lower extremity spasticity and overground walking (i.e., time point T2), as before. Once the post-treadmill measurements are taken, the subject took a seated rest break for twenty minutes.

Following the rest break, subjects repeated the assessment of lower extremity spasticity measurements and overground walking a third time (i.e., time point T3). This time point served as a second baseline, allowing variables to be compared pre- and post- both interventions. Additionally, the spasticity assessment at this time point included both the MTS, as previously described, and the Wartenburg pendulum test. To conduct the pendulum test, the subject sat quietly on the edge of a raised plinth with the hips and knees at 90°. The examiner passively extended one knee, and then dropped the leg, allowing the lower limb to swing freely until it came to rest. The test was first demonstrated to the subject, and then three usable trials were collected, during which kinematic and EMG data were recorded (Ferreira, Liang, & Wu, 2020; Lotfian et al., 2016). Usable trials were defined as trials in which the subject allowed their lower limb to swing freely, did not actively swing their leg, and did not produce associated movements such as lifting the leg off the table (Ferreira et al., 2020). If the subject did not allow the limb to swing freely, or voluntarily moved the leg during the trial, the instructions and demonstration were repeated, and additional trials collected until the goal of three usable trials was met. Two subjects were unable to fully relax their more spastic limb during the pendulum test; this resulted in the collection of unilateral data only (on the less impaired limb) for one subject with diplegia, and the collection of no data for one subject with hemiplegia.

After measurements were completed, the subject moved to stand on a Galileo Med-L side-to-side-alternating WBV plate (StimDesigns LLC, Carmel, CA, USA) and completed eight bouts of 90 seconds of vibration at 20 Hz and an amplitude of 2 mm. This combination of frequency and amplitude has been shown to produce acute improvements in spasticity in children with CP (Cheng, Ju, et al., 2015; H. Liang et al., 2020). During the vibration, the subject held onto an anterior handrail with both hands. If the subject had difficulty maintaining neutral alignment with the knees slightly flexed and the feet flat during the vibration, he or she was manually assisted with maintaining that position by an experienced member of the research team. Between each bout, the subject rested in a seated position for 90 seconds. A single subject (CP06) did not tolerate the vibration well, and only completed four bouts; the remaining subjects completed all eight bouts without difficulty. After completing the final bout of vibration, the subject again completed assessment of lower extremity spasticity and overground walking (i.e., time point T4), and then immediately returned to the treadmill. Ten more minutes of walking at 125% of each subject's overground pace was completed in the same manner as before, with two minutes of data collection in the middle of the trial. Subjects who were unable to maintain the 125% pace during the first bout of treadmill walking utilized the same max speed during the second bout that they did during the first. Following completion of the second bout of treadmill walking, the subjects completed a fifth (i.e., time point T5) and final assessment of lower extremity spasticity and overground walking.

Data analysis

Outcome measures included (1) MTS scores as measured by a clinician, (2) instrumented data collected during performance of the MTS, including joint angles and muscle activity during movement of the limb, and (3) pendulum test variables, including the knee angle achieved during the first flexion excursion, the number of oscillation cycles the lower limb completed before coming to rest, and a Relaxation Index, which is defined as the ratio of the movement during the first flexion excursion to the difference between the starting angle of the knee and the angle of the knee at rest (Ferreira et al., 2020; Greenan Fowler et al., 2000; Lotfian et al., 2016). The utilization of both clinical and instrumented approaches to quantify spasticity allowed for both the investigation of the correlation between the measures as well as ascertaining which aspects of spasticity were being affected by the interventions.

Variables collected during the administration of the MTS included an “R1” angle, which represents the first stop when moving the joint passively at HV, an “R2” angle, which represents the second stop when moving the joint passively at LV (Figure 2-3), the difference between the R1 and R2 angles, and a subjective rating of the severity of the spastic “catch” felt by the examiner (Table 2-2). As previously noted, the joint angles were taken using standardized goniometric assessment measures (Norkin & White, 2016). The joint angles were then subtracted from 180° and made negative, to give a value that describes how much knee extension from vertical subjects are lacking due to their hamstring length. 0° represents full extension and negative values represent the amount of knee extension a subject is lacking due to hamstring tightness. For example, a measurement of -20° would indicate that 20 degrees are lacking from full knee extension. The joint angles at the ankle were reported using standard terminology, with positive angles representing dorsiflexion and negative angles representing plantarflexion.

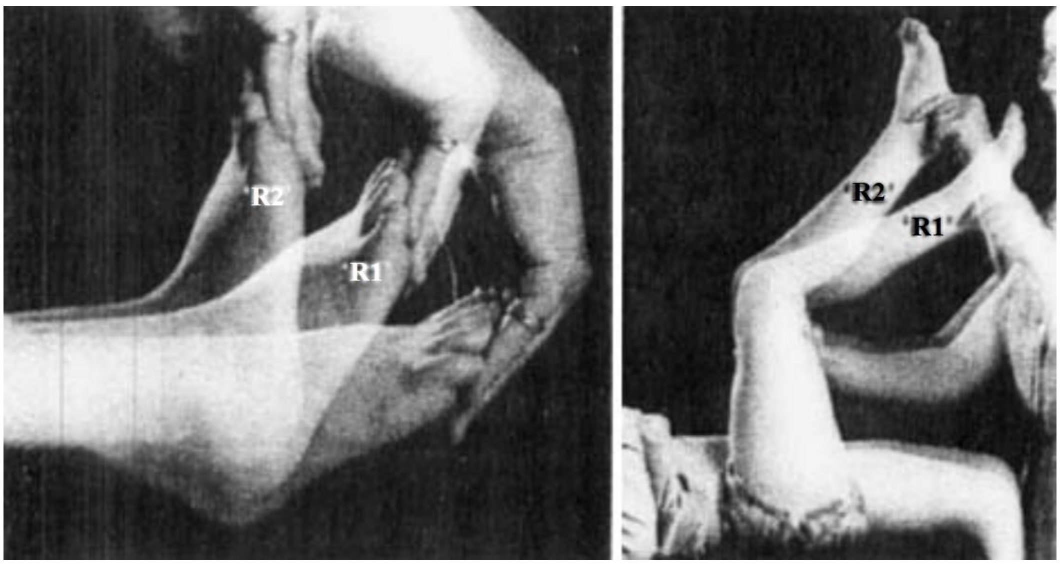


Figure 2-3 Example "R1" and "R2" values for ankle dorsiflexion and knee extension, reprinted from Boyd et. al (1999)

Kinematic data collected during the pendulum test were processed using Vicon Nexus 2.5 (Vicon, Denver, CO). Marker trajectories were smoothed using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 6 Hz (Beerse, Henderson, Liang, Ajisafe, & Wu, 2018; Henderson, Beerse, Liang, Ferreira, & Wu, 2020; Wu, Beerse, Ajisafe, & Liang, 2015). Next, the ipsilateral thigh, knee, and tibia markers were projected to lie in the sagittal plane (Ferreira et al., 2020). Kinematic variables were calculated using custom MATLAB programs; this included the range of the first flexion excursion (A_1), a relaxation index (RI), and the number of oscillations the lower limb completed before coming to rest (Figure 2-4). RI was calculated the ratio between A_1 and A_0, where A_0 is the difference between the starting angle and the resting angle

(Greenan Fowler et al., 2000). The number of oscillations was defined as the number of times the lower leg moved between the two peaks of flexion until the it reached a resting state, defined as a movement of 3° or less towards extension (Ferreira et al., 2020; Lotfian et al., 2016). This can be visualized in the graphic below (Figure 2-4), with one oscillation occurring between F1 and F2, a second between F2 and F3, a third between F3 and F4, etc.

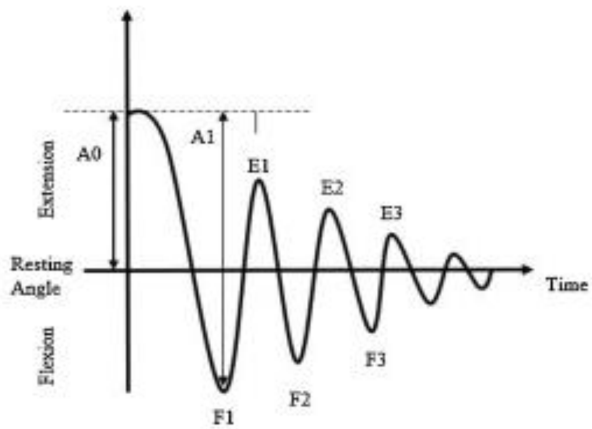


Figure 2-4 Graphical representation of the lower limb motion during the pendulum test, with values used to calculate the Relaxation Index (RI) labeled

Statistical Analysis

All variables were tested for normality of distribution using a Shapiro-Wilk test and found to be normally distributed. A series of 2-way (2 intervention x 2 time) mixed ANOVA with repeated measures on both factors were utilized to compare changes on the spasticity variables. Two intervention levels included treadmill walking and WBV. Two time levels included the time points associated with before and after two interventions such that T1 and T2 were associated with treadmill walking, and T3 and T4 were associated with WBV. A series of 1-way repeated measures ANOVA (3 time) were utilized to compare performance on the pendulum test across time points T3 – T5. All data were analyzed using SAS 9.4 (SAS, Cary, NC, USA). A significance level of α=0.05 was used for all statistical tests.

Additionally, since response to both WBV and treadmill walking varies greatly from person to person in children with CP (Krause et al., 2017; H. Liang et al., 2020; Valentin-Gudiol et al., 2017), subjects' responses to intervention were examined at both the group and individual levels.

Results

Modified Tardieu Scale

1.1.1.1 R1 joint angle

There was not a significant intervention effect, time effect, or intervention by time interaction (Figure 2-5, Table 2-3).

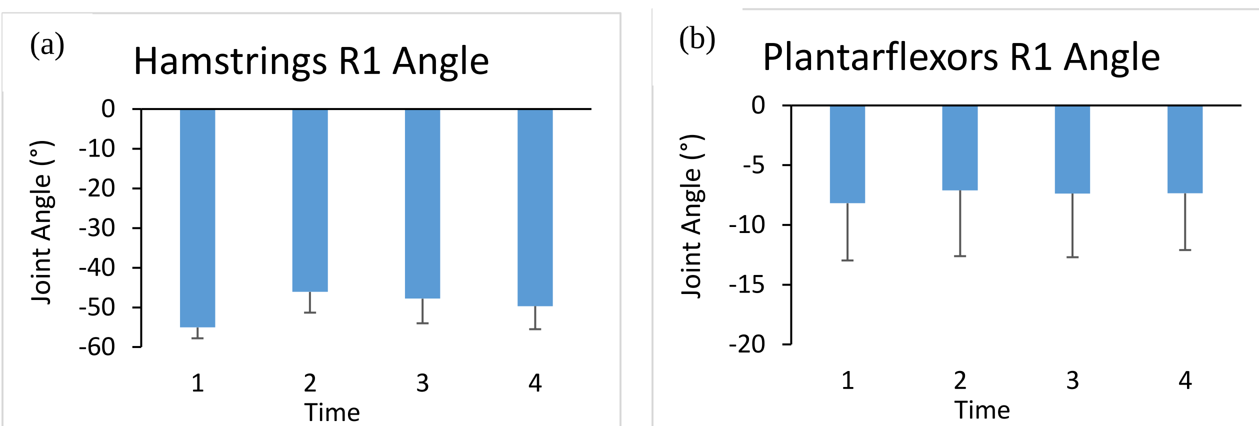


Figure 2-5 Group means for the R1 joint angles of the (a) hamstrings and (b) plantarflexors

Table 2-3 Statistical results for R1 joint angle

Variable	Intervention		Time		Intervention*Time	
	F	*p*	F	*p*	F	*p*
Left Hamstrings	1.58	0.22	1.36	0.26	3.43	0.08
Left	0.01	0.93	0.03	0.86	0.00	0.97

Plantarflexors						
Right Hamstrings	0.00	0.95	0.23	0.64	0.57	0.46
Right Plantarflexors	0.00	0.96	0.02	0.88	0.06	0.81

When results were examined at the individual level, there was significant individual variability in the eight subjects who completed this assessment (Table 2-4); subject CP04 did not undergo these measurements. The three most common overall response trends of the R1 joint angles were: 1) improvement following both treadmill walking and WBV (n = 4, seen in green in Table 2-4), 2) no change following treadmill walking and improvement following WBV (n = 3, seen in yellow in Table 2-4), and 3) improvement following treadmill walking and worsening following WBV (n = 3, seen in red in Table 2-4).

Table 2-4 Individual responses of the R1 joint angle for the hamstrings and plantarflexors at time points T1-T4; results highlighted in green represent improvement following both interventions, results highlighted in yellow represent no change following treadmill walking and improvement following WBV, and results highlighted in red represent improvement following treadmill walking and worsening following WBV.

Subject / Limb	Hamstrings R1 Joint Angle				Plantarflexors R1 Joint Angle			
	Time 1	Time 2	Time 3	Time 4	Time 1	Time 2	Time 3	Time 4
CP01 L	-45	-30	-35	-30	-20	-16	-10	-10
CP02 L	-60	-40	-40	-50	-18	-16	-14	-20
CP02 R	-75	-60	-60	-70	-6	-4	-2	-6

CP03 L	-62	-47	-45	-40	-4	-4	-6	0
CP03 R	-57	-40	-45	-39	1	-1	-2	-2
CP05 R	-47	-40	-47	-45	2	5	3	2
CP06 L	-47	-42	-42	-53	4	0	2	-6
CP06 R	-38	-47	-42	-45	2	2	3	1
CP07 L	-65	-53	-56	-55	-21	-19	-17	-17
CP07 R	-68	-62	-67	-70	-23	-18	-20	-15
CP08 L	-48	-49	-48	-53	-20	-20	-21	-18
CP09 L	-45	-45	-38	-38	-2	-1	-12	-4

The most common response trend, seen in four subjects, was reduction in R1 joint angles following each intervention; examples of this trend can be seen below (Figure 2-6a-c). This response was seen in both the hamstrings (of 4 subjects: CP01, CP03, CP05, and CP07) and plantarflexors (of 1 subject: CP07), and represents an improvement in spasticity, with the spastic "catch" occurring later in the arc of motion. These improvements at the hamstrings were generally larger following the first intervention, the bout of TW, than following the second intervention, the bout of WBV; examples of this can be seen below in Figure 6a-b. Improvements averaged 13.2° at the hamstrings following TW and 3.8° following WBV. However, the joint angles following WBV (averaging -41.8°) were similar to those seen following TW (averaging -42.0°). The improvements at the plantarflexors, in contrast, were generally similar following both interventions, with an improvement of 5° following both WBV and TW. Improvements at the plantarflexors were also smaller, however, barely meeting the minimal detectable change (MDC) in goniometry which, for an experienced examiner, is estimated as 4-5° (Norkin & White, 2016).

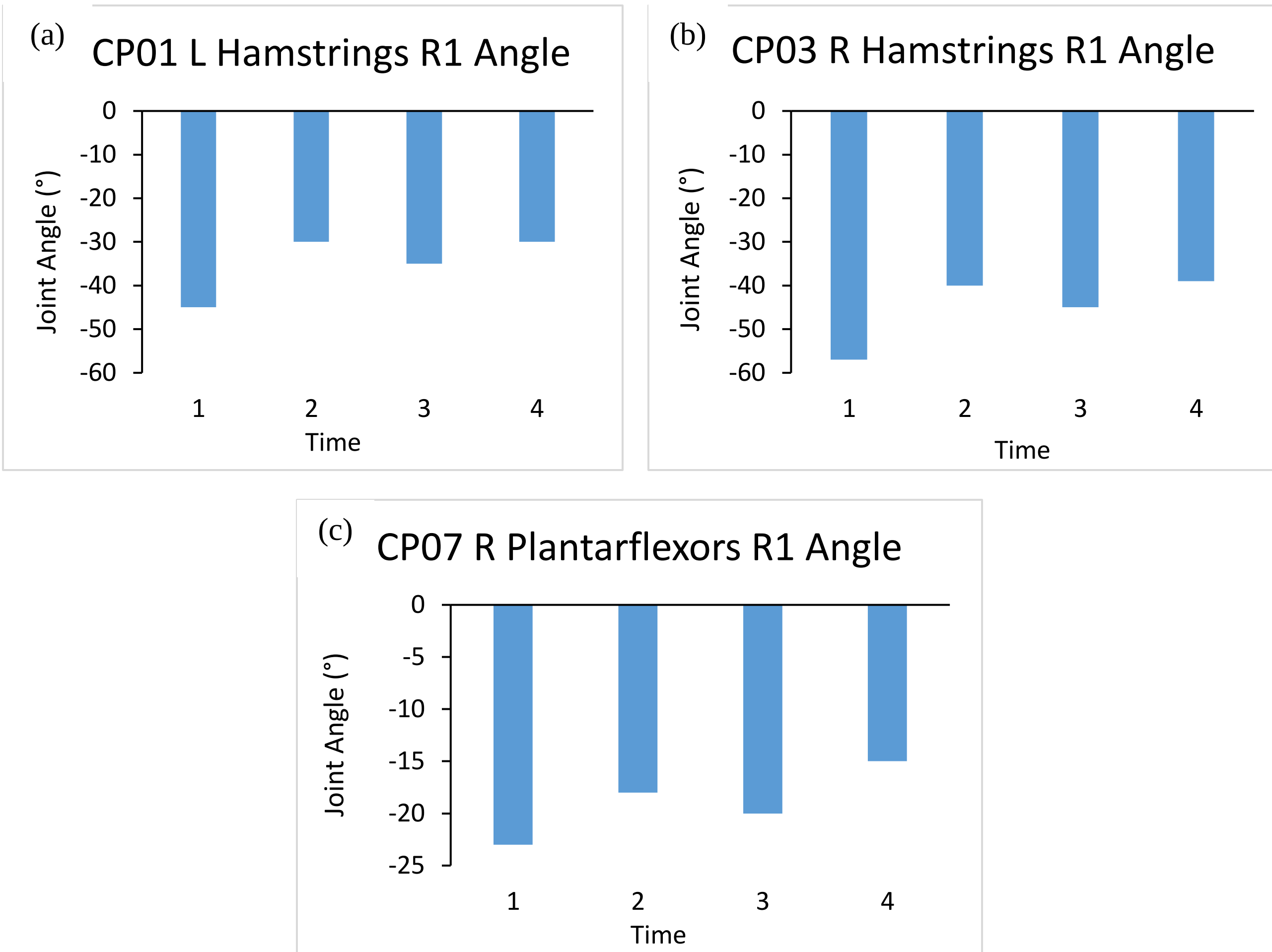


Figure 2-6 R1 joint angles of the hamstrings and lateral gastrocnemius for (a) the left leg of CP01, (b) the right leg of CP03, and (c) the right leg of CP07

Another common response pattern, seen in three subjects (CP03, CP08, and CP09), involved no change in the R1 joint angle following treadmill walking but improvement in this angle following WBV; examples of this trend can be seen below (Figure 2-7a-b). This response was only seen in the plantarflexors. The reduction in the R1 angle following WBV averaged 5.6°. Of note, subject CP03 demonstrated an asymmetrical quadriplegic presentation, and this pattern of change was seen only on the less involved side; the more involved side remained within 2° of neutral throughout all time points.

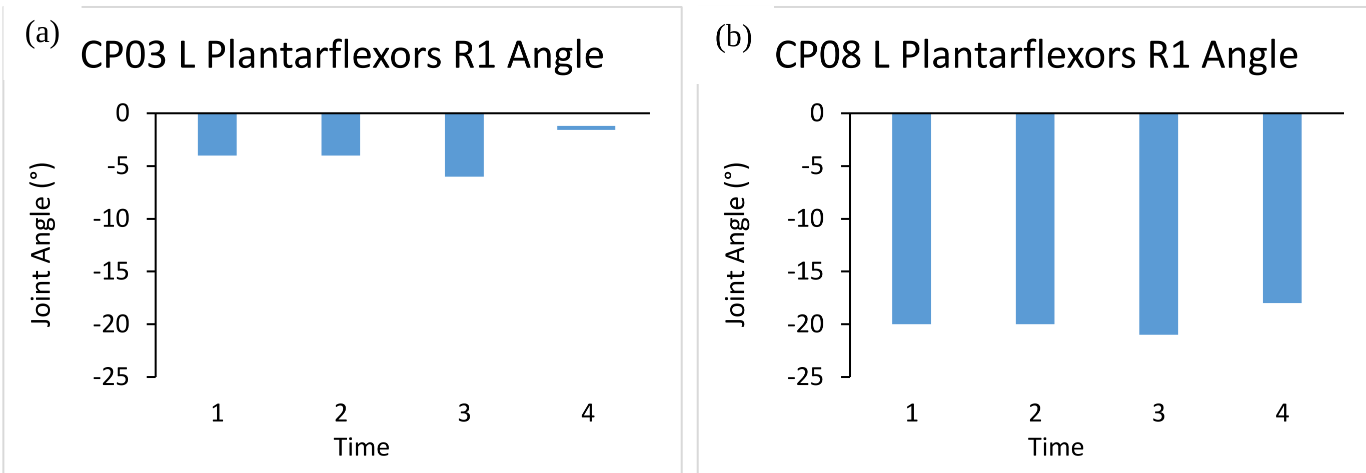


Figure 2-7 R1 joint angles of the plantarflexors for (a) the left leg of CP03 and (b) the left leg of CP08

Finally, three subjects (CP02, CP05, and CP06) demonstrated an improvement in R1 joint angle (indicating decreased spasticity) following TW and a worsening of R1 joint angle (indicating increased spasticity) following WBV; examples of this trend are seen below (Figure 2-8a-c). This response was seen in both the hamstrings (n = 2) and plantarflexors (n = 2). The average improvement was 13.3° in the hamstrings and 2.3° in the plantarflexors following TW, followed by an average worsening of 10.3° in the hamstrings and 3.6° in the plantarflexors following WBV. This resulted in the joint angle following WBV (averaging -57.6° at the hamstrings and -8.0° at the plantarflexors) approaching or surpassing the initial baseline (averaging -60.6° at the hamstrings and -7.3° at the plantarflexors).

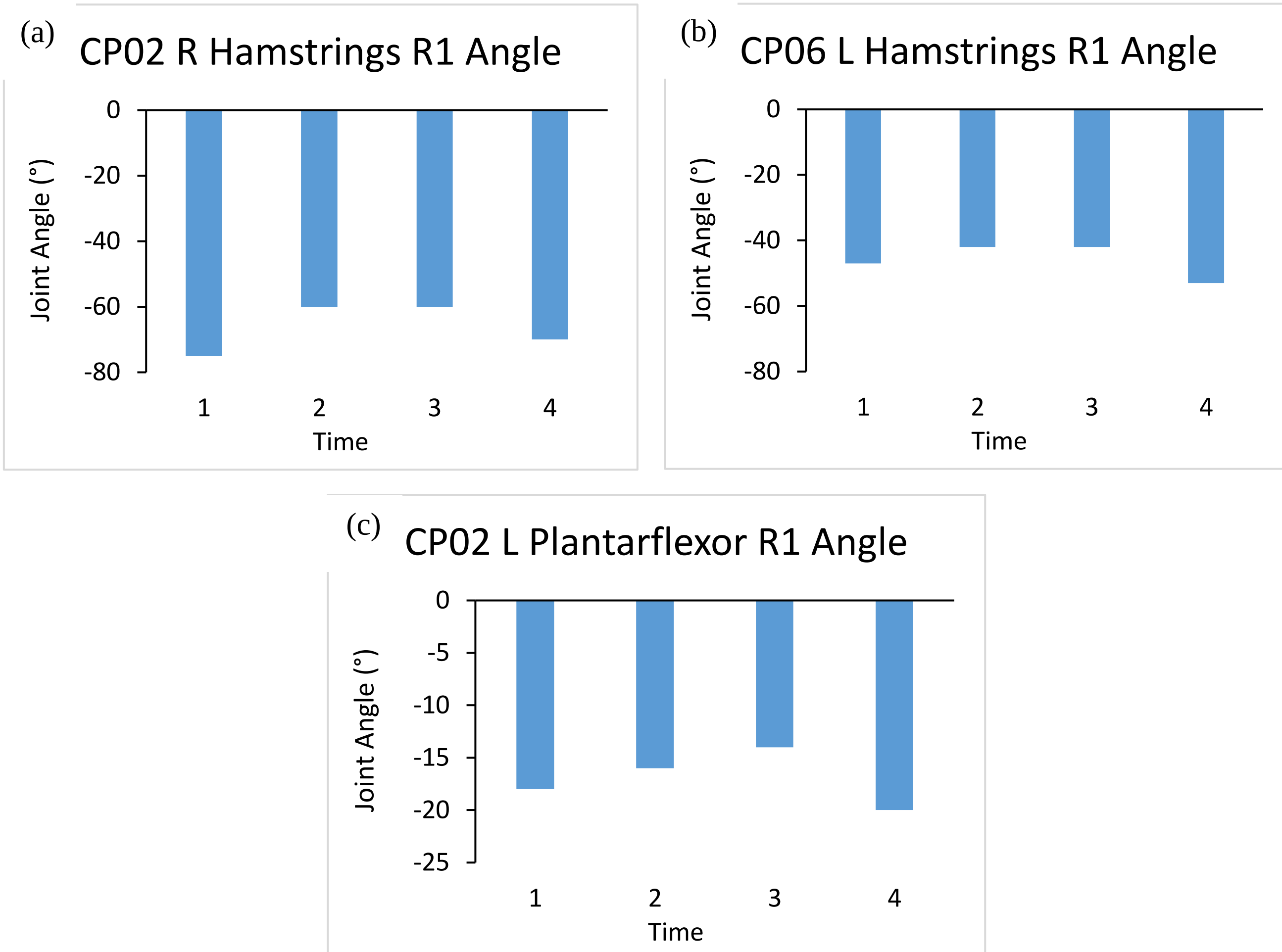


Figure 2-8 R1 joint angles of the (a) hamstrings of the right leg of CP02, (b) hamstrings of the left leg of CP06, and (c) plantarflexors of the left leg of CP02

Other response patterns of the R1 joint angles included spasticity improving following treadmill walking with no change following WBV (n = 1, CP07, at the hamstrings and n = 2, CP01 and CP07, at the plantarflexors), no change following treadmill walking and a worsening of spasticity following WBV (n = 1 at the hamstrings, CP08, and n = 1, CP06, at the plantarflex-ors), and a worsening of spasticity following both interventions (n = 1, CP06, at the hamstrings and n = 1, CP06, at the plantarflexors).

R2 joint angle

There was not a significant intervention effect, time effect, or intervention by time interaction, excepting a significant time effect (F(1,23)=4.25, *p*=0.05) for the left hamstrings (Table 2-5). Less variability of R2 response was seen across the eight subjects who completed this assessment (Table 2-6); subject CP04 did not undergo these measurements. Changes in R2 joint angles were minimal across most subjects (n = 6 at the hamstrings and n = 7 at the plantarflexors), with most being within the standard measurement error of goniometry (Norkin & White, 2016).

Table 2-5 Statistical results for R2 joint angle

Variable	Intervention		Time		Intervention*Time	
	F	*p*	F	*p*	F	*p*
Left Hamstrings	0.40	0.53	4.25	0.05	1.38	0.25
Left Plantarflexors	0.05	0.83	0.02	0.88	0.02	0.88
Right Hamstrings	0.07	0.80	0.30	0.59	0.26	0.62
Right Plantarflexors	0.11	0.74	0.11	0.74	0.01	0.93

Table 2-6 Individual responses of the R2 joint angle for the hamstrings and plantar-flexors at time points T1-T4; results highlighted in green represent those subjects who demonstrated improvements in their hamstring angles, and results highlighted in yellow represent those subjects who demonstrated improvements in the plantarflexion angles

Subject / Limb	Hamstrings R2 Joint Angle				Plantarflexors R2 Joint Angle			
	Time 1	Time 2	Time 3	Time 4	Time 1	Time 2	Time 3	Time 4
CP01 L	-45	-25	n/a	-20	0	0	2	2
CP02 L	-50	-22	-38	-38	-12	-10	-6	-8
CP02 R	-55	-45	-50	-55	-4	0	2	0
CP03 L	-55	-27	-30	-36	12	5	4	5
CP03 R	-34	-25	-27	-25	8	8	8	9
CP05 R	-42	-38	-42	-41	12	12	8	12
CP06 L	-38	-37	-38	-37	8	8	7	4
CP06 R	-32	-34	-37	-38	9	7	8	11
CP07 L	-48	-44	-48	-42	0	0	1	1
CP07 R	-55	-50	-56	-52	-8	-6	-5	-4
CP08 L	-30	-34	-31	-31	-4	2	0	10
CP09 L	-25	-24	-27	-22	8	7	5	4

Three subjects (CP01, CP02, and CP03) did show notable improvements of greater than 20° in the R2 angles of their hamstrings following TW, after which these values either stabilized or began returning to baseline; an example of this pattern is seen in Figure 2-9a. These subjects are highlighted in green in Table 2-6. Each of these subjects demonstrated these changes in their left limb, which may have contributed to the significant time effect that was only noted in the left hamstrings.

At the plantarflexors, a single subject (CP08) demonstrated a consistent improvement in plantarflexion R2 angles across all time points, moving from -4° at baseline to 10° following TW, as seen in Figure 2-9b. This subject is highlighted in yellow in table 2-6.

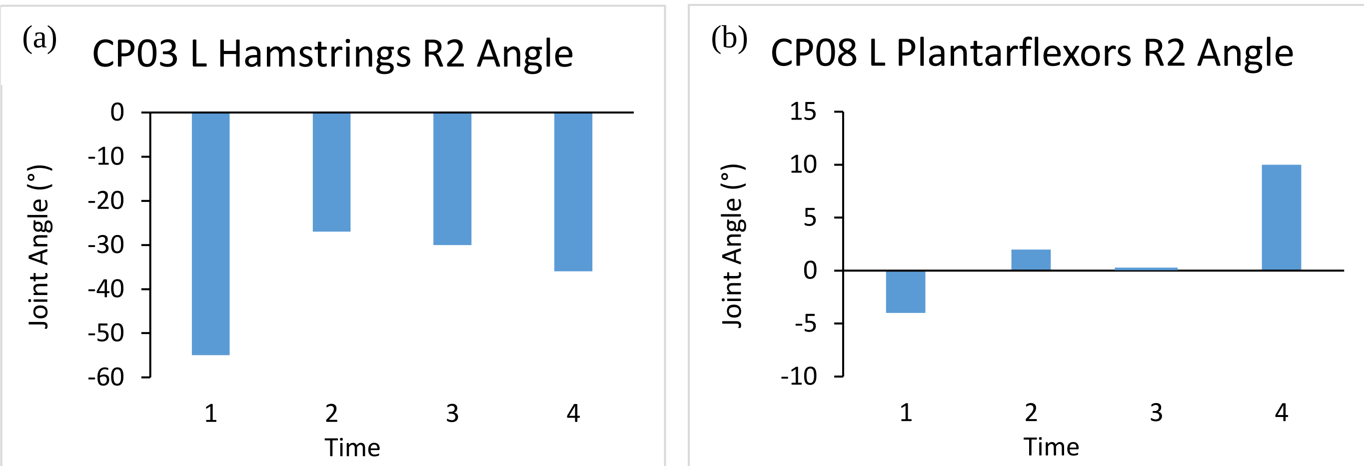


Figure 2-9 R2 joint angles of the (a) hamstrings of the left leg of CP03 and (b) plantarflexors of the left leg of CP08

Scoring of muscle reaction using the modified Tardieu test

Finally, changes in subjective scoring of the muscle reaction were also minimal across all subjects (Table 2-7). Only three subjects (CP02, CP03, and CP04) demonstrated a change in the quality of reaction across all time points. The hamstrings of CP02 and CP03 demonstrated movement between a 2 ("clear 'catch' at a precise angle, interrupting passive movement) and a 1 ("slight resistance to passive movement with no clear 'catch' at a precise angle"), while the plantarflexors of CP03 and CP04 demonstrated movement between a 2 and a 3 ("clonus that fatigues in less than ten seconds, occurring at a precise angle). No subjects demonstrated changes in the quality of muscle reaction greater than one point in either direction, at either muscle group.

Table 2-7 Individual responses of the quality of muscle reaction score on the MTS for the hamstrings and plantarflexors at time points T1-T4; note that values which represent a change from the previous timepoint are presented in bold red text

Subject / Limb	Hamstrings Quality of Muscle Reaction				Plantarflexors Quality of Muscle Reaction			
	T1	T2	T3	T4	T1	T2	T3	T4
CP01 L	0	0	0	0	3	3	3	3
CP02 L	2	2	2	2	1	1	1	1
CP02 R	**2**	**1**	**2**	2	1	1	1	1
CP03 L	2	2	2	2	**2**	**3**	3	3
CP03 R	2	2	2	2	2	**2**	**3**	3
CP04 L	2	2	**2**	**1**	3	3	3	3
CP04 R	2	2	**2**	**1**	3	**3**	**2**	**3**
CP05 R	0	0	0	0	1	1	1	1
CP06 L	1	1	1	1	0	0	0	0
CP06 R	1	1	1	1	0	0	0	0
CP07 L	2	2	2	2	3	3	3	3
CP07 R	2	2	2	2	3	3	3	3
CP08 L	1	1	1	1	2	2	2	2
CP09 L	1	1	1	1	1	1	1	1

Wartenburg pendulum test

In general, all three variables associated with the pendulum test were correlated, with similar patterns seen for the degree of the first flexion excursion (A1 values), the relaxation index, and the number of oscillation cycles observed in several subjects. Results from the eight subjects who completed the pendulum test are presented below; subject CP09 was unable to successfully complete the test.

First flexion excursion (A1 values)

There were no significant group level intervention effects, time effects, or intervention by time interactions for A1 values (F(2,32)=0.08, *p*=0.92) (Figure 2-10).

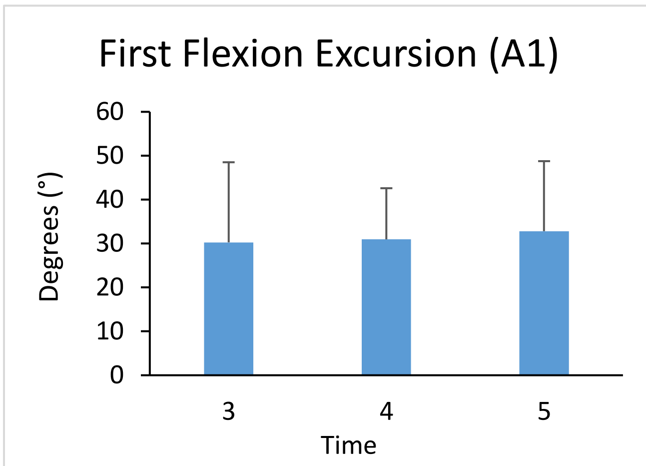


Figure 2-10 Group mean values for A1 values during the pendulum test

When results were examined at the individual level, two primary response trends were noted: 1) worsening (or increased spasticity) after WBV follow by improvement (or decreased spasticity) after treadmill walking (n = 3, seen in green in Table 2-8), and 2) improvement after WBV follow by worsening after treadmill walking (n = 2, seen in yellow in Table 2-8) (Table 2-8).

Table 2-8 Individual responses of the first flexion excursion during the pendulum test at time points T3-T5; results highlighted in green represent worsening following WBV and improvement following treadmill walking, and results highlighted in yellow represent improvement following WBV and worsening following treadmill walking

Subject / Limb	First Flexion Excursion (A1) During Pendulum Test (°)		
	T3	T4	T5
CP01 L	52.55	50.81	48.30
CP02 L	14.31	8.63	14.98
CP02 R	18.82	28.95	28.14
CP03 L	20.46	25.14	41.35
CP03 R	13.22	14.62	20.46
CP04 L	24.57	n/a	4.63
CP05 R	45.32	39.69	47.02
CP06 L	49.58	35.36	52.23
CP06 R	53.88	33.62	52.96
CP07 L	2.17	31.06	27.24
CP07 R	20.27	35.68	19.87
CP08 L	48.05	36.87	36.62

Three subjects (CP02, CP05, and CP06) demonstrated initial decrease of the A1 value, indicative of spasticity of the knee extensors worsening, following WBV and then an increase, indicative of spasticity of the knee extensors improving, following the subsequent bout of TW. The average decrease in the A1 value between T 3 and T4 for these subjects was 11.4°, while the average increase between T 4 and T5 was 12.9°; this resulted in a functional return to baseline after treadmill walking, with the A1 values at T5 returning to within, on average, 1.5° of the values at T3. Examples of this pattern of response can be seen in Figure 2-11a-b.

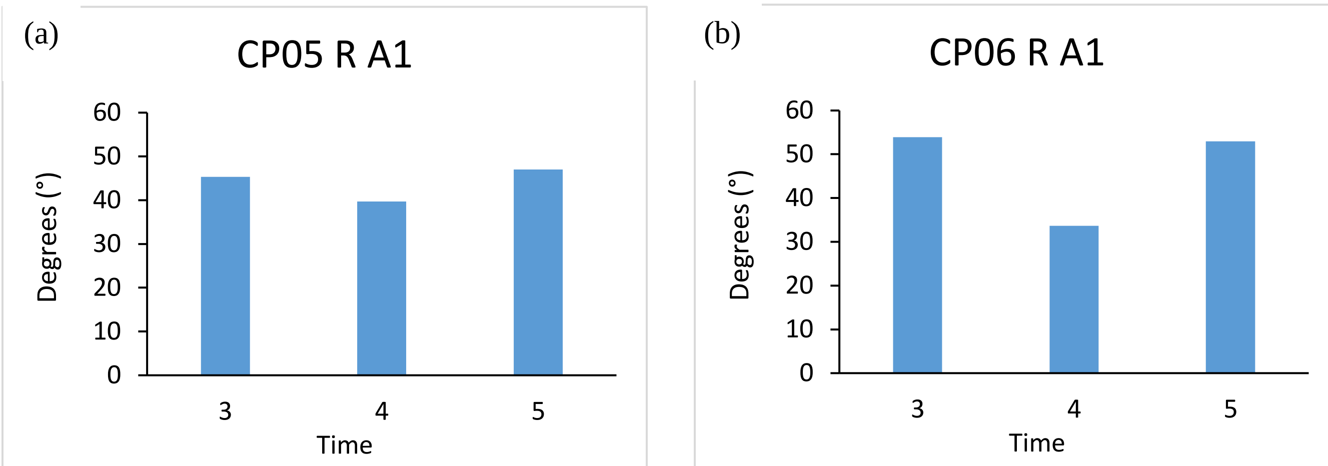


Figure 2-11 First flexion excursion (A1 values) for (a) the right leg of CP05 and (b) the right leg of CP06

Two subjects (CP02 and CP07) demonstrated an initial increase of the A1 value, indicative of spasticity of the knee extensors improving, following WBV and then a decrease, indicative of spasticity of the knee extensors worsening, following the subsequent bout of TW. The average increase in the A1 value between T and 4T for these subjects was 18.1°, while the average decrease between T 4 and T5 was 6.81°. Examples of this pattern of response can be seen in Figure 2-12a-b.

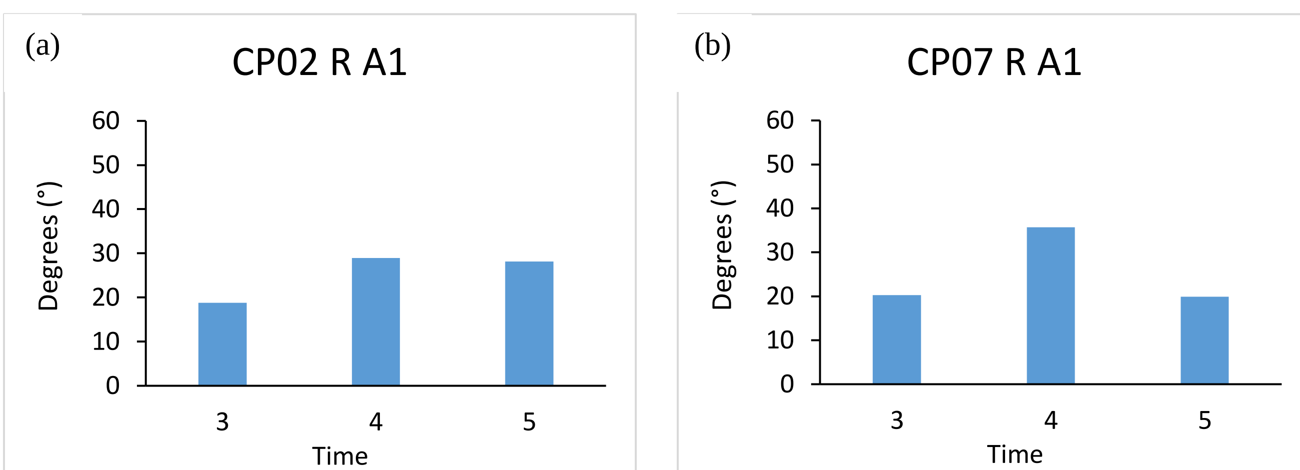


Figure 2-12 First flexion excursion (A1 values) for (a) the right leg of CP02 and (b) the right leg of CP07

Other response patterns of the A1 angle included consistent worsening of spasticity across all time points (n = 1, CP01), consistent improvement of spasticity across all time points (n = 1, C03), and a worsening after WBV followed by no change after treadmill walking (n= 1, CP08) (Table 2-6).

Relaxation Index

There were no significant group level intervention effects, time effects, or intervention by time interactions for the Relaxation Index of the pendulum test (F(2,32)=0.39, *p*=0.68) (Figure 2-13).

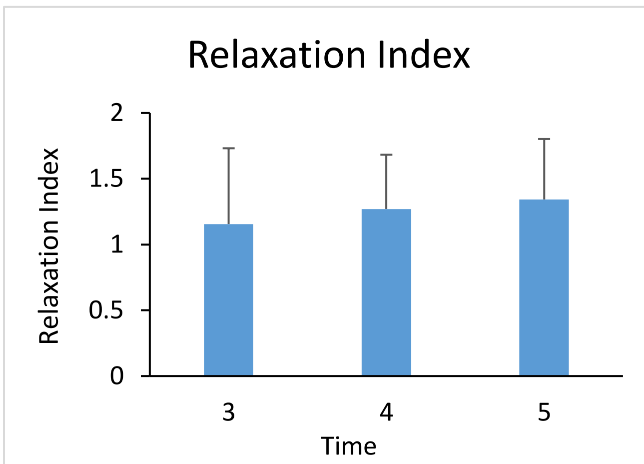


Figure 2-13 Group mean values for the Relaxation Index during the pendulum test

When results were examined at the individual level, three primary response trends were noted: 1) increased Relaxation index (or decreased spasticity) after WBV followed by further increase after treadmill walking (n = 3, seen in green in Table 2-9), 2) decreased Relaxation Index (or increased spasticity) after WBV followed by increased Relaxation Index (or decreased spasticity) after treadmill walking (n = 2, seen in yellow in table 2-9), and 3) increased Relaxation

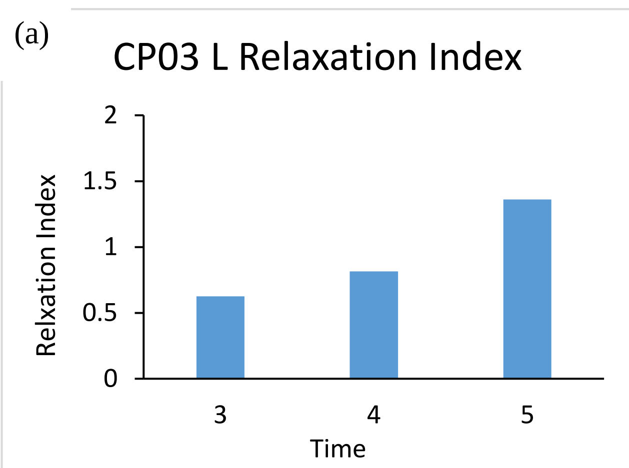
Index (or decreased spasticity) after WBV followed by decreased Relaxation Index (or increased spasticity) after treadmill walking (n = 2, seen in red in Table 2-9) (Table 2-9).

Table 2-9 Individual responses of the Relaxation Index during the pendulum test at time points T3-T5; results highlighted in green represent increases following both interventions, results highlighted in yellow represent decreases following WBV and increases following treadmill walking, and results highlighted in red represent increases following WBV and decreases following treadmill walking

Subject / Limb	Relaxation Index During Pendulum Test		
	T3	T 4	T 5
CP01 L	1.70	1.73	1.56
CP02 L	0.90	0.66	0.91
CP02 R	1.12	1.30	1.45
CP03 L	0.63	0.82	1.36
CP03 R	0.58	0.62	0.87
CP04 L	0.77	n/a	0.55
CP05 R	1.52	1.62	1.82
CP06 L	1.62	1.23	1.87
CP06 R	1.84	1.34	1.91
CP07 L	0.10	1.45	1.06
CP07 R	1.16	1.38	0.98
CP08 L	1.93	1.83	1.77

Three subjects (CP02, CP03, and CP05) demonstrated continued increase of the Relaxation Index, indicative of spasticity of the knee extensors decreasing following WBV and then decreasing further following the subsequent bout of TW. The average increase in the Relaxation Index was 0.41 between T 3 and T5. Decreases in spasticity were typically greater between T4 and T5 (immediately following WBV and immediately following treadmill walking), averaging an increase in the Relaxation Index of 0.28, than they were between T 3 and T4 (baseline and immediately following WBV), averaging an increase of 0.13. Examples of this response pattern can be seen in Figure 2-14a-b.

(a)



(b)

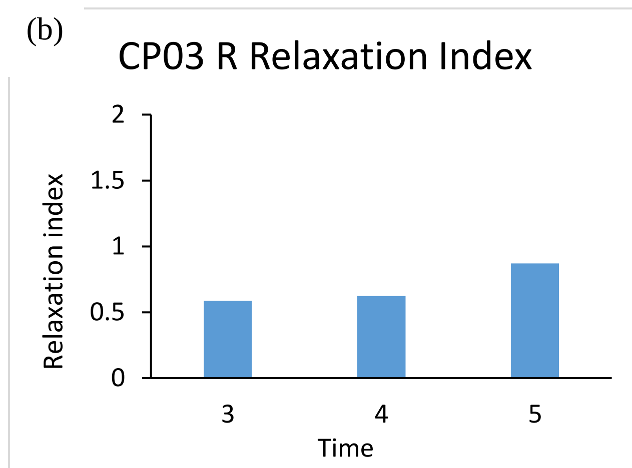


Figure 2-14 Values for the Relaxation Index during the pendulum test for (a) the left leg of CP03 and (b) the right leg of CP03

Two subjects (CP02 and CP06) demonstrated decrease of the Relaxation Index, indicative of spasticity of the knee extensors increasing, following WBV and then increasing, indicative of spasticity of the knee extensors decreasing, following the subsequent bout of TW. The average decrease in the Relaxation Index between T 3 and T4 was 0.38, while the average increase in the Relaxation Index between T4 and T5 was 0.48. This resulted in values at T5 returning to near baseline values, averaging an increase of 0.11 from T3. Thus, although subjects demonstrated worsening spasticity following WBV, the overall effect of the combined intervention was positive, slightly decreasing the spasticity of their knee extensors. Examples of this response pattern can be seen in Figure 2-15a-b.

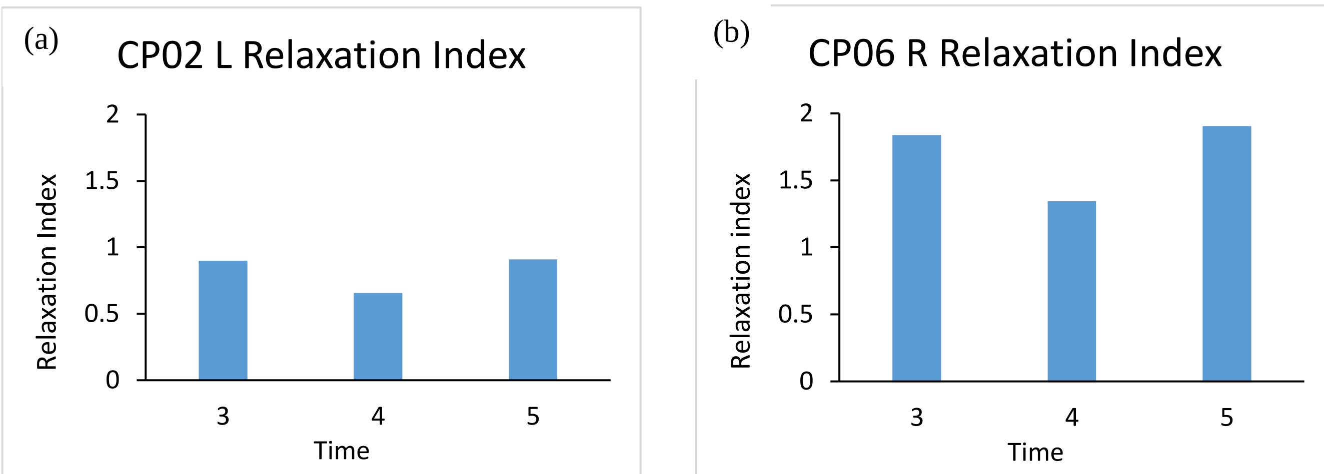
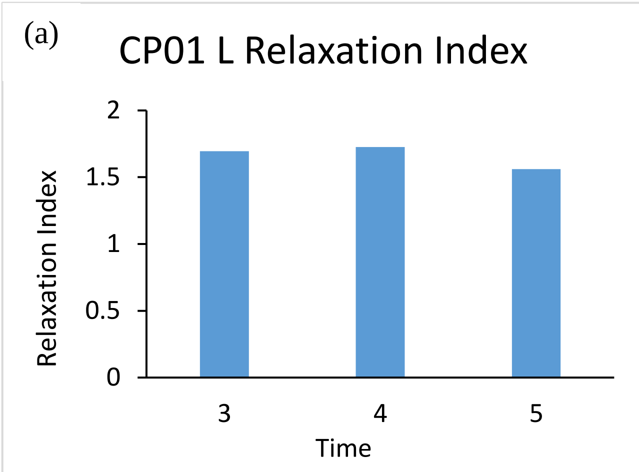


Figure 2-15 Values for the Relaxation Index during the pendulum test for (a) the left leg of CP02, and (b) the right leg of CP06

Finally, two subjects (CP01 and CP07) demonstrated increase of the Relaxation Index, indicative of spasticity of the knee extensors decreasing, following WBV and then decreasing, indicative of spasticity of the knee extensors increasing, following the subsequent bout of TW. The average increase in the Relaxation Index between T3 and T4 was 0.53, while the average decrease in the Relaxation Index between T4 and T5 was 0.95. Overall change in spasticity throughout the combined intervention was not consistent, with subject CP01 and the right leg of subject CP07 demonstrating an overall increase in spasticity (averaging a 0.16 decrease in Relaxation index from baseline), and the left leg of subject CP07 demonstrating an overall decrease in spasticity (0.96 increase in Relaxation Index from baseline). Examples of this response pattern can be seen in Figure 2-16a-b.



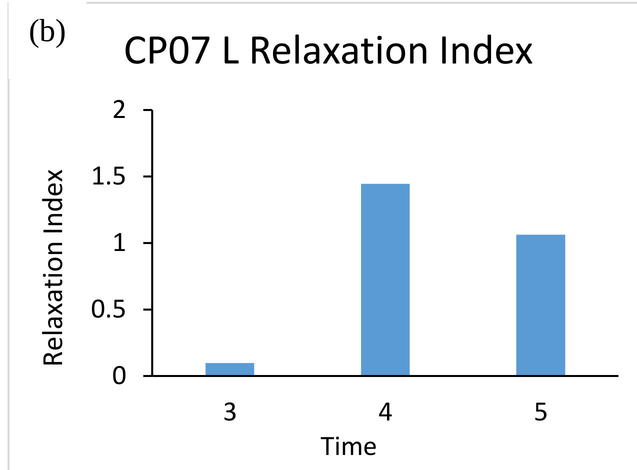


Figure 2-16 Values for the Relaxation Index during the pendulum test for (a) the left leg of CP01, and (b) the left leg of CP07

Other response patterns of the Relaxation Index included consistent worsening of spasticity across all time points (n = 1, CP08); this subject demonstrated a decrease in Relaxation index following WBV and then a further decrease following treadmill walking (Table 2-9).

Number of oscillation cycles

There were no significant group level intervention effects, time effects, or intervention by time interactions for the number of oscillation cycles during the pendulum test ($F(2,32)=0.29$, $p=0.75$) (Figure 2-17).

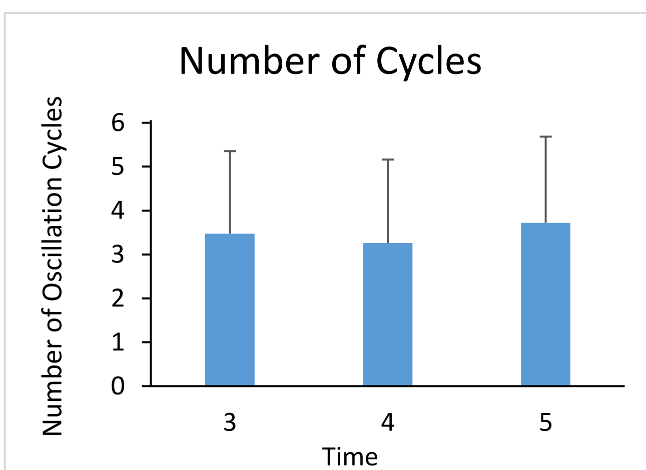


Figure 2-17 Group mean values for the number of oscillation cycles during the pendulum test

When results were examined at the individual level, two primary response trends were noted: 1) a decrease in the number of cycles after WBV followed by an increase after treadmill walking (n = 3, seen in green in Table 2-10), and 2) an increase in the number of cycles after WBV followed by a further increase after treadmill walking (n = 2, seen in yellow in Table 2-10) (Table 2-10).

Table 2-10 Individual responses of the number of oscillation cycles during the pendulum test at time points T3-T5; results highlighted in green represent decreases following WBV and increases following treadmill walking, and results highlighted in yellow represent increases following both interventions

Subject / Limb	Number of Oscillation Cycles During Pendulum Test		
	T3	T4	T5
CP01 L	5.00	4.33	5.67
CP02 L	2.00	2.00	1.67
CP02 R	2.00	2.00	2.33
CP03 L	3.00	1.50	3.67
CP03 R	1.67	2.33	2.33
CP04 L	3.00	n/a	2.00
CP05 R	6.00	7.33	8.50
CP06 L	5.00	2.33	3.00
CP06 R	3.67	2.67	3.67
CP07 L	2.33	3.67	4.50
CP07 R	1.00	1.67	2.33
CP08 L	7.00	6.00	5.00

Three subjects (CP01, CP03, and CP06) demonstrated an initial decrease in the number of oscillation cycles, indicative of spasticity of the knee extensors increasing following WBV, which was and followed by an increase in the number of cycles after treadmill walking. The average decrease in the number of oscillation cycles between T 3 and T4 was 1.18, while the average increase in the number of cycles between T 4 and T5 was 1.28. This represents an overall average increase in the numbers of cycles, suggesting an overall decrease in knee extensor spasticity following the combined intervention. However, two subjects, CP01 and CP03 demonstrated an average increase of 0.67 cycles between T 3 and T5, while subject CP06 demonstrated an average decrease of 1.00 cycle between T3 and T5. Examples of these response patterns can be seen in Figure 2-18a-b.

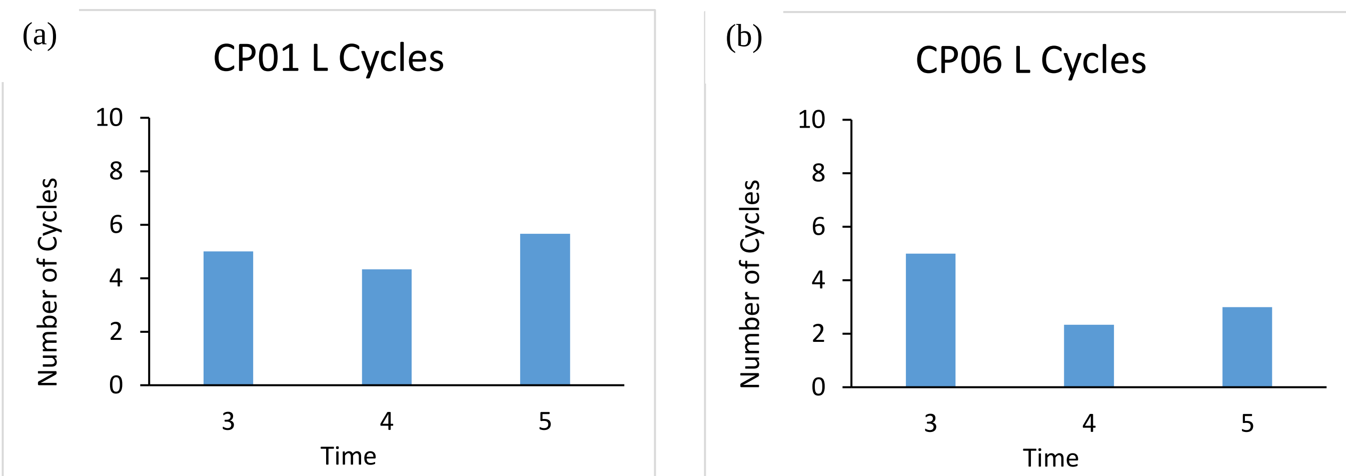


Figure 2-18 Values for the number of oscillation cycles during the pendulum test for (a) the left leg of CP01, and (b) the left leg of CP06

Two subjects (Cp05 and CP07) demonstrated continued increase in the number of oscillation cycles, indicative of spasticity of the knee extensors decreasing, following WBV and then a further increase in the number of cycles following the subsequent bout of treadmill walking. The average increase in the number of oscillation cycles was 2.67 across all three times points; increases were generally greater between T4 and T5 (averaging an increase of 1.58 cycles) than between time points 3 and 4 (averaging an increase of 1.09 cycles). Examples of these response patterns can be seen in Figure 2-19a-b.

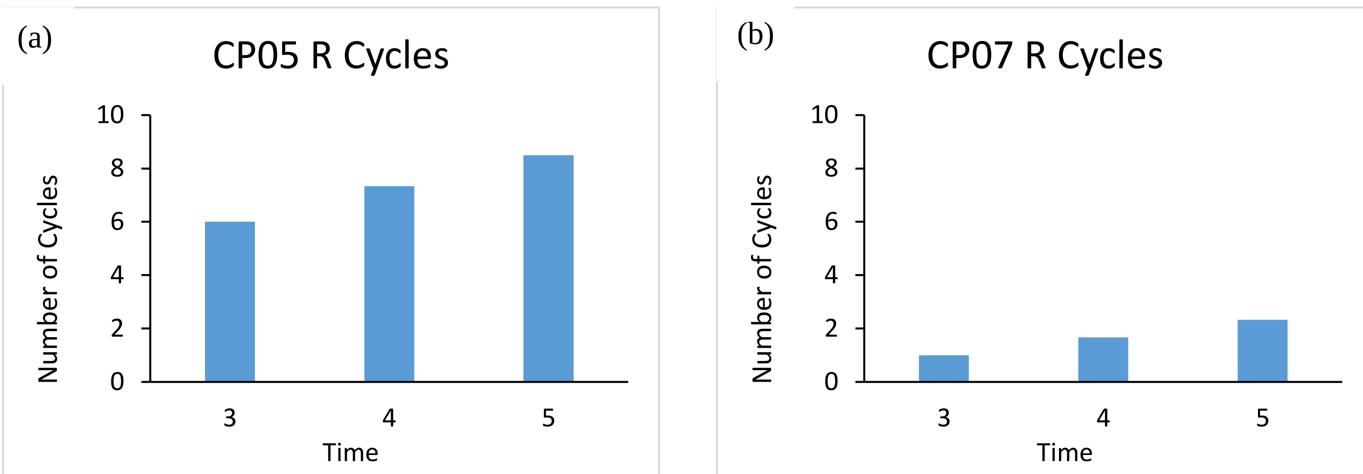


Figure 2-19 Values for the number of oscillation cycles during the pendulum test for (a) the right leg of CP05, and (b) the right leg of CP07

Discussion

In general, only partially supporting my hypothesis, both treadmill walking and WBV were capable of producing positive changes in lower extremity spasticity. In fact, the most commonly seen response was a decrease in the subject's spasticity following both treadmill walking and WBV.

The improvements in lower extremity spasticity following WBV are in line with previous literature investigating the effects of WBV on children with CP (Cheng, Ju, et al., 2015; Duquette et al., 2015; Krause et al., 2017; H. Liang et al., 2020; Park et al., 2017; R. Ritzmann et al., 2018). However, the degree of response amongst those subjects who improved their spasticity following each intervention appears dependent on which modality was used to quantify spasticity. Previous literature has typically measured spasticity using the Modified Ashworth Scale which, as previously described, has some limitations. In this study, four subjects were found to improve their R1 joint angle on the MTS (which essentially measures where, within a subject's full range of motion, a spastic "catch" occurs at the joint) after both interventions. However, the MTS also includes a quality score which is relatively analogous to the Modified Ashworth Scale. When this quality score alone was examined, the improvements in spasticity were notably less, with only three subjects demonstrating improvement across all time points, and none demonstrating improvement after each intervention as was seen when analyzing the R1 joint angles. This seems to support the notion that subjective clinical tests are not always sufficient to detect changes in spasticity.

Further, the MTS also includes a measurement of the R2 joint angle, which theoretically represents the maximum available ROM about a joint. No significant changes in this value were seen following either intervention in most subjects, which is expected as limitations in this measure tend to represent joint contracture rather than spasticity. Three subjects did show clinically significant changes in their R2 joint angles over the course of the study; as true resting muscle length would not be expected to change drastically over a period of one hour, the most likely explanation for this is testing error. Subjects may have demonstrated active muscle guarding during the initial measurement of muscle length, perhaps due to anxiety over an unfamiliar examiner moving their limbs. As subjects became familiarized with the testing procedure, they may have relaxed more, resulting in an apparent increase in muscle length. Future studies may need to compensate for this testing error by taking multiple baseline measurements over a period of time until such measurements stabilize.

While the improvements in spasticity I observed following WBV were expected based on the literature, the notable, and in some cases, comparable, improvements seen following treadmill walking were more surprising. One possible explanation is that the repetitive stretching into ankle dorsiflexion in terminal stance caused by the moving treadmill belt was sufficient to acutely elongate the calf musculature, allowing for increased movement prior to the activation of a muscle spindle response. This is supported by the work of Hosl et al. (2018), who found both increased muscle and fascicle excursion as well as decreased plantarflexor spasticity as measured by the Modified Ashworth Scale following a training program that involved backward downhill walking. He theorized that the dynamic, repeated elongation of the calf muscles during the treadmill activity allowed for an increased percent length change from a resting position. Some notable differences between this study and my current work are the treadmill parameters (backward downhill versus forward at increased pace) and the dosage of training (three times per week for nine weeks versus a single ten-minute bout). Since the proposed mechanism of action is repetitive dynamic elongation of the calf muscles, fast forward treadmill walking could theoretically produce similar results as backward downhill walking. The fact that this study showed improvements after a single ten-minute bout suggest that this elongation occurs fairly rapidly and produces acute effects. However, it is unclear if longer training durations would produce more permanent changes as neither this study nor the work of Hosl et al. (2018) examined persistence of these effects after cessation of training.

Interestingly, three subjects demonstrated findings in line with my hypothesis, demonstrating no change in spasticity following treadmill walking and then improvements following

WBV. However, this pattern of response was only noted at the plantarflexors; there were no instances in which the hamstrings or quadriceps were unaffected by the bout of treadmill walking and then demonstrated decreased spasticity following WBV. Previous work in young adults has demonstrated that vibration is attenuated as it moves up the kinematic chain from where the feet contact the plate (Lelko, 2018). It stands to reason, therefore, that the hamstrings are receiving less vibration than the plantarflexors due to their increased distance from the plate. Conversely, because movement at the knee and ankle are inextricably linked during gait, treadmill walking which facilitates increased passive movement at a joint would theoretically have similar effects at the two joints despite their relative distances from the moving belt. Thus, this pattern may indicate that there are some individuals for whom treadmill walking is ineffective at decreasing spasticity, but for whom WBV can still have a positive effect. Further, it suggests that WBV in general is less effective at affecting spasticity at more proximal joints. This idea is somewhat supported by my finding that those subjects who demonstrated improvements in hamstring spasticity following both modalities demonstrated much greater improvements following treadmill walking than following WBV. However, the sequence of interventions (subjects always completed treadmill walking first) and the baseline spasticity values (which differed between the two intervention conditions) limit my ability to draw any firm conclusions of this nature. There may be some other factor that explains why children who do not demonstrate decreased spasticity following treadmill walking are less likely to demonstrate improvements in hamstring spasticity following WBV.

Finally, although the majority of subjects demonstrated improvements in spasticity following WBV, there were some who actually demonstrated increased spasticity following vibration. Interestingly, those subjects who worsened after WBV tended to demonstrated worsening at one or two muscle groups only. For example, subjects CP02 and CP06 demonstrated increased spasticity at the hamstrings and plantarflexors only, while subject CP08 demonstrated increased spasticity at the hamstrings and quadriceps only. Of particular interest is that subject CP06, who only tolerated four bouts of vibration, still demonstrated improvement in quadriceps spasticity and worsening of the spasticity in her hamstrings and plantarflexors following WBV despite the fact that she received half the dosage as the other subjects.

The lack of consistency in which muscle groups responded positively versus negatively to WBV in these subjects suggests that the changes in spasticity may be caused by a combination of factors, with likely contributions from not only proximity to the vibration plate, but also which muscles the subject was using to maintain the mini-squat position during WBV. Further, although the vibration frequency used in this study was chosen due to its predominance in the literature, some research (Galileo, 2017; Ritzmann, Gollhofer, & Kramer, 2013) suggests that the frequency of 20 Hz may represent a transitional frequency. Higher frequencies are known to facilitate increased muscle activation (Ritzmann et al., 2013), and are therefore recommended to be used to promote muscle strengthening (Galileo, 2017). A frequency of 20 Hz may be a "grey area" between vibration which is believed to decrease chronic spasticity by affecting the sensitivity of the muscle spindle and vibration which is believed to facilitate muscle strengthening by producing rapid muscle fatigue. The relationship between muscle fatigue and spasticity is not well-documented in children with cerebral palsy, so it is unclear if frequency choice may have played a factor in the increased spasticity observed in some subjects. Further research on the relative effects of differing vibration frequencies on muscle fatigue versus spasticity in individuals with cerebral palsy is needed to clarify these findings.

The overall lack of consistency in my findings, however, suggest that, whatever the reasons, individuals with CP experience different outcomes from exposure to WBV. Some subjects were “responders,” demonstrating decreased spasticity in one or more muscle groups following WBV, while others were “non-responders,” demonstrating no notable changes or, in some cases, a worsening of spasticity after WBV. This suggests that examining only group level differences in this population may be concealing important information about individual response; indeed, in this study the group level results were far less remarkable than the findings when the data were analyzed as a case series. While even amongst the “responders” significant variability was still present – subjects with bilateral involvement frequently responded differently on each limb, and improvements were not always consistent across all muscle groups tested – the ability to identify these individuals prior to treatment is critical for successful implementation of WBV in a clinic setting. Interestingly, the changes in spasticity seen here were not correlated with any readily available demographic information such as age, gender, GMFCS level, or baseline spasticity. Thus, just as spasticity itself is a complex phenomenon, an individual’s likelihood to “respond” to WBV appears to be similarly complex and requiring further investigation.

Overall, this study found that short bouts of both treadmill walking and WBV have the potential to acutely improve lower extremity spasticity in children with CP. One of the primary mechanisms of action that has been theorized for the spasticity-decreasing effects of WBV is that it actively decreases the sensitivity of the spinal stretch reflex (Krause et al., 2017). Walking on a treadmill, on the other hand, has been found to induce changes in the passive viscoelastic properties of muscle, decreasing passive stiffness (Lorentzen et al., 2017) and improving passive elongation (Hosl et al., 2018). Other studies have also shown improvements in passive muscle stiffness/spasticity following the application of continuous passive motion machines (Cheng, Ju, Chen, Chang, & Wong, 2013; Cheng, Ju, Chen, & Wong, 2012; Zhang et al., 2002).

If we accept that spasticity is, in fact, a multi-faceted phenomenon that is composed of both neural and mechanical components, it appears that the interventions used in this study have demonstrated that spasticity can therefore be addressed at either of these levels. A single bout of treadmill walking appears to effectively decrease spasticity by improving the muscle's capacity for passive elongation. Lorentzen et al. (2017) also noted, when examining the effects of treadmill walking on spasticity, that while passive stiffness was improved following treadmill walking reflex-mediated spasticity was not; this could explain why improvements were seen in my subjects' R1 joint angles and pendulum test variables without any corresponding changes in the quality of muscle reaction scores on the MTS. Further, a single bout of WBV appears to also decrease spasticity, theoretically by altering the sensitivity of the stretch reflex. Put together, this suggests that perhaps muscle spindle sensitivity can be affected at both a neural and a mechanical level. However, given the high variability of response to both interventions, in which some subjects responded to both interventions and some responded only to one, it is difficulty to conclude with certainty which approach is most effective, or indeed if both approaches are equally valuable. This variability was not easily explained by differences in age, GMFCS level, or baseline spasticity, suggesting that the factors which determine how an individual with CP will respond to treadmill walking or WBV are more complex. Future research investigating the likelihood of individuals to respond to interventions addressing spasticity at the neural versus mechanical level is necessary to make more informed clinical recommendations.

This study has several limitations, most notably my small sample size and its heterogeneity. A larger sample size, or a sample which included children from a smaller range of ages and motor abilities, may have increased my power to detect group level differences and improved the strength of my conclusions. Additionally, although all MTS measurements were conducted by the same clinician (this author), data on intra-rater reliability was not collected. Further, it was not possible to blind the examiner to the study conditions, which could have introduced subconscious bias into the measurements. Finally, my assumption that a short bout of treadmill walking would produce no notable changes in spasticity, and thus that the 20-minute washout period between interventions would be sufficient, was incorrect. Most subjects, by time point 3, had not returned to baseline levels of spasticity as expected. Thus, my ability to draw firm conclusions about the isolated benefits of WBV are limited, as several subjects were demonstrating lingering effects from the bout of treadmill walking when WBV was initiated. Future research comparing the relative effects of these two interventions should consider alternate study designs, such as administering the interventions on two different days, or extending the washout period until the subject has returned to those baseline levels of spasticity.

Conclusions

In conclusion, both treadmill walking and WBV appear to be capable of acutely producing clinically relevant improvements in lower extremity spasticity in children with CP. However, while treadmill walking alone tended to either positively effect spasticity or elicit no change, the response to WBV was more varied. There appear to be some individuals, “responders,” who demonstrate decreased spasticity after WBV, while others, “non-responders,” demonstrated no change or even a worsening of spasticity. Moreover, their response was not related to any easily identifiable factors such as age, motor ability, or baseline spasticity. This suggests that identifying which children are going to respond positively to WBV may be a dependent on identifying a complex set of factors that I was unable to determine with my current small sample size. However, identification of these factors and a greater understanding of why children respond differently to WBV is a critical aspect of making appropriate recommendations about the use of WBV in clinical settings. The high individual variability of response also makes examination of group level means less important than individual analysis; future research should consider utilizing single-subject designs to further explore this variability. WBV is a promising clinical intervention for children with spastic CP, but significant additional research is needed to understand how best to utilize it in a clinical setting.

References

Can high frequencies increase muscle activation during Galileo Training? (2017). *Galileo Training.*

Cheng, H.-Y. K., Ju, Y.-Y., Chen, C.-L., Chang, Y.-J., & Wong, A. M.-K. (2013). Managing lower extremity muscle tone and function in children with cerebral palsy via eight-week repetitive passive knee movement intervention. *Research in Developmental Disabilities, 34*(1), 554-561. doi:https://doi.org/10.1016/j.ridd.2012.09.020

Cheng, H., Ju, Y., Chen, C., & Wong, M. (2012). Managing spastic hypertonia in children with cerebral palsy via repetitive passive knee movements. *Journal of Rehabilitation Medicine, 44*(3), 235-240. doi:10.2340/16501977-0937

Cheng, H. Y., Ju, Y. Y., Chen, C. L., Chuang, L. L., & Cheng, C. H. (2015). Effects of whole body vibration on spasticity and lower extremity function in children with cerebral palsy. *Hum Mov Sci, 39*, 65-72. doi:10.1016/j.humov.2014.11.003

Duquette, S. A., Guiliano, A. M., & Starmer, D. J. (2015). Whole body vibration and cerebral palsy: a systematic review. *J Can Chiropr Assoc, 59*(3), 245-252.

Hosl, M., Bohm, H., Eck, J., Doderlein, L., & Arampatzis, A. (2018). Effects of backward-downhill treadmill training versus manual static plantarflexor stretching on muscle-joint pathology and function in children with spastic Cerebral Palsy. *Gait Posture, 65*, 121-128. doi:10.1016/j.gaitpost.2018.07.171

Krause, A., Schonau, E., Gollhofer, A., Duran, I., Ferrari-Malik, A., Freyler, K., & Ritzmann, R. (2017). Alleviation of Motor Impairments in Patients with Cerebral Palsy: Acute Effects of Whole-body Vibration on Stretch Reflex Response, Voluntary Muscle Activation and Mobility. *Front Neurol, 8*, 416. doi:10.3389/fneur.2017.00416

Lelko, M. (2018). *Effect of Whole-Body Vibration on Acceleration Transmission and Jumping Performance in Children*. Thesis. Georgia State University. Atlanta, GA, USA.

Liang, H., Henderson, G., & Wu, J. (2020). *Neuromuscular response to a single session of whole-body vibration in children with cerebral palsy: A pilot study.*

Lorentzen, J., Kirk, H., Fernandez-Lago, H., Frisk, R., Scharff Nielsen, N., Jorsal, M., & Nielsen, J. B. (2017). Treadmill training with an incline reduces ankle joint stiffness and improves active range of movement during gait in adults with cerebral palsy. *Disabil Rehabil, 39*(10), 987-993. doi:10.1080/09638288.2016.1174745

Park, C., Park, E. S., Choi, J. Y., Cho, Y., & Rha, D. W. (2017). Immediate Effect of a Single Session of Whole Body Vibration on Spasticity in Children With Cerebral Palsy. *Ann Rehabil Med, 41*(2), 273-278. doi:10.5535/arm.2017.41.2.273

Ritzmann, Gollhofer, A., & Kramer, A. (2013). The influence of vibration type, frequency, body position and additional load on the neuromuscular activity during whole body vibration. *European Journal of Applied Physiology, 113*(1), 1-11. doi:10.1007/s00421-012-2402-0

Ritzmann, R., Stark, C., & Krause, A. (2018). Vibration therapy in patients with cerebral palsy: a systematic review. *Neuropsychiatr Dis Treat, 14*, 1607-1625. doi:10.2147/NDT.S152543

Zhang, L.-Q., Chung, S. G., Zhiqiang, B., Dali, X., Van Rey, E. M. T., Rogers, M. W., . . Roth, E. J. (2002). Intelligent stretching of ankle joints with contracture/spasticity. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 10*(3), 149-157. doi:10.1109/tnsre.2002.802857

3 THE EFFECTS OF THE ADDITION OF A SINGLE SESSION OF WHOLE-BODY VIBRATION TO A BOUT OF TREADMILL WALKING ON OVER-GROUND GAIT PARAMETERS IN AMBULATORY CHILDREN WITH CEREBRAL PALSY

Introduction

Cerebral palsy (CP) is the most common motor disability in childhood, with an occurrence of between 1.5 and 4 per 1,000 live births worldwide. Nearly 60% of children with CP walk independently (CDC, 2018), but abnormalities of gait, which can include walking in equinus or walking in a crouch, represent a significant issue for most of this population (Gage, 2009; Woollacott & Shumway-Cook, 2005). These gait abnormalities, along with others, are associated with decreased participation in age-appropriate activities and social roles (Omura et al., 2018), which in turn is associated with decreased quality of life (QOL) in these children (Jaspers et al., 2013). Therefore, improving ambulation abilities is often a major goal of therapeutic interventions for children with CP and their families.

Single bouts of whole-body vibration (WBV) have been shown to improve gait parameters such as walking speed and stride length in children and adults with CP (Cheng, Ju, et al., 2015; Dickin et al., 2013; Han et al., 2019; H. Q. Liang, 2018; R. Ritzmann et al., 2018). The improvements in gait speed are of particular importance, as this has been shown to be one of the best predictors of QOL in children with CP (Jaspers et al., 2013). WBV has also been shown to acutely decrease spasticity and improve isolated active ROM (Cheng, Ju, et al., 2015; Duquette et al., 2015; Krause et al., 2017; Park et al., 2017; R. Ritzmann et al., 2018). However, these effects are transient, generally lasting between 30 minutes (Cheng, Ju, et al., 2015) and two hours (Park et al., 2017), limiting the ability of WBV to affect long-term functional improvements in community-based ambulation. Additionally, response to WBV can be highly variable, with some children with CP demonstrating notable improvement and some failing to significantly respond to intervention at all (Krause et al., 2017; H. Liang et al., 2020). Studies on the cumulative effects of WBV in children with CP are also lacking in the literature; while multiple authors have found improvements in overground gait patterns following prolonged training (Cheng, Yu, et al., 2015; Ibrahim et al., 2014; Yabumoto et al., 2015), persistence of these positive effects after cessation of treatment has not been shown past three days (Cheng, Yu, et al., 2015).

Despite their transient nature, however, the acute effects of WBV are still clinically relevant. Cheng, Ju, et al. (2015) stated that these acute effects could "promote children's active participation in exercise," suggesting that WBV might be most beneficial as a preparatory intervention to improve performance of some activity that immediately follows it. Further, Krause et al. (2017) recommended that "the time frame immediately after WBV…be used for targeted movement therapy," suggesting that this might allow subjects to "take advantage of increased supraspinal input by means of greater voluntary motor control." Thus, the greatest clinical utility of WBV may come from combining it with some other rehabilitation technique whose benefits would be enhanced by its acute effects.

Treadmill training (TT) is a popular intervention technique in pediatric rehabilitation, and is commonly used for children with a wide variety of diagnoses, including CP. Systematic reviews have determined that TT was safe and well-tolerated for children with CP, although outcomes are highly variable (Damiano & DeJong, 2009; Valentin-Gudiol et al., 2017; Willoughby et al., 2009b; Zwicker & Mayson, 2010). Walking on a treadmill provides a repetitive stimulus for stepping, allowing for consistent, task-specific practice of ambulation. When learning or refining a motor skill, motor learning theory states that the most important factor is practice (Shumway-Cook & Woollacott, 2012); it is therefore critical that the stepping practiced during TT mimics a desired gait pattern, in order to facilitate improvement of walking abilities rather than reinforce maladaptive patterns. Further, the parameters of treadmill walking (such as amount of body weight support, speed, direction, and grade) can be modulated to induce changes in gait parameters (Damiano & DeJong, 2009); these modulations can allow clinicians to promote desired adaptations in a consistent fashion during training. Qualitative improvements in gait while on the treadmill can be seen in as little as one session (Simao et al., 2019), however, to date there is minimal literature supporting the idea that overground gait can be qualitatively improved using TT. Improvements in ambulatory children with CP are inconsistently seen in both walking velocity and overall gross motor function, but specific improvements in gait kinematics are not well-documented in the literature (Valentin-Gudiol et al., 2017). This could certainly be an issue of dosage, as there is high variability in both the frequency and duration of training in the literature (Damiano & DeJong, 2009; Valentin-Gudiol et al., 2017; Willoughby et al., 2009a; Zwicker & Mayson, 2010). However, it is also possible that TT performed in the absence of interventions that address body structure and function impairments such as spasticity and selective motor control are simply not effective at improving quality of gait. Thus, the combination of WBV, which acutely improves these impairments, and TT, which could allow for the reinforcement of improved gait patterns, may be more effective at improving overground gait than either intervention in isolation.

Therefore, the purpose of this study is to quantify the acute effects of the addition of a single bout of WBV to a single bout of treadmill walking on the overground gait patterns of ambulatory children with CP. I hypothesize that different effects of the two interventions will be observed, such that 1) both a single bout of treadmill walking alone and a combined intervention, consisting of a single bout of WBV follow by a single bout of treadmill walking, will produce improvements in overground gait patterns, including increased walking speed, increased step lengths, and increased dynamic ROM about the knee and ankle, and that 2) a combined intervention, consisting of a single bout of WBV followed by a single bout of treadmill walking, will produce greater improvements in overground gait than the improvements seen following a single bout of treadmill walking alone.

Methodology

Participants

I recruited 9 ambulatory children (3M/6F) with CP between the ages of 6-17. Mean (SD) height and weight were 133.4(18.8) cm and 32.1(15.2) kg (Table 3-1). Participants were required to have a medical diagnosis of CP, per parent or referring therapist report, and to be classified as a Level I, II, or III on the Gross Motor Function Classification System (GMFCS). Each subject's GMFCS level was confirmed by an experienced physical therapist prior to participation, either by administering the standardized questionnaire (Dietrich et al., 2007) or confirming a parent-reported level using the GMFCS Expanded and Revised (Palisano et al., 2007). Exclusion criteria included a history of Botox injections to the lower extremities within the past three months, a history of musculoskeletal injury within the past six months, a history of lower extremity orthopedic surgery within the past six months, a history of significant uncontrolled cardiac abnormalities, a history of uncontrolled seizures, and any cognitive or behavioral issues that prevented the subject from safely following instructions while walking on the treadmill. This study was approved by the institutional review board at Georgia State University. Written parental permission was obtained from the parents or guardians of all the subjects and assent was obtained from all subjects prior to data collection.

Table 3-1 Descriptive data of all subjects

Subject	Gender	Age	Topography	GMFCS Level	Preferred Overground Speed (m/s)	Height (cm)	Body mass (kg)
CP01	F	11	L hemiplegia	I	1.39	152.0	49.2
CP02	F	7	diplegia	II	1.00	117.0	17.3
CP03	F	17	quadriplegia	III	0.82	158.0	55.4
CP04	M	13	quadriplegia	II	1.04	124.0	24.5
CP05	M	6	R hemiplegia	II	0.75	124.0	20.2
CP06	F	9	diplegia	II	0.54	116.0	19.8
CP07	M	6	quadriplegia	II	0.75	109.5	17.6
CP08	F	17	L hemiplegia	I	0.79	149.0	42.0
CP09	F	17	L hemiplegia	I	0.68	151.5	43.2
Mean (SD)	6 F 3 M	11.4 (4.7)	3 hemiplegia 2 diplegia 3 quadriplegia	3 I 5 II 1 III	0.90 (0.30)	133.4 (18.1)	32.1 (15.2)

Data collection

Anthropometric measures including height, weight, and leg length were taken for each subject. Their skin was then marked with an eyebrow pencil to identify marker placement, and 16 reflective markers were placed on the lower body landmarks specified for the Plug-In Gait Lower Body model using double-sided tape. These landmarks include the anterior superior iliac spine, posterior superior iliac spine, lateral thigh, lateral knee, lateral tibia, lateral malleolus, calcaneus, and second metatarsal bilaterally (Figure 1). Following marker placement, the skin was gently abraded with an alcohol wipe and Trigno Wireless Electromyographic (EMG) sensors (Delsys, Natick, MA, USA) were adhered over the following muscles of the limb(s) being tested using double-sided tape: vastus lateralis, biceps femoris, tibialis anterior, and lateral gastrocnemius. For individuals with hemiplegia, EMG data were only collected on the involved limb, while EMG data were collected bilaterally for individuals with diplegia or quadriplegia. Previous unpublished work has shown that transmission of vertical acceleration due to WBV is significantly reduced above the knee (Lelko, 2018), so the focus was limited to the muscles surrounding the knee and ankle joints only.

After all markers and EMG sensors were secured, subjects completed three trials of walking along a 10-meter hallway at a comfortable pace. The timed trials were averaged to determine each subject's "self-selected" speed, which was utilized to calculate the speed of treadmill walking for each subject. The subject then moved to a plinth and performed three reps of a maximum voluntary isometric contraction (MVIC) of the quadriceps, hamstrings, tibialis anterior, and gastrocnemius for each limb being tested; manual resistance was applied to facilitate a maximum isometric contraction while EMG data were collected. Subject position and the application site of manual resistance were performed in accordance with Daniels and Worthingham's muscle testing parameters (Hislop et al., 2014). If the subject did not appear to utilize maximal effort for a trial, instructions were repeated, and additional trials collected until three successful trials were completed.

Next, spasticity and gait were assessed for the first of five times (Figure 3-1). The subject moved to a supine position on the plinth for assessment of spasticity of the gastrocnemius and hamstrings using the Modified Tardieu Scale (MTS), performed in accordance with standardized procedures (R. N. Boyd & Graham, 1999). The subject then completed five trials of overground walking at a self-selected pace along a 10m walkway through the camera field. During walking, motion data were collected at a frequency of 100 Hz using an 8-camera Vicon motion capture system (Vicon, Denver, CO, USA) and EMG data were collected from all surface electrodes at a frequency of 1000 Hz. If the subject ran, fell, or otherwise did not walk typically through the camera field, the subject was reminded to walk straight forward at a normal pace, and additional trials were conducted until five usable trials have been collected.

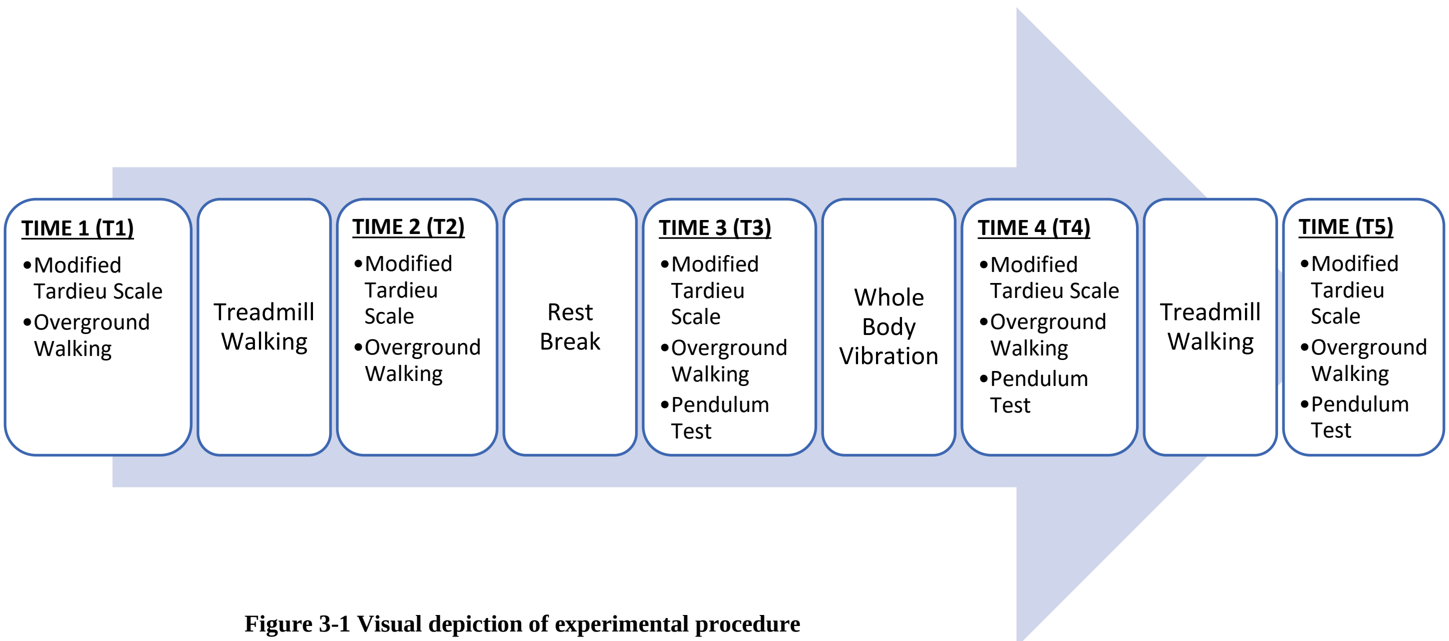


Figure 3-1 Visual depiction of experimental procedure

After completing these baseline assessments (T1), the subject stepped onto a Zebris FDM-T instrumented treadmill (Zebris Medical GmbH, Isny, Germany). A researcher stood near the subject during treadmill walking in order to assist if loss of balance occurred, and soft mats were placed around the treadmill to prevent injury in case of a fall. The subjects also held onto an anterior or lateral support bar on the treadmill. Each subject completed ten minutes of forward treadmill walking at a speed equal to 125% of their self-selected overground speed obtained during the 10m walk test. Three subjects were not able to maintain this pace and walked at slower speeds on the treadmill ranging from 96-104% of their self-selected pace. The other six subjects were able to safely complete the full ten minutes of ambulation at 125% of their overground pace.

During treadmill walking, two minutes of data were collected in the middle of the trial once the subject had visually appeared to reach steady-state walking; this included kinematic data from the Vicon motion capture system and EMG data from all surface EMG electrodes. After completing ten minutes of treadmill walking, the subject immediately repeated assessments of lower extremity spasticity and overground walking, as before (T2). Once the post-treadmill measurements are taken, the subject took a seated rest break for twenty minutes.

Following the rest break, subjects repeated the assessment of overground walking a third time. This time point (T3) served as a second baseline, allowing variables to be compared pre- and post- both interventions. After measurements were completed, the subject moved to stand on a Galileo Med-L side-to-side-alternating WBV plate (StimDesigns LLC, Carmel, CA, USA) and completed eight bouts of 90 seconds of vibration at 20 Hz and an amplitude of 2 mm. During the vibration, the subject held onto an anterior handrail with both hands. If the subject had difficulty maintaining neutral alignment with the knees slightly flexed and the feet flat during the vibration, he or she was manually assisted with maintaining that position by an experienced member of the research team. Between bouts, the subject rested in a seated position for 90 seconds. After completing the final bout of vibration, the subject again completed assessment of overground walking (T4), and then immediately returned to the treadmill. Ten more minutes of walking at 125% of each subject's overground pace was completed in the same manner as before, with two minutes of data collection in the middle of the trial. Following completion of the second bout of treadmill walking, the subjects completed a fifth (T5) and final assessment of overground walking. A single subject (CP06) did not tolerate the vibration well, and only completed four bouts; the remaining subjects completed all eight bouts without difficulty.

Data analysis

Outcome measures included (1) spatiotemporal parameters during overground and treadmill walking (walking speed, step length, stance time and percent, swing time and percent, double support time and percent), (2) sagittal plane joint angles at the hip, knee, and ankle during overground and treadmill walking, and (3) electromyographic parameters during overground and treadmill walking (integrated EMG and co-contraction indices at the knee and ankle).

Spatiotemporal parameters

Spatial variables included bilateral step length and step width. Step length was defined as the anterior/posterior (AP) difference between the ipsilateral heel marker and the contralateral heel marker at foot strike. Step width was defined as the medial/lateral (ML) difference between the ipsilateral heel marker at foot strike and the line connecting the contralateral heel markers of the previous and subsequent steps. Step length and step width were normalized by leg length to accommodate for subjects of differing heights.

Temporal variables included cycle time, stance time, swing time, double support time, stance percentage of gait cycle, swing percentage of gait cycle, and double support percentage of gait cycle. Cycle time was defined as the elapsed time between two consecutive ipsilateral foot strikes. Stance time was defined as the time between each ipsilateral foot strike and subsequent foot off. Double support time and percentage were calculated for the first double support phase of each gait cycle.

Joint angles

Kinematic data were processed using Vicon Nexus 2.5 (Vicon, Denver, CO). Marker trajectories were smoothed using a fourth-order zero-lag Butterworth filter with a cut-off frequency of 6 Hz (Beerse et al., 2018; Henderson, Beerse, et al., 2020; Wu et al., 2015). Minimum foot clearance was calculated as the height of the two marker between the two trajectory peaks during swing phase (Winter, 1992). Peak sagittal plane joint angles were calculated at the hip, knee, and ankle. Hip angles were calculated using the vector formed by the knee and thigh markers and a line perpendicular to the vector formed by the ipsilateral ASIS and PSIS, projected onto the sagittal plane. Positive hip angles represent flexion, while negative values represent extension. Knee angles were calculated using the vector formed by the knee and thigh markers and the vector formed by the knee and tibia markers, which was then subtracted from 180° to give the anatomical angle. Positive knee angles represent flexion, while negative values represent hyperextension. Ankle angles were calculated using the vector formed by the knee and ankle markers and the vector formed by the heel and toe markers, which was then subtracted from 90°. Positive angles represent ankle dorsiflexion, while negative angles represent ankle plantarflexion. Joint angles were then time-normalized to 100% of a gait cycle, and peak joint angles were defined as the maximum angle at each joint for each gait cycle. The peak angles of all trials, for each time point, were then averaged together to produce mean peak angles for each joint.

EMG parameters

EMG data were filtered using a 6^{th} order zero-phase lag Butterworth band-pass filter with cut-offs of 20 Hz and 500 Hz to remove high-frequency noise and correct for baseline drift (Bar-

On et al., 2013). The filtered signal was then rectified and a 6th order zero-phase lag low pass Butterworth filter with a cutoff frequency of 30 Hz was applied (Bar-On et al., 2013). Integration of this data was then performed to obtain muscle activation for each muscle across each gait trial (Ervilha, Graven-Nielsen, & Duarte, 2012). To normalize the data, the muscle activation per frame (of kinematic data, which was collected at 100Hz) was determined for each MVIC trial. The three MVIC trials for each muscle were averaged together to produce an average activation per frame, which was used to normalize EMG activity during walking trials.

Co-contraction indices (CCI) were then calculated about the knee and ankle during both stance and swing phases. CCI was calculated within each of these phases by dividing the less active muscle by the sum of both muscles active about the joint (Gross et al., 2015).

$$\mathrm{CCI} = \frac{\int \min\left(\mathrm{EMG}_{\mathrm{agonist}}, \mathrm{EMG}_{\mathrm{antagonist}}\right)}{\int \mathrm{EMG}_{\mathrm{agonist}} + \int \mathrm{EMG}_{\mathrm{antagonist}}}$$

For the knee joint, the muscle couples used were the vastus lateralis and the biceps femoris. For the ankle joint, the muscle couples used were the tibialis anterior and the lateral gastrocnemius.

Statistical Analysis

All data were processed using custom-written MATLAB programs and then analyzed using SAS 9.4 (SAS, Cary, NC, USA). All variables were tested for normality of distribution using a Shapiro-Wilk test; those variables which were not normally distributed were log-transformed prior to further analysis. A series of two-way (2 intervention x 2 time) repeated measures ANOVAs were utilized to evaluate group-level changes in overground walking at time points T1 andT2 (pre and post treadmill walking), and T3 and T5 (pre and post the combined WBV and treadmill walking). Additionally, a one-way (time) ANOVA with repeated measures on time was used to examine the difference between variables at time points T3, T4, and T5 to assess changes across the combined intervention; again, Bonferroni adjustments were completed as necessary. Finally, a series of paired t-tests were utilized to evaluate group-level changes in treadmill walking between the first bout (between T1 and T2) and the second bout (between T4 and T5). A significance level of $\alpha=0.05$ was used for all statistical tests.

Additionally, since the variability of response to both WBV and TT in children with CP is well-documented in the literature (Krause et al., 2017; H. Liang et al., 2020; Valentin-Gudiol et al., 2017), subjects' responses to intervention were examined at both the group and individual levels. Patterns and trends in the individual data were visually examined in an attempt to evaluate different levels of responses to WBV. A series of correlations between the response of gait variables to both interventions and selected subject demographics was also performed, with Pearson Product Moment correlation coefficients calculated for each pair.

Results

Spatiotemporal parameters

Walking speed

There was not a significant intervention effect ($F(1,31)=0.001$, $p=0.92$), time effect ($F(1,31)=0.24$, $p=0.63$), or intervention by time interaction ($F(1,31)=0.16$, $p=0.69$) (Figure 3-2).

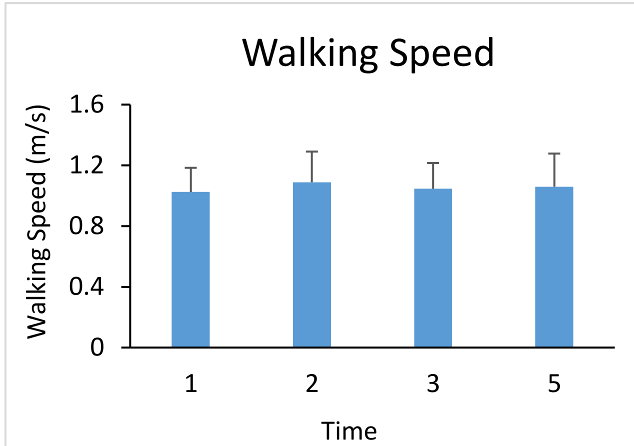


Figure 3-2 Group mean and standard deviation for walking speed at time points T1, T2, T3, and T5

When results were examined at the individual level, the two most common response trends were 1) improvement following both treadmill walking and combined WBV and treadmill walking (n = 4, seen in green in Table 3-2) and 2) worsening following both treadmill walking and combined WBV and treadmill walking (n = 2, seen in red in Table 3-2) (Table 3-2). Minimal detectable change values for gait speed in cerebral palsy are not specifically reported on in the literature, so a value of 0.05 m/s, which Perera, Mody, Woodman, and Studenski (2006) reported was the minimum meaningful change in gait speed for older adults, was used as a guideline during individual analysis.

Table 3-2 Individual responses of walking speed in m/s at time points T1, T2, T3, and T5 (denotes missing data); data highlighted in green represent those subjects who improved after both interventions and data highlighted in red represent those subjects who worsened following both interventions**

Subject	Walking Speed (m/s)			
	T1	T2	T3	T5
CP01	1.34	1.28	1.27	1.33
CP02	1.05	1.27	1.10	1.15
CP03	0.82	0.83	0.78	0.73
CP04	1.14	1.39	n/a	1.17
CP05	0.91	0.97	0.84	0.89
CP06	1.00	0.85	1.10	0.96
CP07	1.06	0.95	1.06	0.82
CP08	0.85	1.08	1.23	1.32
CP09	1.05	1.18	1.00	1.16

Four subjects (CP02, CP05, CP08, and CP09) demonstrated improvement in overground walking speed following both interventions. The average increase following treadmill walking was 0.16 m/s while the average increase following combined WBV and treadmill walking was 0.09 m/s. Three subjects (CP02, CP05, and CP09) demonstrated a return to near-baseline values at T3, such that their average walking speed was slightly lower at T5, averaging 1.07 m/s, than at T2, averaging 1.14 m/s; an example of this response can be seen in Figure 3-3a. Subject CP08, however, demonstrated consistent improvement in walking speed across all time points, as seem in Figure 3-3b.

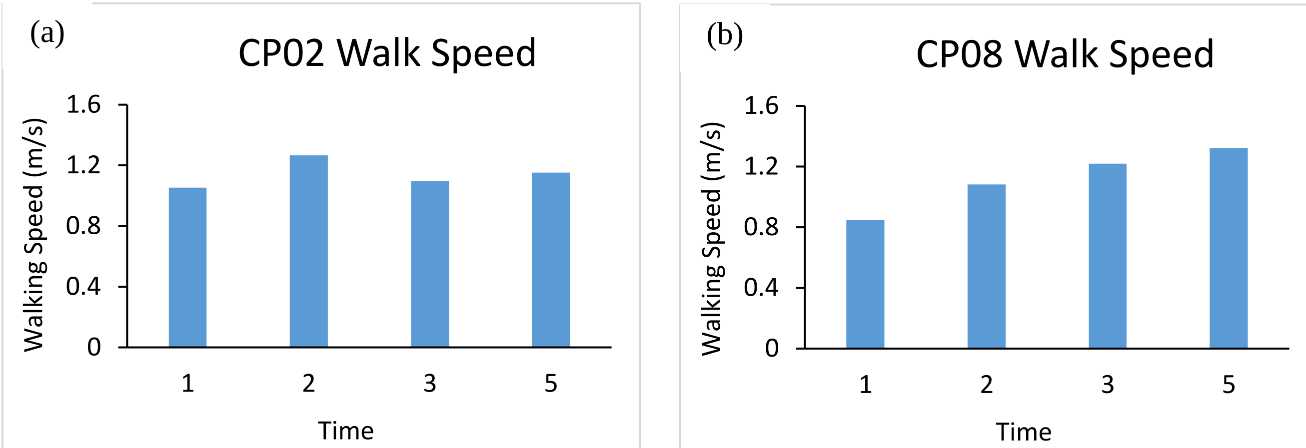


Figure 3-3 Overground walking speed at time points T1, T2, T3, and T5 for subjects (a) CP02 and (b) CP08

Two subjects (CP06 and CP07) demonstrated slowing of overground walking speed following both interventions; an example of this response pattern is seen in Figure 3-4. The average decrease following treadmill walking was 0.13 m/s while the average decrease following combined WBV and treadmill walking was 0.19 m/s.

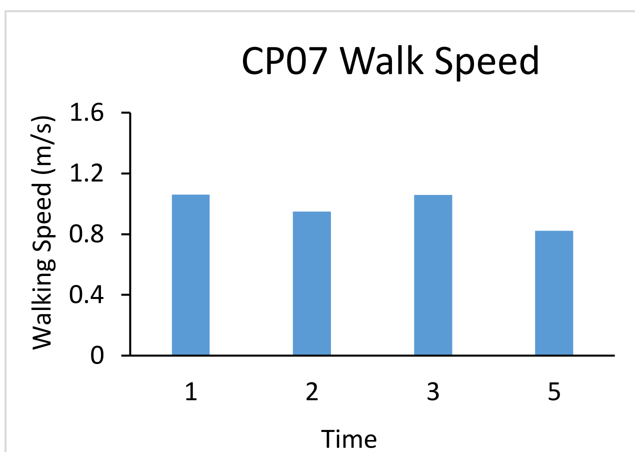


Figure 3-4 Overground walking speed at time points T1, T2, T3, and T5 for subject CP07

Other response patterns of overground walking speed included a decrease in speed after treadmill walking followed by an increase in speed after combined WBV and treadmill walking (n=1, CP01) and an increase in speed after treadmill walking followed by a decrease in speed after combined WBV and treadmill walking (n=1, CP03) (Table 3-2).

Step Length

There was not a significant intervention effect (F(1,31)=0.00, *p*=0.95), time effect (F(1,31)=0.39, *p*=0.54), or intervention by time interaction (F(1,31)=0.15, *p*=0.70) (Figure 3-5). Of note, step length was normalized by leg length, but the normalized data did not differ notably from the raw data in terms of response trends. Minimal detectable change values for step length in cerebral palsy are not specifically reported on in the literature, so a value of 1.4cm, which Almarwani, Perera, VanSwearingen, Sparto, and Brach (2016) reported was the minimum detectable change for step length in young adults, was used as a guideline during individual analysis.

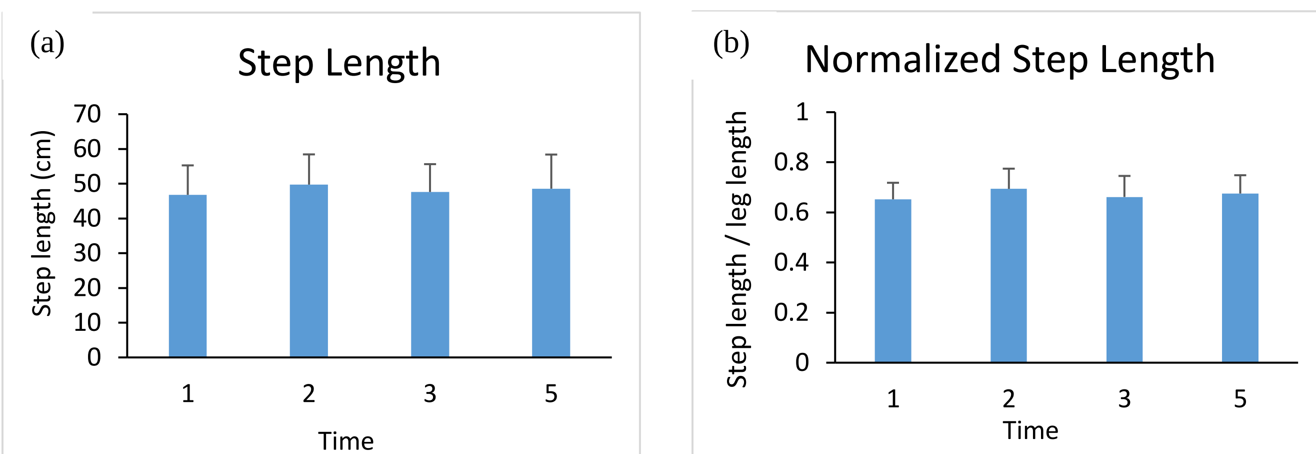


Figure 3-5 Group mean and standard deviation for (a) step length and (b) normalized step length at time points T1, T2, T3, and T5

When results were examined at the individual level, two overall response trends in the raw step length data were noted: 1) improvement following both interventions (n = 4, seen in green in Table 3-3), and 2) improvement following treadmill walking and worsening following combined WBV and treadmill walking (n = 2, seen in yellow in table 3-3) (Table 3-3). Response trends were identical in normalized step length excepting one subject who demonstrated improvement following treadmill walking in both instances, but who demonstrated no change in normalized step length following combined WBV and treadmill walking (Table 3-4).

Table 3-3 Individual responses of step length in cm at time points T1, T2, T3, and T5 (denotes missing data); data highlighted in green represents subjects who demonstrated increases following both interventions, and data highlighted in yellow represents subjects who demonstrated increases following treadmill walking and then decreases following the combined intervention**

Subject	Step Length (cm)			
	Time 1	Time 2	Time 3	Time 5
CP01	62.1	64.6	58.9	62.5
CP02	42.0	44.0	43.5	44.1
CP03	45.6	47.6	43.6	43.5
CP04	47.5	56.0	n/a	52.6
CP05	38.4	42.5	38.6	39.7
CP06	41.7	43.0	46.8	40.1
CP07	35.9	38.2	39.0	36.9
CP08	53.1	57.2	58.0	61.9
CP09	54.7	54.5	52.5	55.8

Table 3-4 Individual responses of normalized step length at time points T1, T2, T3, and T5 (denotes missing data)**

Subject	Normalized Step Length (step length / leg length)			
	Time 1	Time 2	Time 3	Time 5
CP01	0.73	0.76	0.70	0.74
CP02	0.69	0.72	0.72	0.72
CP03	0.52	0.55	0.50	0.50
CP04	0.71	0.84	**	0.78
CP05	0.59	0.65	0.59	0.61
CP06	0.69	0.71	0.78	0.65
CP07	0.63	0.67	0.67	0.65
CP08	0.64	0.68	0.70	0.74
CP09	0.67	0.67	0.64	0.68

The four subjects (CP01, CP02, CP05, CP08) that demonstrated improvements following both interventions demonstrated an average increase in step length of 3.2 cm following treadmill walking and 2.1 cm following combined WBV and treadmill walking, resulting in average step lengths of 52.1 cm and 52.6 cm after each intervention, respectively. Three subjects (CP01, CP02, and CP05) demonstrated a return to near-baseline values at T3, followed by a second increase in step length following the combined TW and WBV intervention at T5; an example of this pattern can be seen in Figure 3-6a. One subject (CP08) demonstrated consistent increases in step length across all time points (Figure 3-6b).

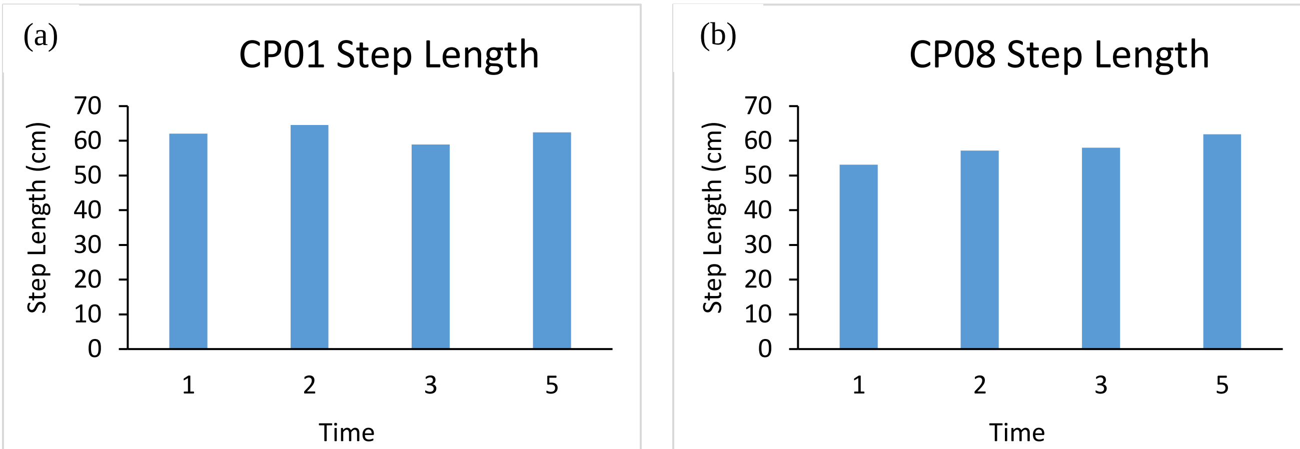


Figure 3-6 Step length at time points T1, T2, T3, and T5 for subjects (a) CP01 and (b) CP08

Two subjects (CP06 and CP07) demonstrated increased step length following the bout of treadmill walking only, and then decreased step length following the combined WBV and treadmill walking intervention. The average increase following treadmill walking was 1.8 cm, followed by an average decrease of 4.4 cm following combined WBV and treadmill walking; these patterns can be seen in Figure 3-7a-b.

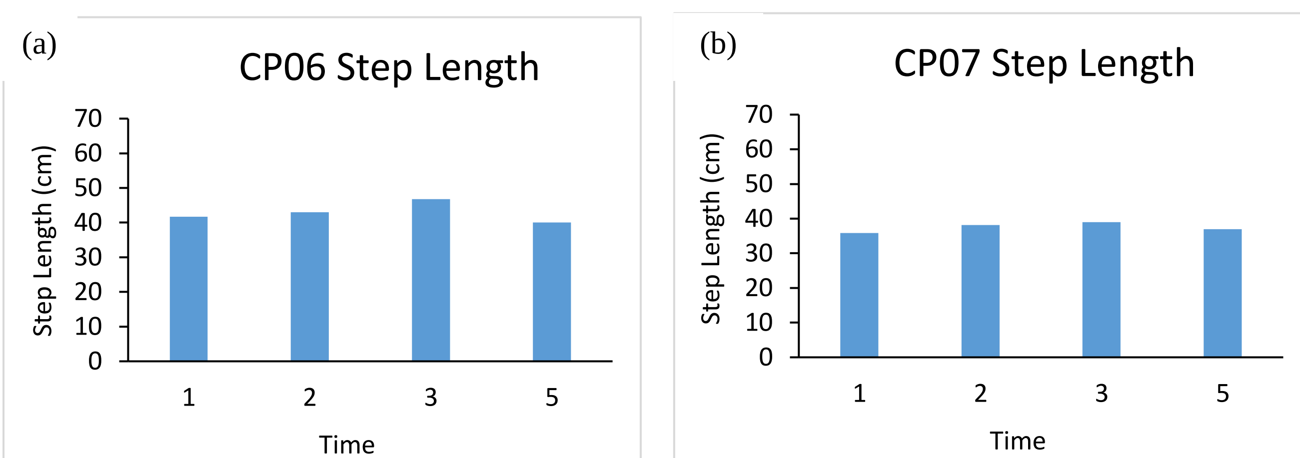


Figure 3-7 Step length at time points T1, T2, T3, and T5 for subjects (a) CP06 and (b) CP07

As previously noted, trends between raw and normalized step length were nearly identical. Subject CP02 was the exception; both variables increased following treadmill walking, but the increase after the combined WBV and treadmill walking intervention that was seen in raw step length disappeared when step length was normalized by leg length (Figure 3-8a-b).

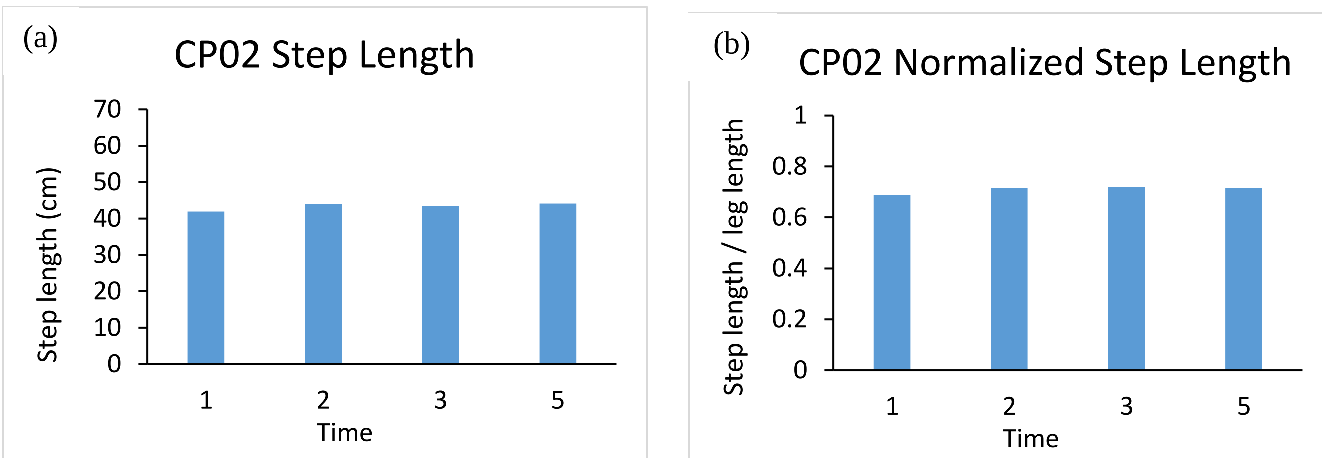


Figure 3-8 Step length (a) and normalized step length (b) at time points T1, T2, T3, and T5 for subject CP02

Other response patterns of step length included an increase after treadmill walking followed by no change after the combined WBV and treadmill walking (n=1, CP03), and no change after treadmill walking followed by an increase after the combined intervention (n = 1, CP09) (Table 3-3).

Double Support Time

There was not a significant intervention effect (F(1,31)=0.26, p=0.61), time effect (F(1,31)=0.01, p=0.91), or intervention by time interaction (F(1,31)=0.34, p=0.56) (Figure 3-9).

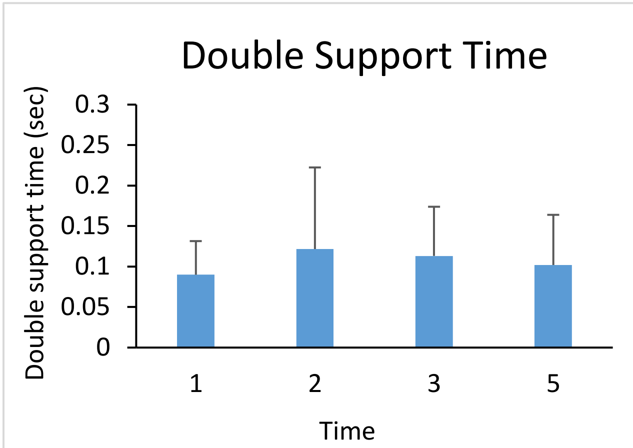


Figure 3-9 Group mean and standard deviation for double support time at time points T1, T2, T3, and T5

When results were examined at the individual level, three primary response trends were noted: 1) a decrease following treadmill walking followed by an increase following combined WBV and treadmill walking (n = 2, seen in green in Table 3-5), 2) an increase following tread-mill walking followed by a decrease following combined WBV and treadmill walking (n = 2, seen in yellow in Table 3-5), and an increase following both interventions (n = 2, seen in red in Table 3-5) (Table 3-5). Minimal detectable change values for double support time in cerebral palsy are not specifically reported on in the literature, so young adult values of <0.001 were used as a guideline (Almarwani et al., 2016).

Table 3-5 Individual responses of double support time at time points T1, T2, T3, and T5 (denotes missing data); data highlighted in green represents subjects who demonstrated a decrease following treadmill walking followed by an increase following the combined intervention, data highlighted in yellow represents subjects who demonstrated an increase following treadmill walking followed by a decrease following the combined intervention, and data highlighted in red represents subjects who demonstrated an increase following both interventions**

Subject	Double Support Time (sec)			
	Time 1	Time 2	Time 3	Time 5
CP01	0.069	0.081	0.086	0.078
CP02	0.056	0.043	0.048	0.048
CP03	0.180	0.330	0.217	0.223
CP04	0.056	0.032	**	0.056
CP05	0.093	0.087	0.086	0.109
CP06	0.097	0.253	0.198	0.125
CP07	0.045	0.081	0.078	0.099
CP08	0.117	0.098	0.087	0.097
CP09	0.096	0.089	0.107	0.082

Two subjects (CP05 and CP08) demonstrated a decrease in double support time after the bout of treadmill walking, followed by an increase after combined WBV and treadmill walking. The average decrease following treadmill walking was 0.040 sec, while the average increase following the combined intervention was 0.017 sec; an example of this pattern can be seen in Figure 3-10.

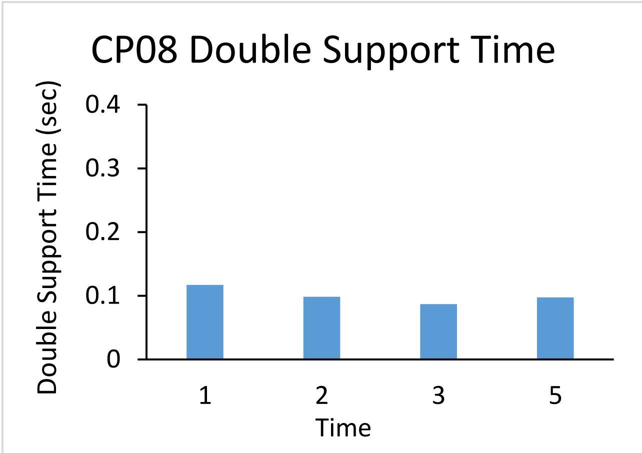


Figure 3-10 Double support time (in sec) at time points T1, T2, T3, and T5 for subject CP08

Two subjects (CP01 and CP06) demonstrated an increase in double support time after the bout of treadmill walking, followed by a decrease after combined WBV and treadmill walking. The average increase following treadmill walking was 0.084 sec, while the average decrease following the combined intervention was 0.040 sec; an example of these pattern can be seen in Figure 3-11.

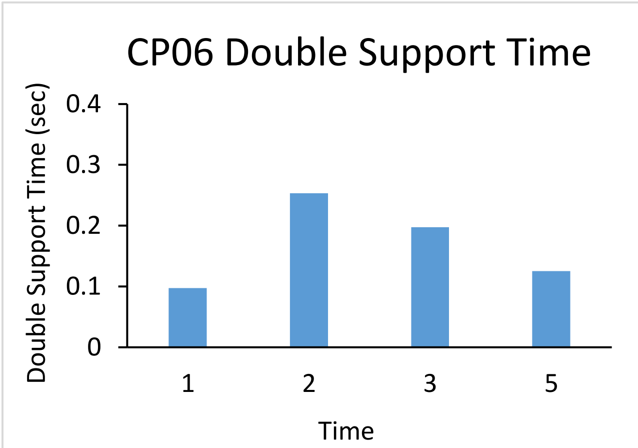


Figure 3-11 Double support time (in sec) at time points T1, T2, T3, and T5 for subject CP06

Two subjects (CP03 and CP07) demonstrated an increase in double support time following both interventions. The average increase following treadmill walking was 0.037 sec, while the average increase following the combined intervention was 0.013 sec; an example of these pattern can be seen in Figure 3-12.

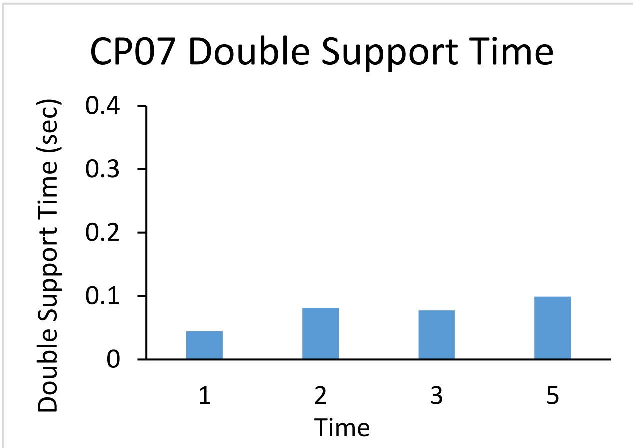


Figure 3-12 Double support time (in sec) at time points T1, T2, T3, and T5 for subject CP07

Other response patterns of double support time included a decrease after treadmill walking followed by no change after the combined WBV and treadmill walking (n = 1, CP02), and a decrease following both interventions (n = 1, CP09) (Table 3-5).

Stance Percent

There was not a significant intervention effect ($F(1,31)=0.48$, $p=0.49$), time effect ($F(1,31)=0.34$, $p=0.57$), or intervention by time interaction ($F(1,31)=0.14$, $p=0.71$) (Figure 3-13).

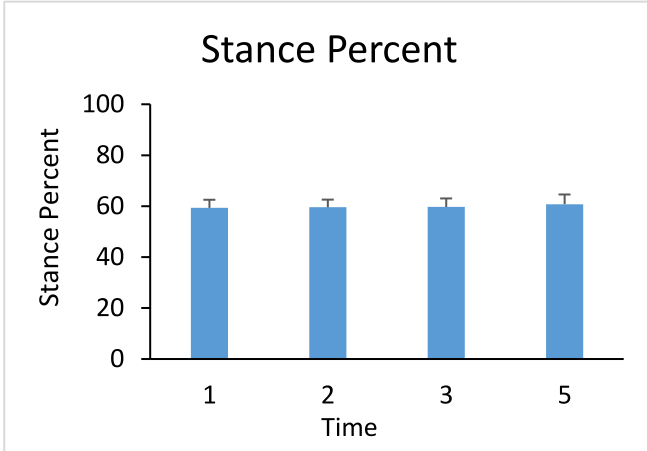


Figure 3-13 Group mean and standard deviation for stance percent at time points T1, T2, T3, and T5

When results were examined at the individual level, two primary response trends were noted: 1) a decrease following treadmill walking followed by an increase following combined WBV and treadmill walking (n = 3, seen in green in Table 3-6), 2) an increase following both interventions (n = 3, seen in red in Table 3-6) (Table 3-6).

Table 3-6 Individual responses of stance percent at time points T1, T2, T3, and T5 (denotes missing data); data highlighted in green represents subjects who demonstrated a decrease following treadmill walking followed by an increase following the combined intervention, and data highlighted in yellow represents subjects who demonstrated an increase following both interventions**

Subject	Stance Percent			
	Time 1	Time 2	Time 3	Time 5
CP01	57.0	58.6	59.6	59.0
CP02	57.5	56.0	55.8	56.0
CP03	65.9	64.6	67.2	68.2
CP04	56.4	54.3	**	56.2

CP05	59.9	60.5	58.1	61.3
CP06	60.9	61.3	59.0	63.8
CP07	55.4	60.1	58.0	62.7
CP08	60.8	60.5	59.3	60.9
CP09	60.1	60.0	60.5	59.2

Three subjects (CP02, CP03, and CP08) demonstrated a decrease in stance percent following treadmill walking, followed by an increase in stance percent following combined WBV and treadmill walking. The average decrease after treadmill walking was 1.0% and the average increase following the combined intervention was 0.1%. Even within this response trend there was notable variability present, with subject CP02 demonstrating a lower stance percent at T5 than at T1, subject CP03 demonstrating a higher stance percent at T5 than T1, and subject CP08 returning to their T1 baseline by T5. An example of this response is seen below in Figure 3-14.

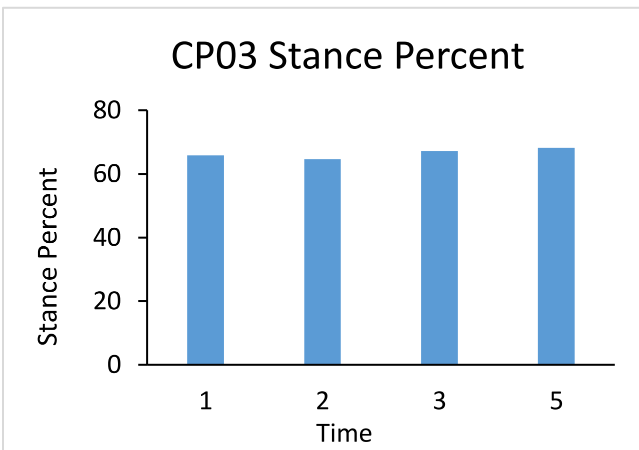


Figure 3-14 Stance percent at time points T1, T2, T3, and T5 for subject CP03

Three subjects (CP05, CP06, and CP07) also demonstrated an increase in stance percent following both interventions. The average increase was 2.2% following treadmill walking, while the average increase following combined WBV and treadmill walking was 4.2%. This resulted in an average increase in stance percent of 3.9% from time point T1 to T5. Examples of this pattern can be seen below in Figure 3-15a-b.

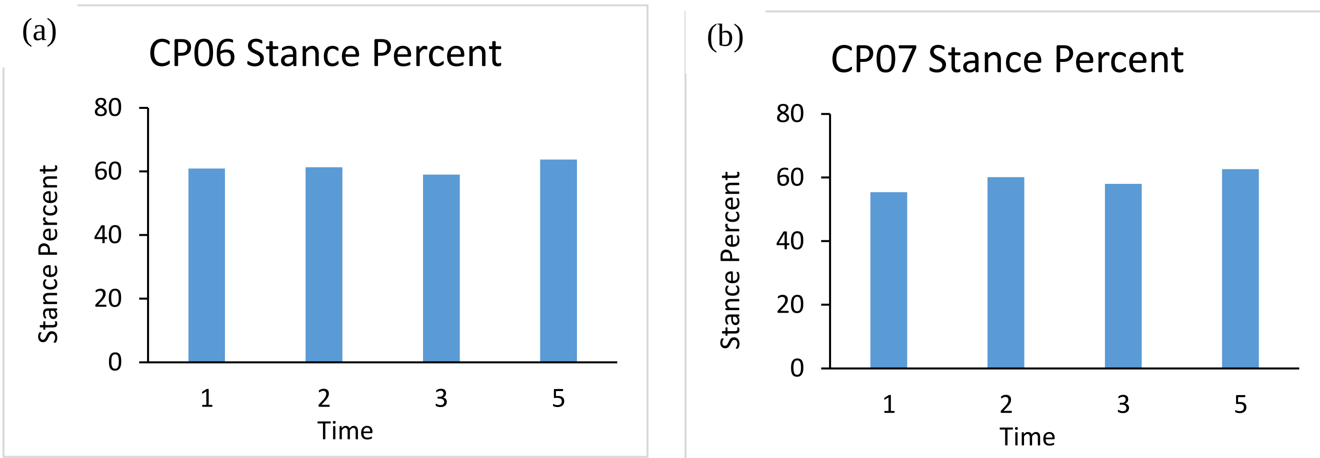


Figure 3-15 Stance percent at time points T1, T2, T3, and T5 for subjects (a) CP06 and (b) CP07

Other response patterns of stance percent included an increase after treadmill walking followed by a decrease after the combined WBV and treadmill walking (n = 1, CP01), and no change following either intervention (n = 1, CP09) (Table 3-6).

Joint angles

Foot clearance

There was not a significant intervention effect (F(1,26)=0.00, *p*=0.94), time effect (F(1,26)=0.27, *p*=0.61), or intervention by time interaction (F(1,26)=0.01, *p*=0.93) (Figure 3-16).

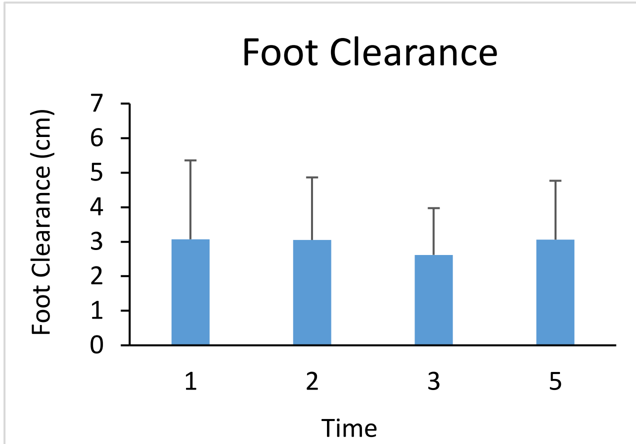


Figure 3-16 Group mean and standard deviation for foot clearance at time points T1, T2, T3, and T5

When results were examined at the individual level, the two most common response trends were 1) improvement in foot clearance following treadmill walking (n = 3, seen in green in Table 3-7), and 2) improvement in foot clearance following both interventions (n = 3, seen in yellow in Table 3-7) (Table 3-7).

Table 3-7 Individual responses of foot clearance (in cm) at time points T1, T2, T3, and T5; data highlighted in green represents subjects who demonstrated an improvement following treadmill walking only, and data highlighted in yellow represents subjects who demonstrated an improvement following both interventions

Subject	Foot Clearance (cm)			
	T 1	T2	T3	T5
CP01	2.14	1.95	2.11	2.34
CP02	n/a	n/a	n/a	n/a
CP03	1.40	1.56	1.87	1.97
CP04	5.82	5.03	n/a	6.54
CP05	5.89	5.90	4.04	3.30

CP06	5.69	5.49	4.61	4.77
CP07	1.01	2.37	n/a	2.38
CP08	1.29	1.47	1.68	1.73
CP09	1.30	1.45	1.41	1.46

Six subjects (CP03, CP04, CP06, CP07, CP08, and CP09) demonstrated improvements in foot clearance following the first bout of treadmill walking. Average foot clearance in healthy young adults ranges from 10-20mm (Winter, 1992), so foot clearance was considered to "improve" if it was initially insufficient or excessive and moved towards a more typical range. Of the six subjects that showed improvements, three subjects did so by increasing their foot clearance (CP03, CP08, and CP09) and three subjects did so by decreasing their foot clearance (CP04, CP06, and CP07). The average increase in foot clearance was 0.56cm, while the average decrease was 0.60 cm; examples of these patterns can be seen in Figure 3-17a-b.

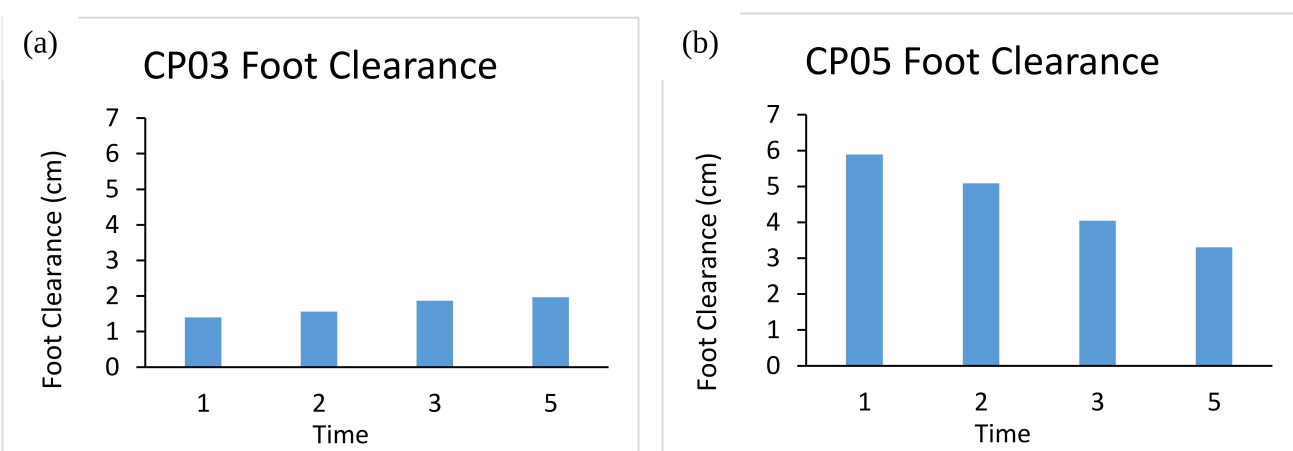


Figure 3-17 Foot clearance (in cm) at time points T1, T2, T3, and T5 for subjects (a) CP03 and (b) CP05

Three (CP03, CP08, and CP09) of these six subjects that improved following treadmill walking also demonstrated further improvement in foot clearance following the combined intervention. This improvement averaged 0.08cm for those subjects who were increasing their foot clearance (n = 2) and 0.74cm for those subjects who were decreasing their foot clearance (n = 1). Of note, of the three subjects who improved following treadmill walking but did not demonstrate further improvement, only one of those subjects (CP06) demonstrated a slight worsening of foot clearance following the combined intervention; the remaining two (CP04 and CP07) were missing data that did not allow for calculation of improvement after the combined intervention (Table 3-7).

Peak ankle dorsiflexion

There was not a significant intervention effect (F(1,27)=0.25, *p*=0.62), time effect (F(1,27)=0.41, *p*=0.53), or intervention by time interaction (F(1,27)=0.28, *p*=0.60) (Figure 3-18).

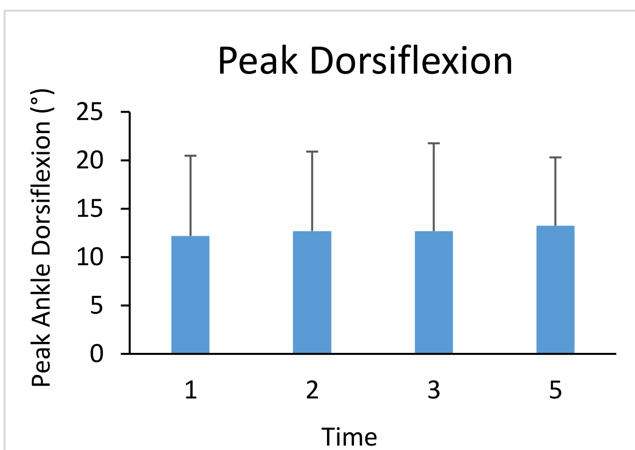


Figure 3-18 Group mean and standard deviation for peak ankle dorsiflexion at time points T1, T2, T3, and T5

When results were examined at the individual level, a response trend of increasing peak dorsiflexion was noted in five subjects (seen in green in Table 3-8). The actual increases in dorsiflexion, however, were quite small, averaging 2.3° across all time points; an example of this trend can be seen in Figure 3-19. Of these five subjects, all showed improvements following the bout of treadmill walking only, and four of them also showed improvements following the combined bout of WBV and treadmill walking; of the four subjects who improved after both interventions, the improvements were generally greater following the combined intervention (averaging 2.3°) than following treadmill walking alone (averaging 1.0°).

Table 3-8 Individual responses of peak ankle dorsiflexion at time points T1, T2, T3, and T5; data highlighted in green represents subjects who demonstrated an increase in dorsiflexion following treadmill walking

Subject	Peak Ankle Dorsiflexion (°)			
	T1	T2	T3	T5
CP01	18.5	18.7	17.2	17.8
CP02	-0.4	0.6	0.9	2.3
CP03	19.9	20.2	20.4	19.7
CP04	11.3	10.6	n/a	9.9
CP05	20.5	21.0	23.3	20.6
CP06	16.5	18.3	16.3	17.8
CP07	-2.0	-1.3	-2.5	3.1
CP08	13.0	13.1	12.4	13.9
CP09	12.4	13.0	13.3	14.2

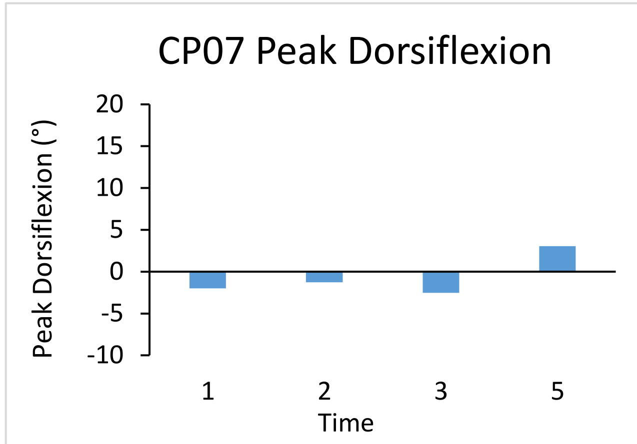
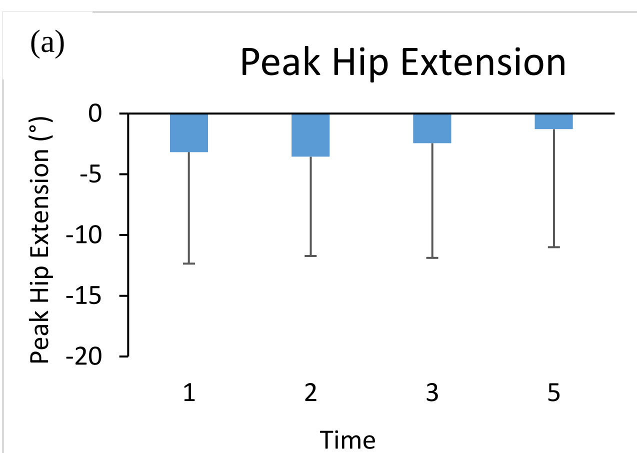
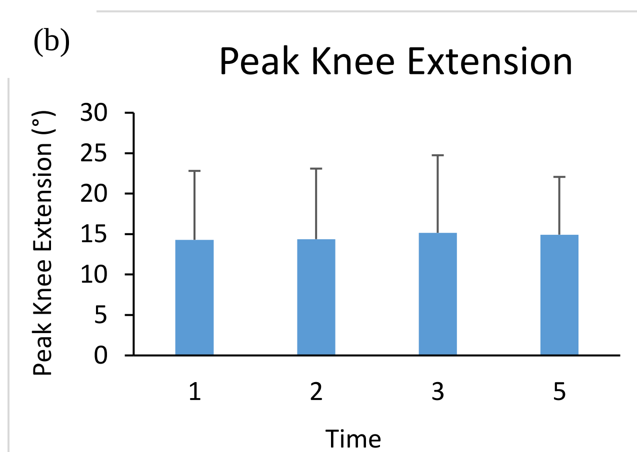


Figure 3-19 Peak ankle dorsiflexion at time points T1, T2, T3, and T5 for subject CP07

Peak extension angles

There was not a significant intervention effect, time effect, or intervention by time interaction for peak hip extension, peak knee extension, or peak ankle plantarflexion (Figure 3-20a-c, Table 3-9).





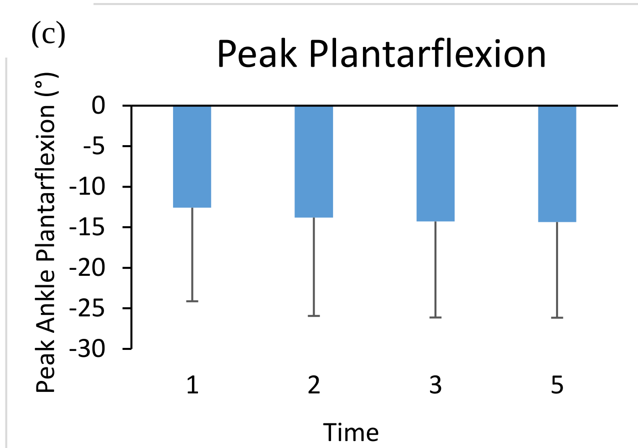


Figure 3-20 Group mean and standard deviation at time points T1, T2, T3, and T5 for (a) peak hip extension, (b) peak knee extension, and (c) peak ankle plantarflexion

Table 3-9 Statistical results for peak extension angles

Variable	Intervention		Time		Intervention*Time	
	F	*p*	F	*p*	F	*p*
Peak Hip Extension	0.26	0.61	0.02	0.90	0.07	0.80
Peak Knee Extension	0.11	0.74	0.00	0.96	0.00	0.97
Peak Ankle Plantarflexion	0.08	0.78	0.02	0.88	0.02	0.89

When results were examined at the individual level, no consistent response trends were noted, with most joint angles varying 5° or less across all time points. However, two subjects did demonstrate consistent changes of a larger magnitude. Subject CP07 demonstrated improvements into peak hip extension, knee extension, and ankle plantarflexion following both interventions (Figure 3-21a-c). Hip extension improvements were similar between the two interventions, improving 5.5 ° after treadmill walking and 5.6° after combined WBV and treadmill walking (Figure 3-21a). Knee extension and ankle plantarflexion improvements, however, were greater following the combined intervention, improving 1.4° and 1.1° respectively after treadmill walking alone and improving 6.1° and 3.2° respectively after the combined intervention (Figure 3-21b-c).

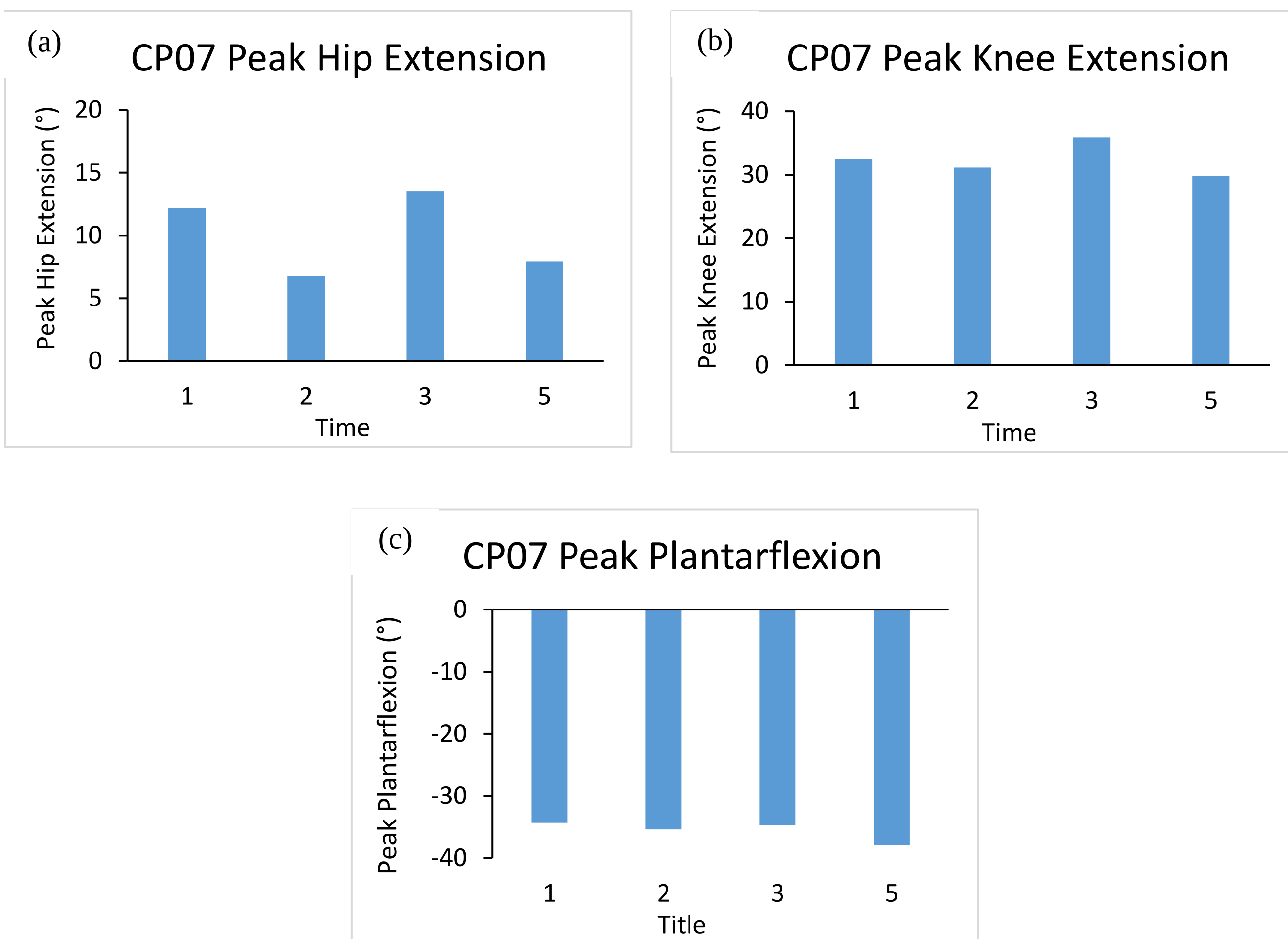


Figure 3-21 Subject CP07 (a) peak hip extension, (b) peak knee extension, and (c) peak plantarflexion at time points T1, T2, T3, and T5

Conversely, subject CP06 demonstrated worsening of peak hip extension, knee extension, and ankle plantarflexion following both interventions (Figure 3-22a-c). Peak hip extension decreased by 4.6° following treadmill walking and by 4.7° following combined WBV and treadmill walking (Figure 3-22a). Peak knee extension decreased by 3.9° following treadmill walking, and by 5.6° following the combined intervention (Figure 3-22b), and peak plantarflexion decreased 5.7° following treadmill walking and then by 5.4° following the combined intervention (Figure 3-22c).

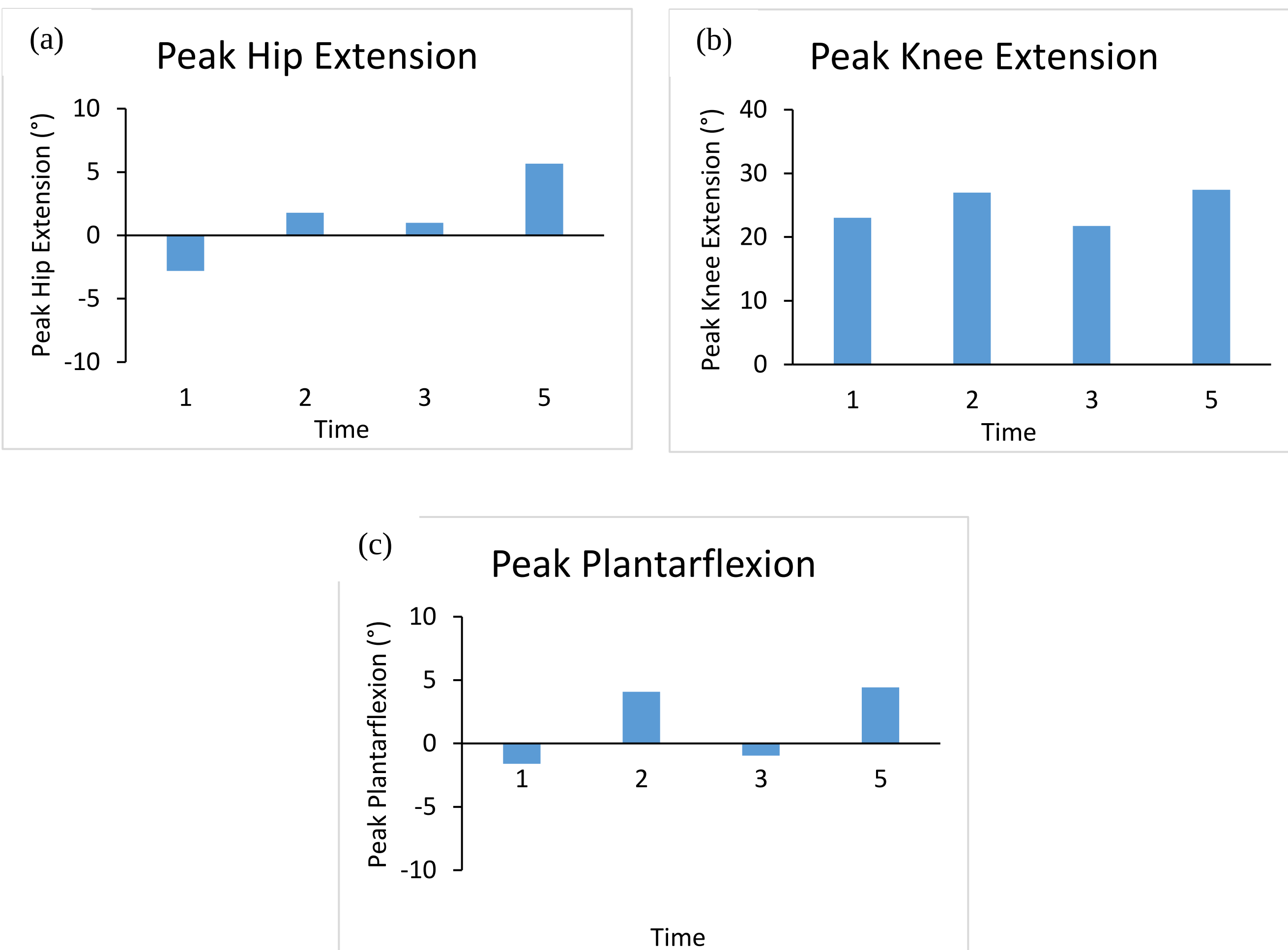


Figure 3-22 Subject CP06 (a) peak hip extension, (b) peak knee extension, and (c) peak plantarflexion at time points T1, T2, T3, and T5

Other joint angles

There was not a significant intervention effect, time effect, or intervention by time interaction for any other joint angles. Further, when results were examined at the individual level, no consistent response trends were noted with regard to peak hip flexion or peak knee flexion.

EMG parameters

Muscle activity about the knee (vastus lateralis and biceps femoris)

There was not a significant intervention effect, time effect, or intervention by time interaction for normalized EMG activity at the vastus lateralis or biceps femoris (Figure 3-23, Table 3-10).

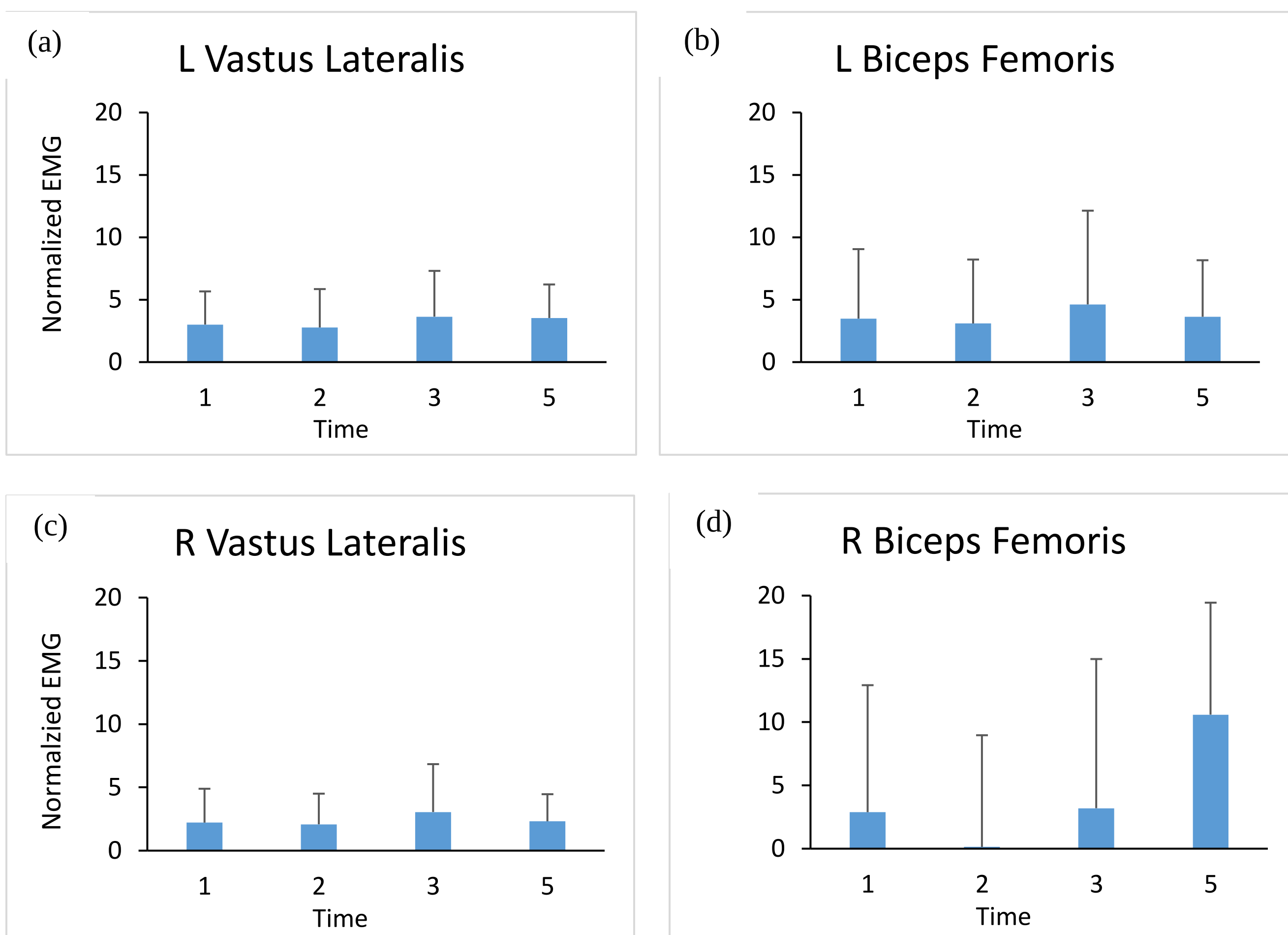


Figure 3-23 Normalized EMG activity per 1/100th sec for the (a) left vastus lateralis, (b) left biceps femoris, (c) right vastus lateralis, and (d) right biceps femoris at time points T1, T2, T3, and T5

Table 3-10 Statistical results for EMG activity about the knee

Variable	Intervention		Time		Intervention*Time	
	F	*p*	F	*p*	F	*p*
Left Vastus Lateralis	0.26	0.61	0.17	0.68	0.30	0.59
Left Biceps Femoris	0.01	0.91	0.12	0.74	0.01	0.94
Right Vastus Lateralis	0.00	0.96	0.13	0.72	0.06	0.81
Right Biceps Femoris	0.10	0.76	0.13	0.73	0.41	0.53

Further, when results were examined at the individual level, significant variability was still present. Examination at the individual level was complicated by a fair amount of missing data that was discarded after processing; several trials demonstrated high variability with significant outliers that were believed to be the result of electrodes that became insecure or moved during data collection.

All four muscles (bilateral vastus lateralis and bilateral biceps femoris) demonstrated a trend toward decreasing muscle activity following the initial bout of treadmill walking. Further, each muscle excepting the right biceps femoris also demonstrated decreased muscle activity following the combined intervention of WBV and treadmill walking. However, in contrast, the most common trend observed on an individual level was increased activity in the quadriceps and decreased activity in the hamstrings (n=3) following both interventions.

With regard to co-contraction indices, there was not a significant intervention effect, time effect, or intervention by time interaction about the knee during either stance or swing phase (Figure 3-24, Table 3-11).

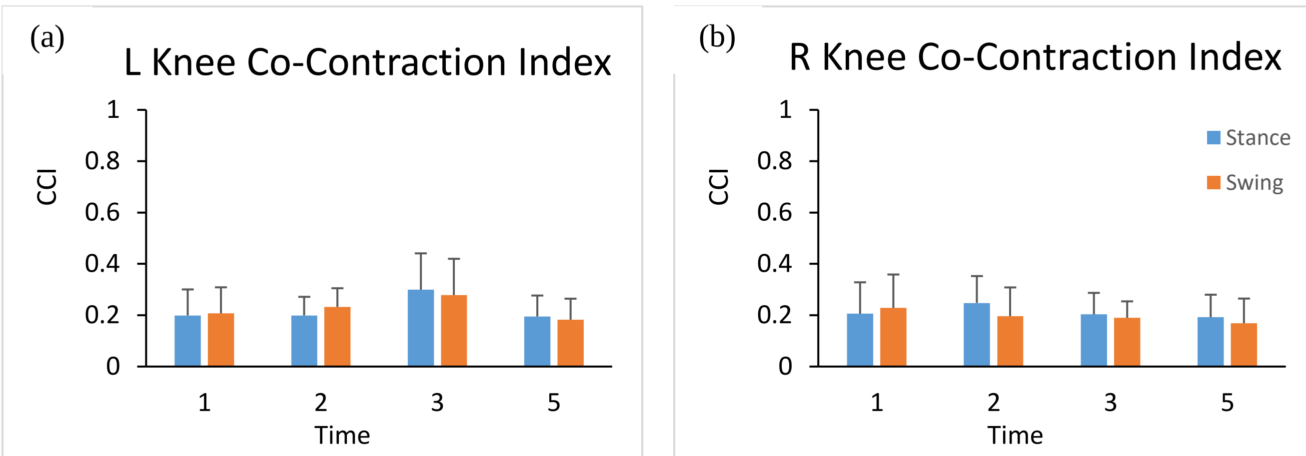


Figure 3-24 Co-contraction indices about the (a) left and (b) right knee during both stance and swing phase at time points T1, T2, T3, and T5

Table 3-11 Statistical results for co-contraction indices about the knee

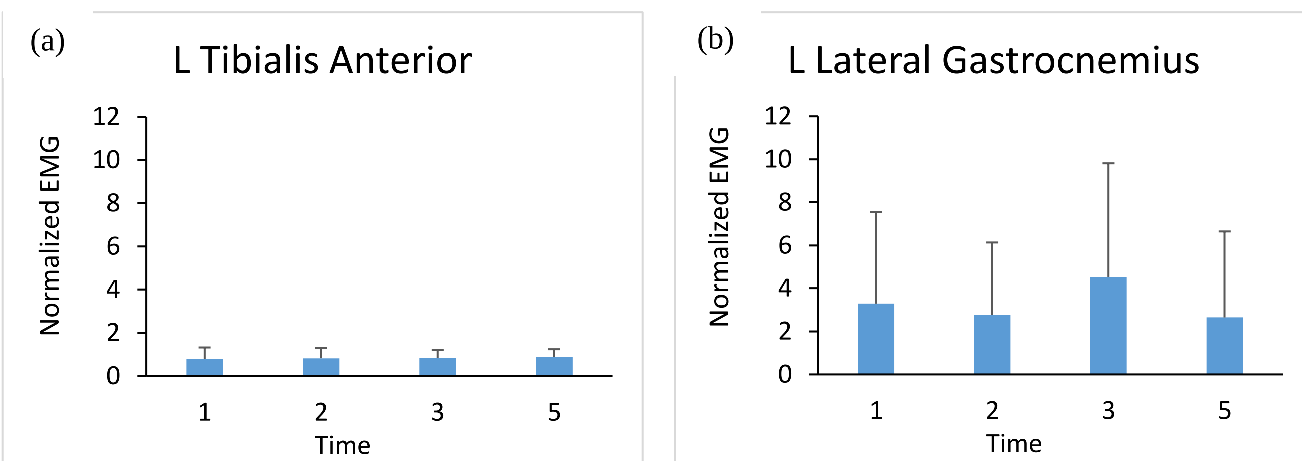
Variable	Intervention		Time		Intervention*Time	
	F	*p*	F	*p*	F	*p*
Left Knee CCI Stance	0.02	0.90	0.40	0.53	0.95	0.34
Left Knee CCI Swing	0.32	0.58	1.95	0.18	3.20	0.09
Right Knee CCI Stance	0.42	0.52	0.01	0.94	1.01	0.33

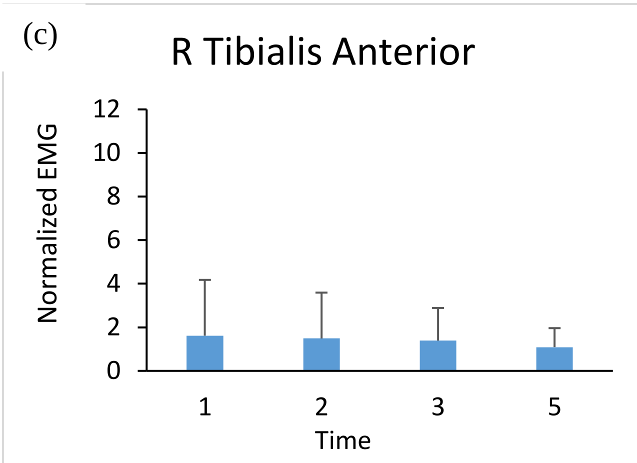
Right Knee CCI Swing	0.56	0.46	1.03	0.32	0.41	0.53

Further, when results were examined at the individual level, no notable trends emerged. Interestingly, even the three subjects (CP06, CP07, and CP08) who demonstrated consistent increases in quadriceps activity and consistent decreases in hamstring activity, all demonstrated different response patterns with regard to co-contraction at the knee.

1.1.1.2 Muscle activity about the ankle (tibialis anterior and lateral gastrocnemius)

There was not a significant intervention effect, time effect, or intervention by time interaction for normalized EMG activity at the tibialis anterior or lateral gastrocnemius (Figure 3-25, Table 3-12).





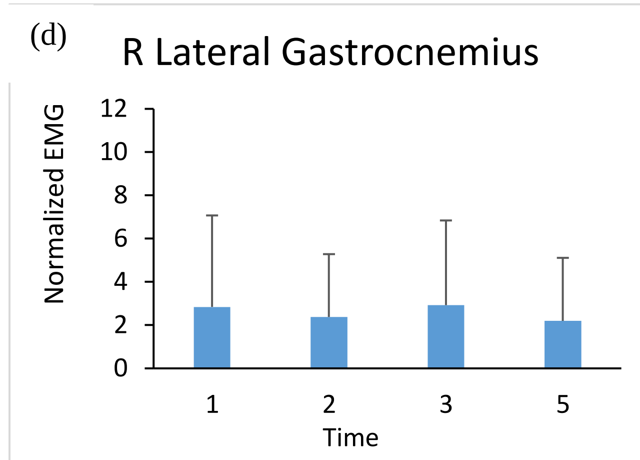


Figure 3-25 N**ormalized EMG activity per 1/100th sec for the (a) left tibialis anterior, (b) left lateral gastrocnemius, (c) right tibialis anterior, and (d) right lateral gastrocnemius**

Table 3-12 Statistical results for EMG activity about the ankle

Variable	Intervention		Time		Intervention*Time	
	F	*p*	F	*p*	F	*p*
Left Tibialis Anterior	0.27	0.61	0.03	0.86	0.06	0.81
Left Lateral Gastrocnemius	0.11	0.74	0.11	0.74	0.03	0.87
Right Tibialis Anterior	0.00	0.99	0.13	0.72	0.07	0.80
Right Lateral Gastrocnemius	0.00	0.97	0.00	0.98	0.00	0.96

Further, when results were examined at the individual level, significant variability was still present. Examination at the individual level about the ankle was, similarly to the knee, complicated by a fair amount of missing data that was discarded after processing; several trials demonstrated high variability with significant outliers that were believed to be the result of electrodes that became insecure or moved during data collection.

Three muscles (the right tibialis anterior and bilateral lateral gastrocnemius) demonstrated a trend toward decreasing muscle activity following both treadmill walking and combined WBV and treadmill walking. The left tibialis anterior, in contrast, remained relatively stable across all time points, with very slight increases following each intervention.

With regard to co-contraction indices, there was not a significant intervention effect, time effect, or intervention by time interaction about the ankle during either stance or swing phase (Figure 3-26, Table 3-13).

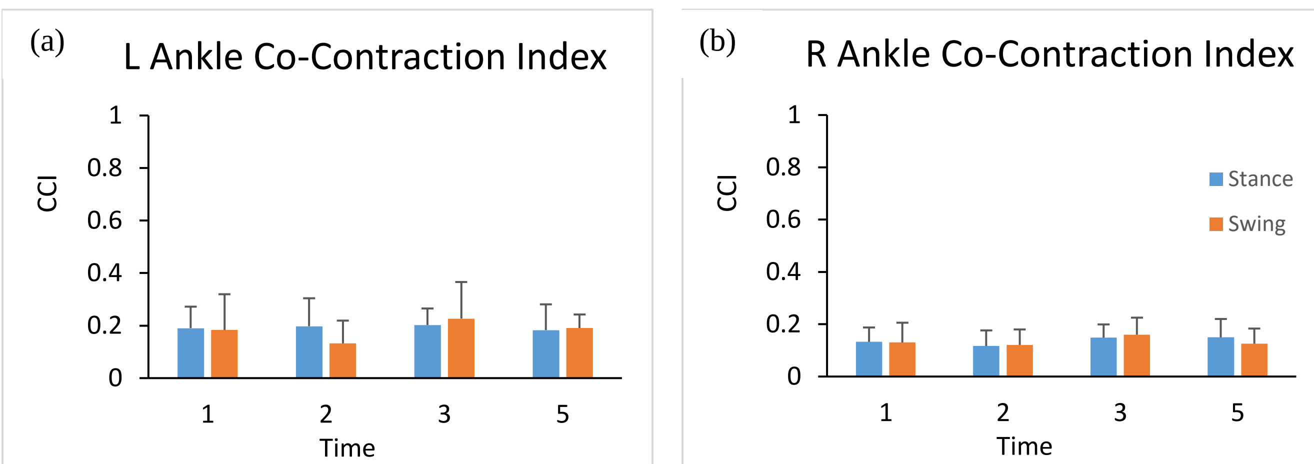


Figure 3-26 Co-contraction indices about the (a) left and (b) right ankle during both stance and swing phase at time points T1, T2, T3, and T5

Table 3-13 Statistical results for co-contraction indices about the ankle

Variable	Intervention		Time		Intervention*Time	
	F	*p*	F	*p*	F	*p*
Left Ankle CCI Stance	0.09	0.77	0.31	0.58	0.03	0.87
Left Ankle CCI Swing	1.95	0.18	0.55	0.46	0.19	0.67
Right Ankle CCI Stance	0.92	0.35	0.52	0.48	0.16	0.69
Right Ankle CCI Swing	0.55	0.47	0.21	0.65	0.38	0.55

Despite the lack of statistical significance, a trend emerged with regard to group-level co-contraction about the ankle. Co-contraction during stance phase remained relatively unchanged across all time points, while co-contraction during swing phase trended downward following both interventions. However, when results were examined at the individual level, significant variability was still present and no notable trends emerged.

Treadmill gait patterns

Treadmill walking patterns between the first and second bouts were compared to evaluate the effect of the bout of WBV on gait quality during treadmill walking. There was no significant group-level difference between the two for any of the chosen spatiotemporal parameters (Figure 3-27a-c, Table 3-14).

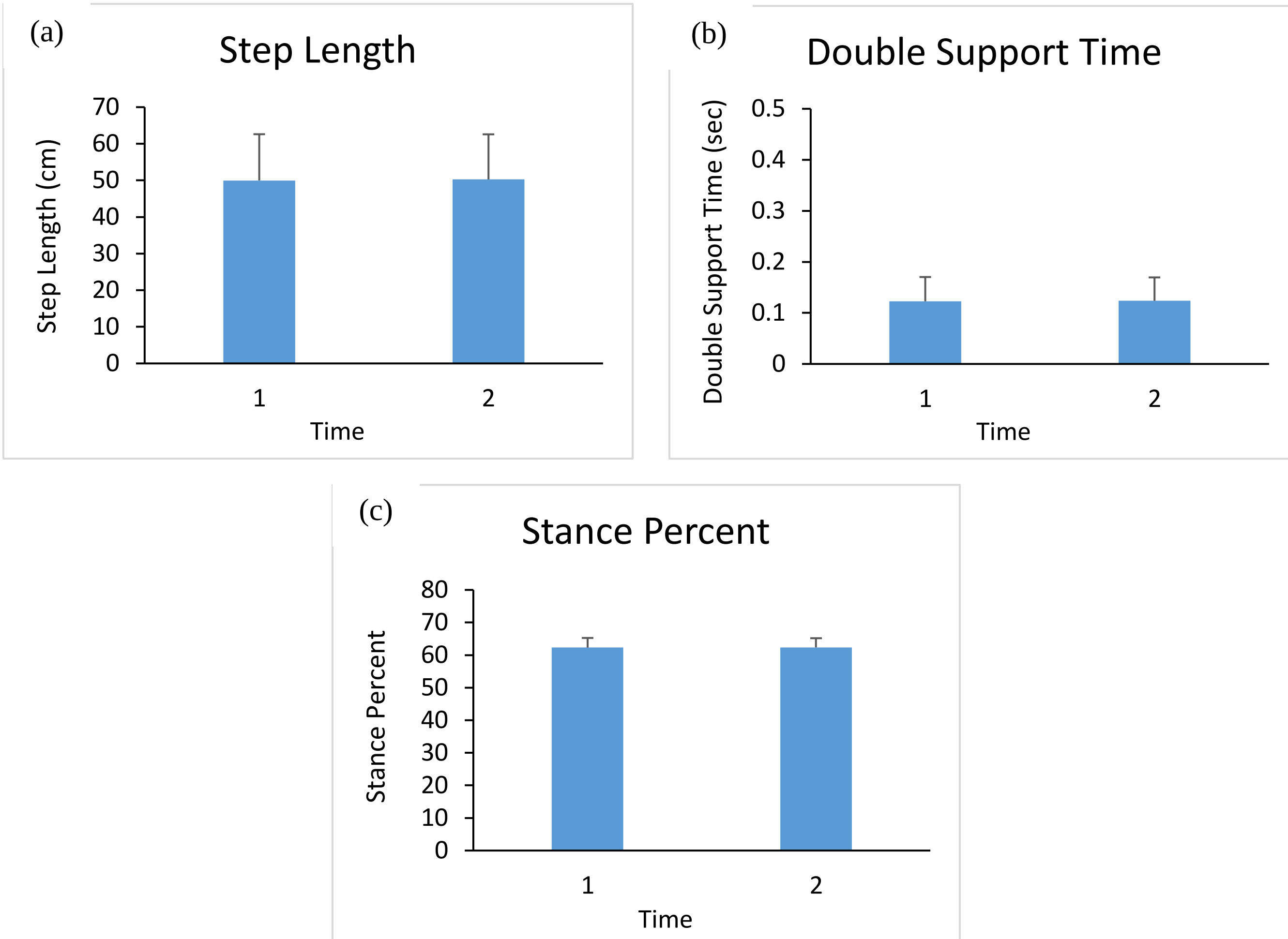


Figure 3-27 Group-level means for (a) step length, (b) double support time, and (c) stance percent during the first and second bouts of treadmill walking

Table 3-14 Statistical results for selected spatiotemporal variables during treadmill walking

Variable	t	*p*
Step Length	-1.00	0.35
Double Support Time	-0.75	0.47
Stance Percent	-0.68	0.52

When trends were examined at the individual level, similar patterns were noted; that is, most subjects demonstrated no notable changes in their spatiotemporal variables between the two treadmill bouts. An example of subject-by-subject changes can be seen in Figure 3-28.

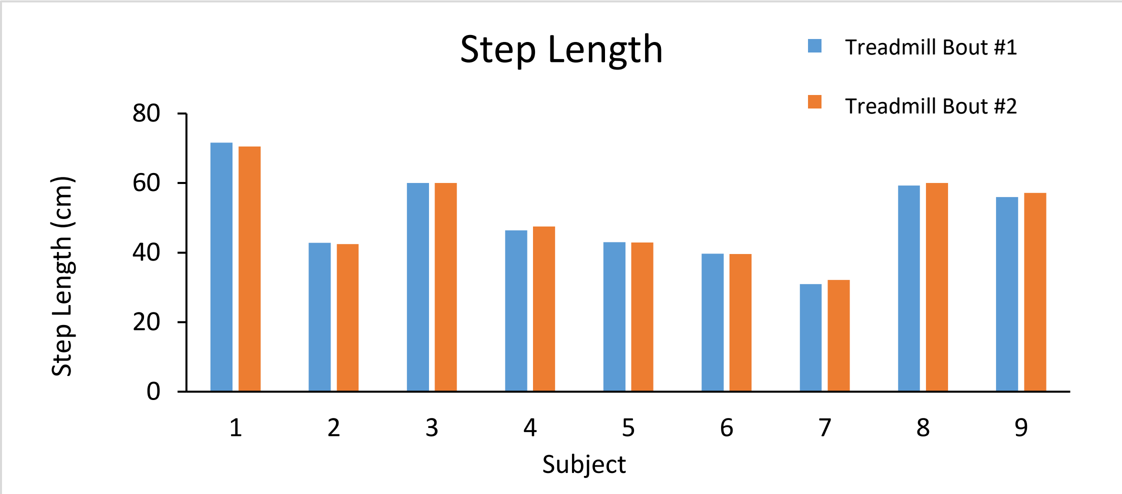


Figure 3-28 Step length for all subjects during the first and second bouts of treadmill walking

There was no significant group-level difference between any peak joint angles between the two treadmill bouts (Table 3-15).

Table 3-15 Statistical results for selected spatiotemporal variables during treadmill walking

Variable	t	*p*
Peak Hip Flexion	0.09	0.93
Peak Hip Extension	-1.98	0.08
Peak Knee Flexion	-0.44	0.67
Peak Knee Extension	-0.72	0.49
Peak Dorsiflexion	-1.49	0.17
Peak Plantarflexion	-0.33	0.75

However, changes in peak hip extension did approach statistical significance (p = 0.08) despite the mean change in joint angle being just over 1°; peak hip extension was slightly decreased during the second treadmill bout, as seen in Figure 3-29.

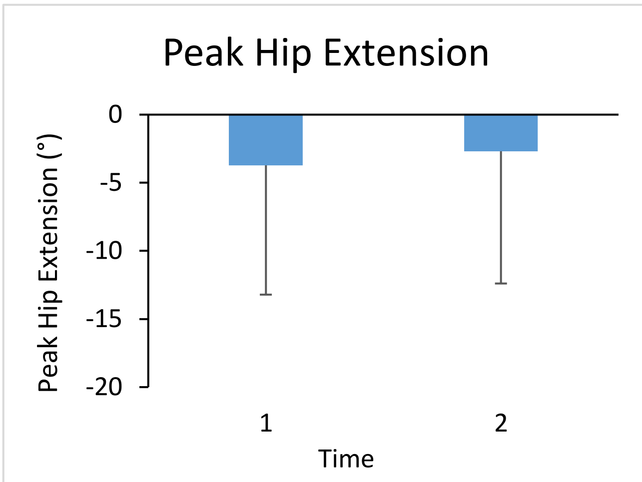


Figure 3-29 Group-level means for peak hip extension during the first and second bouts of treadmill walking

When trends were examined at the individual level, similar patterns were noted; that is, most subjects demonstrated no notable changes in their peak joint angles between the two treadmill bouts. Although some subjects demonstrated slight increases in peak hip extension while others demonstrated slight decreases, for most subjects these changes were less than 2°. An example of subject-by-subject changes can be seen in Figure 3-30.

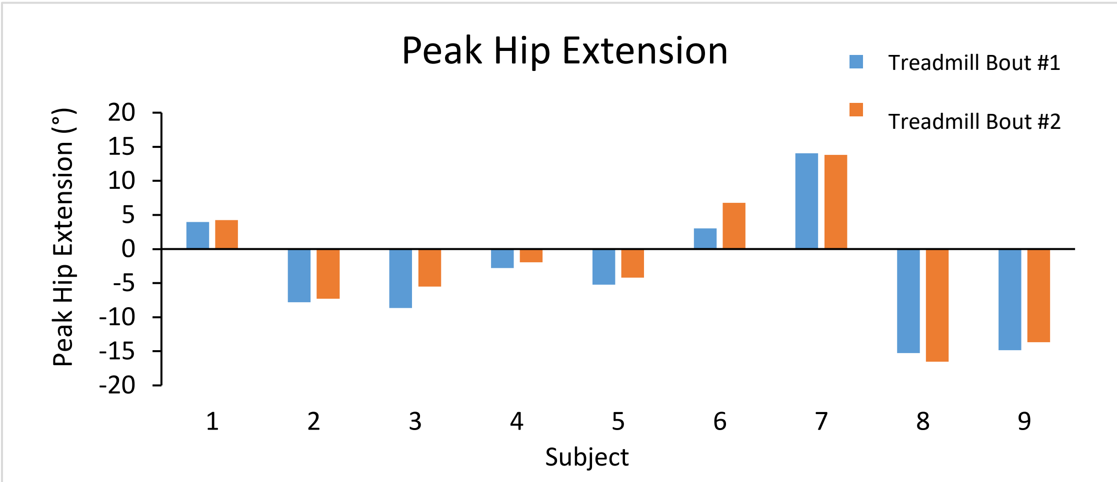


Figure 3-30 Peak hip extension for all subjects during the first and second bouts of treadmill walking

1.1.1.3 Correlations

No significant patterns were seen when the correlations between subject demographics and responsiveness to intervention were investigated. There were a few scattered significant correlations that were present, but no consistent correlations were present between the response to either intervention and subject age, GMFCS level, topography, baseline walking speed, or baseline spasticity. A full view of these data can be found in Appendix A.

1.1.1.4 One-Way ANOVA

There was not a significant effect for time between time points T3, T4, and T5 for any spatiotemporal, kinematic, or EMG variables (Table 3-15). However, a few variables did approach statistical significance. Stance percent ($F(2,15)=2.89$, $p=0.09$) was higher at T5 (60.8%) than at T3 (59.7%). Peak hip flexion ($F(2,15)=1.98$, $p=0.17$) was lower at T 4 (43.0°) than at T5 (45.2°), and peak dorsiflexion ($F(2,15)=2.66$, $p=0.10$) was lower at T3 (12.7°) than at T4 (14.0°).

Table 3-16 Statistical results from one-way ANOVAs investigating changes between time points T3, T4, and T5

Variable	F	*p*
Walking Speed	0.17	0.85
Step Length	0.19	0.83
Stance Percent	2.89	0.09
Double Support Time	0.48	0.63
Peak Hip Flexion	1.98	0.17
Peak Hip Extension	0.70	0.51
Peak Knee Flexion	0.02	0.98
Peak Knee Extension	0.12	0.89
Peak Dorsiflexion	2.66	0.10
Peak Plantarflexion	0.33	0.72
Left Vastus Lateralis	0.27	0.77
Left Biceps Femoris	1.12	0.36
Right Vastus Lateralis	0.91	0.44
Right Biceps Femoris	0.52	0.62
Left Tibialis Anterior	0.17	0.85
Left Lateral Gastrocnemius	2.05	0.17
Right Tibialis Anterior	2.44	0.14
Right Lateral Gastrocnemius	0.69	0.53

Discussion

In general, I found no consistent, significant group-level differences in overground walking parameters before and after either treadmill walking alone or a combined intervention consisting of WBV and treadmill walking. However, my findings were characterized by significant individual variability of response, consistent with that seen in the literature (Krause et al., 2017).

In line with my first hypothesis, and similar to the measurements of lower extremity spasticity reported in the previous chapter, overground gait parameters, when they improved, tended to improve after both interventions. However, contrary to my second hypothesis, many spatio-temporal variables tended towards greater improvements following the bout of treadmill walking alone, rather than following the combined intervention. Interestingly, three of the subjects were unable to tolerate walking at 125% of their preferred overground pace on the treadmill, and yet demonstrated similar changes in walking speed to those subjects that were. This suggests that even walking at speeds as low as 83% of preferred overground pace (the maximum treadmill speed tolerated by the slowest subject) may be sufficient to replicate the results of this study.

Previous studies that have looked at the acute effects of WBV on individuals with CP have reported significant improvements in overground walking speed following a single bout of WBV; these improvements ranged from 0.03m/s (Dickin et al., 2013) to 0.05m/s (Cheng, Ju, et al., 2015). While my results for the current study did not reach statistical significance, subjects averaged improvements of 0.09m/s followed the combined intervention and 0.16m/s following the bout of treadmill walking alone. The reasons for the discrepancy in significance could be twofold; while Dickin et al. (2013)also had a small number of subjects across a wide range of ambulatory gross motor abilities, they were adults who had potentially stabilized into a more homogenous presentation than the children and adolescents in this study, who represented a wider range of developmental ranges. Cheng, Ju, et al. (2015) utilized younger subjects of similar ages to this study, but had sixteen subjects, which likely improved their statistical power. Thus, despite the current study's lack of statistical power to show a difference, the subjects' acute response to WBV produced similar changes in walking speed to previous work (Cheng, Ju, et al., 2015; Dickin et al., 2013). Further, these changes were also similar to those reported following immediately WBV protocols lasting between one and five weeks (Ruck, Chabot, & Rauch, 2010; Yabumoto et al., 2015). This suggests that despite the lack of statistically significant group-level changes, my findings on walking speed are in line with that previously reported in the literature.

With regard to other spatiotemporal parameters, step length also frequently increased following both treadmill walking and the combined intervention. The changes in step length also frequently mirrored those seen in walking speed, suggesting that most subjects who increased speed did so by modulating their step length rather than their cadence. However, some of those subjects who increased their step length following treadmill walking actually decreased step length following combined WBV and treadmill walking. Increases after treadmill walking tended to be greater than those after the combined intervention, and moreover, tended to be greater in those who responded positively to both. As discussed in chapter 2, the frequency of 20 Hz used in this study, although well-documented in the literature, may represent a transitional frequency between vibration that helps modulate the stretch reflex and vibration that induces rapid muscle fatigue. Certainly, fatigue could explain some of the variability in response here; those subjects that were more susceptible to fatigue may have been able to reap the benefits of the treadmill walking intervention, which was always administered first, and then been fatigued by the combination of WBV and an additional bout of walking, resulting in either less improvements or, if fatigue was excessive, a decrease in walking parameters.

Temporal parameters demonstrated minimal consistent changes after either intervention. This is in line with previous work that reported a lack of change in stride time immediately following single bouts of WBV (Dickin et al., 2013). Stance percent tended to respond similarly to both interventions, either increasing or decreasing following both treadmill walking and the combined intervention. Double support time behaved in the opposite fashion, with most subjects increasing after one of the interventions and decreasing after the other. Two subjects did increase their double support time following both interventions, which may also be related to fatigue, as discussed previously.

Regarding joint angles, previous literature has reported improvements in dynamic range of motion following WBV, both in isolation (Krause et al., 2017) and during overground gait (Dickin et al., 2013). The current study showed similar trends, despite a lack of statistical significance in any of the kinematic variables. The most consistent changes were seen in peak ankle dorsiflexion, which trended upwards following both interventions, but more aggressively following combined WBV and treadmill training. Similar to walking speed, the results from this study mimicked those of previous work. Dickin et al. (2013) showed a statistically significant increase in dynamic ankle ROM during gait of 1.5°; this study showed improvements of 2.3°, although statistical significance was lacking. As noted before, this may be due to a combination of increased variability of response due to the age of the subjects in this study. However, while most variables investigated in this study responded similarly to both interventions, or responded more to the initial bout of treadmill walking, peak dorsiflexion responded more positively to the combined intervention. Changes in spasticity were more notable in the plantarflexors following

WBV, as discussed in the previous chapter, so this increase in active dorsiflexion could be related to those alterations in tone. If so, this combination of findings supports the notion that, at least with regard to ankle motion, WBV can function effectively as a preparatory modality.

Additionally, several subjects demonstrated normalization of foot clearance, which, to my knowledge, has not been previously evaluated before and after acute WBV. This normalization of foot clearance saw some subjects increasing their clearance, and others decreasing it; while this seems, on the surface, at odds with my other kinematic findings, it is possible that both outcomes could be caused by the trend towards improving ankle dorsiflexion. Those subjects who initially had low foot clearance may have increased their clearance by achieving more active dorsiflexion in swing phase. Conversely, those who initially had high foot clearance may have been overcompensating for a lack of ankle motion by increasing hip and knee flexion during swing phase; if they were able to access additional ankle dorsiflexion following intervention, it may have resulted in a decrease in these excessive compensations. This theory is somewhat supported by the finding that, at T4 immediately following vibration, increases in ankle dorsiflexion and decreases in hip flexion approached statistical significance. However, changes at the knee and hip were far less consistent among this small group of subjects, so further research is certainly needed to more thoroughly understand the kinematic changes occurring after both treadmill walking and combined WBV and treadmill walking.

Overall muscle activity trended downward after each intervention. One possible explanation for this is muscle fatigue, which would support the conclusions above that subject fatigue likely played a role in my spatiotemporal findings. Alternately, since I noted decreased spasticity following each intervention, this decreased muscle activity may represent the decreased force necessary to achieve the subject's desired gait pattern; in the setting of decreased spasticity, the subject may not need as much effort to move out of the stereotypical patterns that often limit their gait. Interestingly, a downward trend in CCI during swing phase was also noted at the knee following combined WBV and treadmill walking, and at the ankle following both interventions. Excessive co-contraction of an agonist and antagonist about a joint is a common finding in individuals with spastic CP, which is thought to improve stability at the expense of metabolic efficiency (Pinto et al., 2018; Unnithan, Dowling, Frost, & Bar-Or, 1996). Thus, a decrease in co-contraction in this population likely represents movement towards a more normalized force couple about a given joint. Krause et al. (2017) found acute improvements in selective control, via measurements of improved movement during isolated active ROM, following a bout of WBV; it is possible that this decrease in CCI represents an improvement in my subjects' ability to activate muscles in isolation during gait.

Finally, the notable lack of changes in gait pattern between the two bouts of treadmill walking is an important finding of this study. My secondary hypothesis, that a combined intervention of WBV and treadmill walking would be more effective than a bout of treadmill walking alone at improving overground gait, was based on the theory that WBV could act as a preparatory modality that allowed an individual to perform treadmill walking in a more appropriate fashion. Instead, I found that WBV had almost no effects on a subjects' gait pattern during the subsequent bout of treadmill walking, despite the fact that changes in overground gait were seen. When walking on a treadmill, speed is both kept constant and defined by an external force – the moving belt. This moving belt may be such a primary driver of the resulting gait pattern during treadmill walking that the addition of the effects of WBV may be negligible. However, it is also important to note that this study design was unbalanced, with subjects always completing the bout of treadmill walking without WBV first. Thus, it could be that fatigue from the first bout of walking affected the subjects' ability to alter their gait patterns to take advantage of the decreased spasticity seen after WBV.

This finding, taken in tandem with the finding that both treadmill walking and the combined intervention often had similar effects on overground gait, calls into question if these interventions may be addressing similar underlying issues. Indeed, underlying spasticity, as discussed previously, is known to be able to be mitigated at both a neural and mechanical level. Thus, it stands to reason that gait parameters may react similarly. Further research investigating the effect on treadmill walking alone versus WBV alone on overground gait patterns should be conducted to investigate this. Additionally, it suggests that, at least acutely, WBV may function more effectively as a preparatory modality prior to overground gait training rather than treadmill training.

As previously noted, this study has several limitations, particularly its small sample size and its heterogeneity. A larger sample size of children from a smaller range of ages and motor abilities would likely have increased the power to detect group level differences and improved the strength of my conclusions. Additionally, the assumption that a short bout of treadmill walking would produce minimal changes in gait, and thus that a 20-minute washout period between interventions would be sufficient for subjects to rest and return to baseline, was incorrect. Most subjects, by time point T3, still demonstrated changes in their gait patterns as compared to baseline. This also suggests fatigue may have been a factor in how subjects responded to the second, combined, intervention. This, in combination with the study's unbalanced design where subjects always completed the bout of treadmill walking alone first, also limits my ability to appropriately compare the two interventions. Future research comparing the relative effects of these two interventions should consider alternate study designs, such as administering the interventions on two different days or extending the washout period until the subject has returned to those baseline levels of spasticity, as well as balancing the design by having some subjects complete the combined intervention first. Finally, my EMG findings were complicated by several issues. Despite efforts at quality control, such as by confirming a clear signal after initially attaching the electrodes and securing the electrodes with wrappings, large portions of data were still lost due to poor quality. Abnormally high or low signals that were most likely due to a loss of skin contact and/or proper position over the muscle belly were removed from analysis, resulting in inconsistent sample sizes for most variables that ranged as low as 6 subjects. Thus, these preliminary EMG findings should be interpreted with caution.

Overall, these findings support the idea that both treadmill walking and WBV may be effective interventions to improve the overground gait patterns of children with spastic CP. The trends observed with regard to decreased co-contraction at the ankle in swing phase and increased active dorsiflexion in particular suggest that WBV in particular may be specifically useful at addressing underlying neural control issues that limit gait patterns in this population. Conversely, the observation that many parameters improved following both interventions may suggest that the repetitive mechanical stress of walking on a moving treadmill belt may also effectively address some aspects of atypical spastic gait. Most importantly, however, this study shows that the variability of response to both interventions is highly, highly variable.

Conclusions

This significant variability of individual response remains a critical factor to be addressed before appropriate recommendations can be made for clinical use. Changes in gait in response to both interventions were not consistently correlated with subjects' age, GMFCS level, topography, baseline walking speed, or baseline spasticity levels – and, indeed, were not always consistent within subjects, with several demonstrating positive effects on one affected limb and neutral or negative effects on the other. Rather, there seems to be a more complex set of factors that determines which individuals will be “responders” versus “non-responders” to WBV. While those individuals that are “responders” demonstrated acute clinically meaningful improvements in ankle function, several subjects were “non-responders,” demonstrating no change or worsening of function immediately after intervention. Use of this intervention in the clinic, therefore, should be accompanied by regular assessment to ascertain if the individual patient is achieving the desired outcomes. Further, additional research should heavily focus on attempting to identify the complex factors that predict response to WBV, and then using these factors to investigate the effects of WBV on more homogenous subject groups.

References

Abdel-Aziem, A. A., & El-Basatiny, H. M. (2017). Effectiveness of backward walking training on walking ability in children with hemiparetic cerebral palsy: a randomized controlled trial. *Clin Rehabil, 31*(6), 790-797. doi:10.1177/0269215516656468

Adolph, K. E. (2008). Motor and Physical Development: Locomotion. In M. M. Haith & J. B. Benson (Eds.), *Encyclopedia of infant and early childhood development* (pp. 359-373). San Diego, CA: Academic Press.

Adolph, K. E., Cole, W. G., Komati, M., Garciaguirre, J. S., Badaly, D., Lingeman, J. M., . . . Sotsky, R. B. (2012). How do you learn to walk? Thousands of steps and dozens of falls per day. *Psychol Sci, 23*(11), 1387-1394. doi:10.1177/0956797612446346

Ahlborg, L., Andersson, C., & Julin, P. (2006). Whole-body vibration training compared with resistance training: effect on spasticity, muscle strength and motor performance in adults with cerebral palsy. *J Rehabil Med, 38*(5), 302-308. doi:10.1080/16501970600680262

Alashram, A. R., Padua, E., & Annino, G. (2019). Effects of Whole-Body Vibration on Motor Impairments in Patients With Neurological Disorders: A Systematic Review. *Am J Phys Med Rehabil, 98*(12), 1084-1098. doi:10.1097/PHM.0000000000001252

Almarwani, M., Perera, S., VanSwearingen, J. M., Sparto, P. J., & Brach, J. S. (2016). The test-retest reliability and minimal detectable change of spatial and temporal gait variability during usual over-ground walking for younger and older adults. *Gait & Posture, 44*, 94-99. doi:10.1016/j.gaitpost.2015.11.014

Bar-On, L., Aertbelien, E., Wambacq, H., Severijns, D., Lambrecht, K., Dan, B., . . . Desloovere, K. (2013). A clinical measurement to quantify spasticity in children with cerebral palsy by integration of multidimensional signals. *Gait Posture, 38*(1), 141-147. doi:10.1016/j.gaitpost.2012.11.003

Beerse, M., Henderson, G., Liang, H., Ajisafe, T., & Wu, J. (2018). Variability of spatiotemporal gait parameters in children with and without Down syndrome during treadmill walking. *Gait Posture, 68*, 207-212. doi:10.1016/j.gaitpost.2018.11.032

Biering-Sorensen, F., Nielsen, J. B., & Klinge, K. (2006). Spasticity-assessment: a review. *Spinal Cord, 44*(12), 708-722. doi:10.1038/sj.sc.3101928

Bohannon, R. W., & Smith, M. B. (1987). Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys Ther, 67*(2), 206-207.

Booth, A. T. C., Buizer, A. I., Meyns, P., Oude Lansink, I. L. B., Steenbrink, F., & van der Krogt, M. M. (2018). The efficacy of functional gait training in children and young adults with cerebral palsy: a systematic review and meta-analysis. *Dev Med Child Neurol, 60*(9), 866-883. doi:10.1111/dmcn.13708

Boyd, Pliatsios, V., Starr, R., Wolfe, R., & Graham, H. K. (2000). Biomechanical transformation of the gastroc-soleus muscle with botulinum toxin A in children with cerebral palsy. *Dev Med Child Neurol, 42*(1), 32-41.

Boyd, R. N., & Graham, H. K. (1999). Objective measurement of clinical findings in the use of botulinum toxin type A for the management of children with cerebral palsy. *Eur J Neurol, 6*(S4), s23-s35. doi:doi:10.1111/j.1468-1331.1999.tb00031.x

CDC. (2018, March 9, 2018). Data & Statistics for Cerebral Palsy. Retrieved from https://www.cdc.gov/ncbddd/cp/data.html

Chang, Y. J., Liang, J. N., Hsu, M. J., Lien, H. Y., Fang, C. Y., & Lin, C. H. (2013). Effects of continuous passive motion on reversing the adapted spinal circuit in humans with chronic spinal cord injury. *Arch Phys Med Rehabil, 94*(5), 822-828. doi:10.1016/j.apmr.2012.11.035

Cheng, H. Y., Ju, Y.-Y., Chen, C.-L., Chang, Y.-J., & Wong, A. M.-K. (2013). Managing lower extremity muscle tone and function in children with cerebral palsy via eight-week repetitive passive knee movement intervention. *Research in Developmental Disabilities, 34*(1), 554-561. doi:https://doi.org/10.1016/j.ridd.2012.09.020

Cheng, H. Y., Ju, Y., Chen, C., & Wong, M. (2012). Managing spastic hypertonia in children with cerebral palsy via repetitive passive knee movements. *Journal of Rehabilitation Medicine, 44*(3), 235-240. doi:10.2340/16501977-0937

Cheng, H. Y., Ju, Y. Y., Chen, C. L., Chuang, L. L., & Cheng, C. H. (2015). Effects of whole body vibration on spasticity and lower extremity function in children with cerebral palsy. *Hum Mov Sci, 39*, 65-72. doi:10.1016/j.humov.2014.11.003

Cheng, H. Y., Yu, Y. C., Wong, A. M., Tsai, Y. S., & Ju, Y. Y. (2015). Effects of an eight-week whole body vibration on lower extremity muscle tone and function in children with cerebral palsy. *Res Dev Disabil, 38*, 256-261. doi:10.1016/j.ridd.2014.12.017

Choi, J. Y., Park, E. S., Park, D., & Rha, D. W. (2018). Dynamic spasticity determines hamstring length and knee flexion angle during gait in children with spastic cerebral palsy. *Gait Posture, 64*, 255-259. doi:10.1016/j.gaitpost.2018.06.163

Crenna, P. (1998). Spasticity and 'spastic' gait in children with cerebral palsy. *Neurosci Biobehav Rev, 22*(4), 571-578.

Damiano, D. L., & DeJong, S. L. (2009). A systematic review of the effectiveness of treadmill training and body weight support in pediatric rehabilitation. *J Neurol Phys Ther, 33*(1), 27-44. doi:10.1097/NPT.0b013e31819800e2

Damiano, D. L., Quinlivan, J. M., Owen, B. F., Payne, P., Nelson, K. C., & Abel, M. F. (2002). What does the Ashworth scale really measure and are instrumented measures more valid and precise? *Dev Med Child Neurol, 44*(2), 112-118.

Desloovere, K., Molenaers, G., Feys, H., Huenaerts, C., Callewaert, B., & Van de Walle, P. (2006). Do dynamic and static clinical measurements correlate with gait analysis parameters in children with cerebral palsy? *Gait Posture, 24*(3), 302-313. doi:10.1016/j.gaitpost.2005.10.008

Dickin, D. C., Faust, K. A., Wang, H., & Frame, J. (2013). The acute effects of whole-body vibration on gait parameters in adults with cerebral palsy. *J Musculoskelet Neuronal Interact, 13*(1), 19-26.

Dietrich, A., Abercrombie, K., Fanning, J., & Bartlett, D. (2007). GMFCS Family Report Questionnaire. In. Hamilton, ON: CanChild Centre for Childgood Disability Research, McMaster University.

Dodd, K. J., & Foley, S. (2007). Partial body-weight-supported treadmill training can improve walking in children with cerebral palsy: a clinical controlled trial. *Dev Med Child Neurol, 49*(2), 101-105. doi:10.1111/j.1469-8749.2007.00101.x

Duquette, S. A., Guiliano, A. M., & Starmer, D. J. (2015). Whole body vibration and cerebral palsy: a systematic review. *J Can Chiropr Assoc, 59*(3), 245-252.

El-Basatiny, H. M., & Abdel-Aziem, A. A. (2015). Effect of backward walking training on postural balance in children with hemiparetic cerebral palsy: a randomized controlled study. *Clin Rehabil, 29*(5), 457-467. doi:10.1177/0269215514547654

El-Shamy, S. M. (2017). Effects of Antigravity Treadmill Training on Gait, Balance, and Fall Risk in Children With Diplegic Cerebral Palsy. *Am J Phys Med Rehabil, 96*(11), 809-815. doi:10.1097/PHM.0000000000000752

Elder, G. C., Kirk, J., Stewart, G., Cook, K., Weir, D., Marshall, A., & Leahey, L. (2003). Contributing factors to muscle weakness in children with cerebral palsy. *Dev Med Child Neurol, 45*(8), 542-550.

Elnahhas, A. M., Elshennawy, S., & Aly, M. G. (2019). Effects of backward gait training on balance, gross motor function, and gait in children with cerebral palsy: a systematic review. *Clin Rehabil, 33*(1), 3-12. doi:10.1177/0269215518790053

Enoka, R. M. (2015). *Neuromechanics of human movement* (Fifth edition. ed.). Champaign, IL: Human Kinetics.

Ervilha, U. F., Graven-Nielsen, T., & Duarte, M. (2012). A simple test of muscle coactivation estimation using electromyography. *Brazilian Journal of Medical and Biological Research, 45*(10), 977-981. doi:10.1590/s0100-879x2012007500092

Exercise principles and guidelines for persons with cerebral palsy and neuromuscular disorders. (1999). In T. U. C. P. R. a. E. Foundation (Ed.): The United Cerebral Palsy Research and Educational Foundation.

Fattal-Valevski, A., Domenievitz, D., Giladi, N., Wientroub, S., & Hayek, S. (2008). Long-term effect of repeated injections of botulinum toxin in children with cerebral palsy: a prospective study. *Journal of Children's Orthopaedics, 2*(1), 29-35. doi:10.1007/s11832-007-0075-8

Ferreira, D. M., Liang, H., & Wu, J. (2020). Knee joint kinematics of the pendulum test in children with and without Down syndrome. *Gait & Posture, 76*, 311-317. doi:https://doi.org/10.1016/j.gaitpost.2019.12.025

Forssberg, H. (1999). Neural control of human motor development. *Current Opinion in Neurobiology, 9*, 676-682.
Gage, J. R. (2009). *The identification and treatment of gait problems in cerebral palsy* (2nd ed. ed.). London: Mac Keith Press.
Galileo. (2017). Can high frequencies increase muscle activation during Galileo Training? *Galileo Training.*
Germanotta, M., Taborri, J., Rossi, S., Frascarelli, F., Palermo, E., Cappa, P., . . . Petrarca, M. (2017). Spasticity Measurement Based on Tonic Stretch Reflex Threshold in Children with Cerebral Palsy Using the PediAnklebot. *Front Hum Neurosci, 11*, 277. doi:10.3389/fnhum.2017.00277
Greenan Fowler, E., Nwigwe, A. I., & Wong Ho, T. (2000). Sensitivity of the pendulum test for assessing spasticity in persons with cerebral palsy. *Developmental Medicine & Child Neurology, 42*(3), 182-189. doi:10.1017/S0012162200000323
Gross, R., Leboeuf, F., Hardouin, J. B., Perrouin-Verbe, B., Brochard, S., & Remy-Neris, O. (2015). Does muscle coactivation influence joint excursions during gait in children with and without hemiplegic cerebral palsy? Relationship between muscle coactivation and joint kinematics. *Clin Biomech (Bristol, Avon), 30*(10), 1088-1093. doi:10.1016/j.clinbiomech.2015.09.001
Hadders-Algra, M. (2000). The Neuronal Group Selection Theory: a framework to explain variation in normal motor development. *Developmental Medicine & Child Neurology, 42*, 566-572.
Han, Y. G., Lee, S. W., & Yun, C. K. (2019). The immediate influence of various whole-body vibration frequency on balance and walking ability in children with cerebral palsy: a pilot study. *J Exerc Rehabil, 15*(4), 597-602. doi:10.12965/jer.1938318.159
Hanna, S. E., Rosenbaum, P. L., Bartlett, D. J., Palisano, R. J., Walter, S. D., Avery, L., & Russell, D. J. (2009). Stability and decline in gross motor function among children and youth with cerebral palsy aged 2 to 21 years. *Dev Med Child Neurol, 51*(4), 295-302.
Henderson, G., Beerse, M., Liang, H., Ferreira, D., & Wu, J. (2020). Improvement in Overground Walking After Treadmill-Based Gait Training in a Child With Agenesis of the Corpus Callosum. *Phys Ther, 100*(1), 157-167. doi:10.1093/ptj/pzz144
Henderson, G., Ferreira, D., & Wu, J. (2020). *The effects of direction and speed on treadmill walking in typically developing children*.
Hislop, H. J., Avers, D., Brown, M., & Daniels, L. (2014). *Daniels and Worthingham's muscle testing : techniques of manual examination and performance testing* (Ninth edition / ed.). St. Louis, Mo.: Elsevier.
Hosl, M., Bohm, H., Eck, J., Doderlein, L., & Arampatzis, A. (2018). Effects of backward-downhill treadmill training versus manual static plantarflexor stretching on muscle-joint pathology and function in children with spastic Cerebral Palsy. *Gait Posture, 65*, 121-128. doi:10.1016/j.gaitpost.2018.07.171
Ibrahim, M. M., Eid, M. A., & Moawd, S. A. (2014). Effect of whole-body vibration on muscle strength, spasticity, and motor performance in spastic diplegic cerebral palsy children. *Egyptian Journal of Medical Human Genetics, 15*(2), 173-179. doi:10.1016/j.ejmhg.2014.02.007
Jaspers, E., Verhaegen, A., Geens, F., Van Campenhout, A., Desloovere, K., & Molenaers, G. (2013). Lower limb functioning and its impact on quality of life in ambulatory children

with cerebral palsy. *Eur J Paediatr Neurol, 17*(6), 561-567. doi:10.1016/j.ejpn.2013.04.006

Kenyon, L. K. P. D. P. P., Westman, M. P. D., Hefferan, A. P. D., McCrary, P. P. D., & Baker, B. J. P. P. N. (2017). A home-based body weight supported treadmill training program for children with cerebral palsy: A case series. *Physiother Theory Pract, 33*(7), 576-585. doi:10.1080/09593985.2017.1325956

Kim, S. G., Ryu, Y. U., Je, H. D., Jeong, J. H., & Kim, H. D. (2013). Backward walking treadmill therapy can improve walking ability in children with spastic cerebral palsy: a pilot study. *Int J Rehabil Res, 36*(3), 246-252. doi:10.1097/MRR.0b013e32835dd620

Krause, A., Schonau, E., Gollhofer, A., Duran, I., Ferrari-Malik, A., Freyler, K., & Ritzmann, R. (2017). Alleviation of Motor Impairments in Patients with Cerebral Palsy: Acute Effects of Whole-body Vibration on Stretch Reflex Response, Voluntary Muscle Activation and Mobility. *Front Neurol, 8*, 416. doi:10.3389/fneur.2017.00416

Krishnan, C., Dharia, A. K., Augenstein, T. E., Washabaugh, E. P., Reid, C. E., Brown, S. R., & Ranganathan, R. (2019). Learning new gait patterns is enhanced by specificity of training rather than progression of task difficulty. *J Biomech, 88*, 33-37. doi:10.1016/j.jbiomech.2019.03.014

Kurz, M. J., Stuberg, W., & DeJong, S. L. (2011). Body weight supported treadmill training improves the regularity of the stepping kinematics in children with cerebral palsy. *Dev Neurorehabil, 14*(2), 87-93. doi:10.3109/17518423.2011.552459

Lacquaniti, F., Ivanenko, Y. P., & Zago, M. (2012). Development of human locomotion. *Curr Opin Neurobiol, 22*(5), 822-828. doi:10.1016/j.conb.2012.03.012

Lelko, M. (2018). *Effect of Whole-Body Vibration on Acceleration Transmission and Jumping Performance in Children*. Thesis. Georgia State University. Atlanta, GA, USA.

Liang, H., Henderson, G., & Wu, J. (2020). *Neuromuscular response to a single session of whole-body vibration in children with cerebral palsy: A pilot study.*

Liang, H. Q. (2018). *Effect of Single-Session Whole-Body Vibration on Motor Function and Spasticity of Children with Cerebral Palsy*. Dissertation. Georgia State University. Atlanta, GA, USA.

Lorentzen, J., Frisk, R., Willerslev-Olsen, M., Bouyer, L., Farmer, S. F., & Nielsen, J. B. (2020). Gait training facilitates push-off and improves gait symmetry in children with cerebral palsy. *Hum Mov Sci, 69*, 102565. doi:10.1016/j.humov.2019.102565

Lorentzen, J., Kirk, H., Fernandez-Lago, H., Frisk, R., Scharff Nielsen, N., Jorsal, M., & Nielsen, J. B. (2017). Treadmill training with an incline reduces ankle joint stiffness and improves active range of movement during gait in adults with cerebral palsy. *Disabil Rehabil, 39*(10), 987-993. doi:10.1080/09638288.2016.1174745

Lotfian, M., Mirbagheri, M. M., Kharazi, M. R., Dadashi, F., Nourian, R., Irani, A., & Mirbagheri, A. (2016). Pendulum test measure correlates with gait parameters in children with cerebral palsy. *Conf Proc IEEE Eng Med Biol Soc, 2016*, 1708-1711. doi:10.1109/embc.2016.7591045

Malhotra, S., Pandyan, A. D., Day, C. R., Jones, P. W., & Hermens, H. (2009). Spasticity, an impairment that is poorly defined and poorly measured. *Clin Rehabil, 23*(7), 651-658. doi:10.1177/0269215508101747

Masi, A. T., & Hannon, J. C. (2008). Human resting muscle tone (HRMT): narrative introduction and modern concepts. *J Bodyw Mov Ther, 12*(4), 320-332. doi:10.1016/j.jbmt.2008.05.007

Moreau, N. G., Bodkin, A. W., Bjornson, K., Hobbs, A., Soileau, M., & Lahasky, K. (2016). Effectiveness of Rehabilitation Interventions to Improve Gait Speed in Children With Cerebral Palsy: Systematic Review and Meta-analysis. *Phys Ther, 96*(12), 1938-1954. doi:10.2522/ptj.20150401

Moreau, N. G., Falvo, M. J., & Damiano, D. L. (2012). Rapid force generation is impaired in cerebral palsy and is related to decreased muscle size and functional mobility. *Gait Posture, 35*(1), 154-158. doi:10.1016/j.gaitpost.2011.08.027

Mutlu, A., Krosschell, K., & Spira, D. G. (2009). Treadmill training with partial body-weight support in children with cerebral palsy: a systematic review. *Dev Med Child Neurol, 51*(4), 268-275. doi:10.1111/j.1469-8749.2008.03221.x

Norkin, C. C., & White, D. J. (2016). *Measurement of joint motion: a guide to goniometry*: FA Davis.

Numanoğlu, A. (2012). Intraobserver reliability of modified Ashworth scale and modified Tardieu scale in the assessment of spasticity in children with cerebral palsy. *Acta Orthopaedica et Traumatologica Turcica, 46*(3), 196-200. doi:10.3944/aott.2012.2697

Omura, J., Fuentes, M., & Bjornson, K. (2018). Participation in Daily Life: Influence on Quality of Life in Ambulatory Children with Cerebral Palsy. *PM R*. doi:10.1016/j.pmrj.2018.05.010

Palisano, R. J., Hanna, S. E., Rosenbaum, P. L., Russell, D. J., Walter, S. D., Wood, E. P., . . . Galuppi, B. E. (2000). Validation of a model of gross motor function for children with cerebral palsy. *Phys Ther, 80*(10), 974-985.

Palisano, R. J., Orlin, M. N., & Schreiber, J. (2017). *Campbell's Physical Therapy for Children* (5th ed. ed.). St. Louis, MO: Elsevier Saunders.

Palisano, R. J., Rosenbaum, P., Bartlett, D., & Livingston, M. H. (2007). Gross Motor Function Classification System Expanded and Revised. In (pp. 4). Hamilton, ON: CanChild Centre for Childhood Disability Research, McMaster University.

Palisano, R. J., Rosenbaum, P., Bartlett, D., & Livingston, M. H. (2008). Content validity of the expanded and revised Gross Motor Function Classification System. *Dev Med Child Neurol, 50*(10), 744-750. doi:10.1111/j.1469-8749.2008.03089.x

Pandyan, A. D., Gregoric, M., Barnes, M. P., Wood, D., Wijck, F. V., Burridge, J., . . . Johnson, G. R. (2005). Spasticity: Clinical perceptions, neurological realities and meaningful measurement. *Disability and Rehabilitation, 27*(1-2), 2-6. doi:10.1080/09638280400014576

Park, C., Park, E. S., Choi, J. Y., Cho, Y., & Rha, D. W. (2017). Immediate Effect of a Single Session of Whole Body Vibration on Spasticity in Children With Cerebral Palsy. *Ann Rehabil Med, 41*(2), 273-278. doi:10.5535/arm.2017.41.2.273

Perera, S., Mody, S. H., Woodman, R. C., & Studenski, S. A. (2006). Meaningful change and responsiveness in common physical performance measures in older adults. *J Am Geriatr Soc, 54*(5), 743-749. doi:10.1111/j.1532-5415.2006.00701.x

Pinto, T. P. S., Fonseca, S. T., Gonçalves, R. V., Souza, T. R., Vaz, D. V., Silva, P. L. P., & Mancini, M. C. (2018). Mechanisms contributing to gait speed and metabolic cost in children with unilateral cerebral palsy. *Brazilian journal of physical therapy, 22*(1), 42-48. doi:10.1016/j.bjpt.2017.06.015

Rittweger, J. (2010). Vibration as an exercise modality: how it may work, and what its potential might be. *European Journal of Applied Physiology, 108*(5), 877-904. doi:10.1007/s00421-009-1303-3

Ritzmann, Gollhofer, A., & Kramer, A. (2013). The influence of vibration type, frequency, body position and additional load on the neuromuscular activity during whole body vibration. *European Journal of Applied Physiology, 113*(1), 1-11. doi:10.1007/s00421-012-2402-0

Ritzmann, R., Stark, C., & Krause, A. (2018). Vibration therapy in patients with cerebral palsy: a systematic review. *Neuropsychiatr Dis Treat, 14*, 1607-1625. doi:10.2147/NDT.S152543

Rose, J. (2009). Selective motor control in spastic cerebral palsy. *Dev Med Child Neurol, 51*(8), 578-579. doi:10.1111/j.1469-8749.2009.03401.x

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.

Ross, S. A., & Engsberg, J. R. (2007). Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. *Arch Phys Med Rehabil, 88*(9), 1114-1120. doi:10.1016/j.apmr.2007.06.011

Ruck, J., Chabot, G., & Rauch, F. (2010). Vibration treatment in cerebral palsy: A randomized controlled pilot study. *J Musculoskelet Neuronal Interact, 10*(1), 77-83.

Sa-Caputo, D. C., Costa-Cavalcanti, R., Carvalho-Lima, R. P., Arnobio, A., Bernardo, R. M., Ronikeile-Costa, P., . . . Bernardo-Filho, M. (2016). Systematic review of whole body vibration exercises in the treatment of cerebral palsy: Brief report. *Dev Neurorehabil, 19*(5), 327-333. doi:10.3109/17518423.2014.994713

Saquetto, M., Carvalho, V., Silva, C., Conceicao, C., & Gomes-Neto, M. (2015). The effects of whole body vibration on mobility and balance in children with cerebral palsy: a systematic review with meta-analysis. *J Musculoskelet Neuronal Interact, 15*(2), 137-144.

Shumway-Cook, A., & Woollacott, M. H. (2012). *Motor control : translating research into clinical practice* (4. ed. ed.). Philadelphia: Wolters Kluwer Health, Lippincott Williams & Wilkins.

Simao, C. R., Regalado, I. C. R., Spaniol, A. P., Fonseca, D. O. S., Ribeiro, T. S., & Lindquist, A. R. (2019). Immediate effects of a single treadmill session with additional ankle loading on gait in children with hemiparetic cerebral palsy. *NeuroRehabilitation, 44*(1), 9-17. doi:10.3233/NRE-182516

Unnithan, V. B., Dowling, J. J., Frost, G., & Bar-Or, O. (1996). Role of cocontraction in the O2 cost of walking in children with cerebral palsy. *Medicine & Science in Sports & Exercise, 28*(12).

Valentin-Gudiol, M., Mattern-Baxter, K., Girabent-Farres, M., Bagur-Calafat, C., Hadders-Algra, M., & Angulo-Barroso, R. M. (2017). Treadmill interventions in children under six years of age at risk of neuromotor delay. *Cochrane Database Syst Rev, 7*, Cd009242. doi:10.1002/14651858.CD009242.pub3

Verschuren, O., Peterson, M. D., Balemans, A. C. J., & Hurvitz, E. A. (2016). Exercise and physical activity recommendations for people with cerebral palsy. *Developmental Medicine And Child Neurology, 58*(8), 798-808. doi:10.1111/dmcn.13053

Visser, A., Westman, M., Otieno, S., & Kenyon, L. (2017). A Home-Based Body Weight-Supported Treadmill Program for Children With Cerebral Palsy: A Pilot Study. *Pediatr Phys Ther, 29*(3), 223-229. doi:10.1097/PEP.0000000000000406

Wiley, M. E., & Damiano, D. L. (1998). Lower-extremity strength profiles in spastic cerebral palsy. *Dev Med Child Neurol, 40*(2), 100-107.

Willerslev-Olsen, M., Lorentzen, J., & Nielsen, J. B. (2014). Gait training reduces ankle joint stiffness and facilitates heel strike in children with Cerebral Palsy. *NeuroRehabilitation, 35*(4), 643-655. doi:10.3233/NRE-141180

Willerslev-Olsen, M., Petersen, T. H., Farmer, S. F., & Nielsen, J. B. (2015). Gait training facilitates central drive to ankle dorsiflexors in children with cerebral palsy. *Brain, 138*(Pt 3), 589-603. doi:10.1093/brain/awu399

Willoughby, K. L., Dodd, K. J., & Shields, N. (2009a). A systematic review of the effectiveness of treadmill training for children with cerebral palsy. *Disabil Rehabil, 31*(24), 1971-1979. doi:10.3109/09638280902874204

Willoughby, K. L., Dodd, K. J., & Shields, N. (2009b). A systematic review of the effectiveness of treadmill training for children with cerebral palsy. *Disability & Rehabilitation, 31*(24), 1971-1979. doi:10.3109/09638280902874204

Winter, D. A. (1992). Foot trajectory in human gait: a precise and multifactorial motor control task. *Phys Ther, 72*(1), 45-53; discussion 54-46.

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

Wu, J. H., Beerse, M., Ajisafe, T., & Liang, H. Q. (2015). Walking Dynamics in Preadolescents With and Without Down Syndrome. *Phys Ther, 95*(5), 740-749.

Yabumoto, T., Shin, S., Watanabe, T., Watanabe, Y., Naka, T., Oguri, K., & Matsuoka, T. (2015). Whole-body vibration training improves the walking ability of a moderately impaired child with cerebral palsy: a case study. *J Phys Ther Sci, 27*(9), 3023-3025. doi:10.1589/jpts.27.3023

Zhang, L.-Q., Chung, S. G., Zhiqiang, B., Dali, X., Van Rey, E. M. T., Rogers, M. W., . . . Roth, E. J. (2002). Intelligent stretching of ankle joints with contracture/spasticity. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 10*(3), 149-157. doi:10.1109/tnsre.2002.802857

Zhou, J., Butler, E. E., & Rose, J. (2017). Neurologic Correlates of Gait Abnormalities in Cerebral Palsy: Implications for Treatment. *Front Hum Neurosci, 11*, 103. doi:10.3389/fnhum.2017.00103

Zwicker, J. G., & Mayson, T. A. (2010). Effectiveness of treadmill training in children with motor impairments: an overview of systematic reviews. *Pediatric Physical Therapy, 22*(4), 361-377 317p. doi:10.1097/PEP.0b013e3181f92e54

APPENDICES

Appendix A

Correlation coefficients (*r*) and significance levels (*p*) between the change in each variable (first column) after each intervention (second column), and selected subject demographic information (first row). Significant correlations are highlighted in blue.

Variable	Intervention	Age		GMFCS		Topography		Baseline Walking Speed		Baseline L Hamstring Spasticity		Baseline R Hamstring Spasticity		Baseline L Gastroc Spasticity		Baseline R Gastroc Spasticity	
		r	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
L Step Length	Treadmill	0.04	0.92	0.50	0.17	0.48	0.20	0.23	0.56	0.58	0.13	0.18	0.74	0.55	0.16	0.60	0.21
	Combined	0.21	0.59	0.02	0.96	0.36	0.35	0.22	0.57	0.25	0.55	0.27	0.60	0.45	0.26	0.56	0.25
L Stance Percent	Treadmill	-0.49	0.18	-0.22	0.57	0.09	0.83	0.05	0.90	-0.19	0.65	-0.10	0.85	0.44	0.27	0.35	0.49
	Combined	0.01	0.98	0.19	0.63	0.43	0.25	0.09	0.81	0.36	0.38	0.13	0.81	0.35	0.39	0.46	0.36
L Double Support Time	Treadmill	0.36	0.35	0.68	0.04	0.47	0.20	-0.05	0.91	0.29	0.49	0.30	0.56	0.04	0.92	0.12	0.83
	Combined	0.16	0.67	-0.06	0.87	0.14	0.72	0.45	0.22	0.32	0.43	0.38	0.46	0.78	0.02	0.80	0.05
R Step Length	Treadmill	-0.06	0.87	-0.41	0.27	-0.08	0.83	0.33	0.38	-0.23	0.58	-0.11	0.84	0.47	0.25	0.32	0.53
	Combined	0.20	0.61	0.01	0.98	0.32	0.39	0.31	0.42	0.29	0.49	0.30	0.57	0.53	0.18	0.61	0.20
R Stance Percent	Treadmill	-0.39	0.31	-0.17	0.66	-0.08	0.84	-0.09	0.82	-0.24	0.56	-0.08	0.88	0.12	0.78	0.03	0.96
	Combined	0.11	0.78	0.15	0.70	0.52	0.15	0.12	0.75	0.36	0.38	0.35	0.50	0.40	0.33	0.56	0.25
R Double Support Time	Treadmill	-0.28	0.46	0.16	0.68	0.10	0.80	-0.47	0.21	-0.18	0.67	-0.29	0.57	-0.59	0.12	-0.61	0.20
	Combined	-0.47	0.20	0.56	0.11	0.50	0.17	-0.28	0.47	0.47	0.23	-0.50	0.32	0.11	0.79	0.07	0.90
Walking Speed	Treadmill	0.38	0.32	-0.21	0.58	-0.14	0.72	0.10	0.79	0.26	0.53	0.24	0.65	0.08	0.85	0.25	0.63
	Combined	0.26	0.50	-0.06	0.89	0.21	0.59	0.24	0.53	0.20	0.64	0.21	0.69	0.35	0.39	0.45	0.38
L Foot Clearance	Treadmill	0.25	0.54	-0.15	0.72	0.14	0.74	0.01	0.97	-0.11	0.82	0.63	0.25	0.05	0.91	0.27	0.66
	Combined	0.04	0.92	0.08	0.85	0.45	0.26	0.22	0.60	0.39	0.38	0.39	0.51	0.41	0.36	0.55	0.34

L Peak Knee Extension	Treadmill	-0.40	0.29	0.58	0.10	0.58	0.11	-0.43	0.24	0.67	0.07	0.38	0.46	-0.19	0.66	-0.22	0.68
	Combined	-0.11	0.78	0.48	0.19	0.67	0.05	-0.10	0.79	0.67	0.07	0.38	0.45	0.22	0.59	0.54	0.27
L Peak Knee Flexion	Treadmill	-0.09	0.81	0.22	0.57	0.44	0.24	-0.11	0.77	0.44	0.28	0.18	0.74	0.07	0.87	0.22	0.67
	Combined	0.11	0.78	0.11	0.78	0.40	0.29	0.17	0.66	0.29	0.48	0.23	0.66	0.33	0.42	0.45	0.37
L Peak Hip Extension	Treadmill	-0.40	0.28	0.22	0.57	-0.13	0.74	-0.20	0.61	0.06	0.88	-0.20	0.71	-0.78	0.02	-0.86	0.03
	Combined	0.09	0.81	0.19	0.63	-0.17	0.66	-0.31	0.41	-0.31	0.46	-0.23	0.66	-0.60	0.12	-0.65	0.16
L Peak Hip Flexion	Treadmill	-0.45	0.22	0.11	0.77	-0.16	0.68	-0.38	0.31	0.00	0.99	-0.27	0.60	-0.50	0.21	-0.58	0.22
	Combined	0.22	0.56	0.16	0.67	0.47	0.20	0.17	0.67	0.34	0.41	0.32	0.54	0.43	0.29	0.56	0.25
L Peak Plantarflexion	Treadmill	-0.27	0.49	0.10	0.80	-0.30	0.43	-0.25	0.51	-0.22	0.60	-0.32	0.54	-0.64	0.09	-0.74	0.09
	Combined	0.14	0.72	-0.29	0.45	-0.55	0.13	-0.09	0.82	-0.57	0.14	-0.21	0.68	-0.57	0.14	-0.75	0.09
L Peak Dorsiflexion	Treadmill	-0.51	0.16	0.41	0.28	0.16	0.68	-0.40	0.28	0.38	0.35	-0.13	0.81	-0.50	0.20	-0.67	0.14
	Combined	0.18	0.64	-0.03	0.93	0.38	0.31	0.06	0.87	0.22	0.60	0.38	0.46	0.18	0.67	0.33	0.52
R Foot Clearance	Treadmill	-0.46	0.25	0.32	0.44	0.67	0.07	-0.18	0.67	0.69	0.09	0.52	0.37	0.47	0.28	0.74	0.15
	Combined	0.05	0.90	0.19	0.66	0.66	0.07	0.16	0.70	0.57	0.18	0.66	0.23	0.49	0.26	0.70	0.19
R Peak Knee Extension	Treadmill	-0.52	0.15	0.14	0.72	-0.41	0.28	-0.32	0.41	-0.28	0.51	-0.97	0.00	-0.80	0.02	-0.67	0.14
	Combined	0.18	0.64	0.41	0.27	0.55	0.13	-0.05	0.90	0.33	0.43	0.19	0.71	0.06	0.90	0.20	0.70
R Peak Knee Flexion	Treadmill	-0.23	0.55	0.22	0.58	-0.32	0.40	-0.28	0.47	0.02	0.97	-0.91	0.01	-0.26	0.53	-0.38	0.46
	Combined	0.18	0.65	0.28	0.47	0.54	0.14	0.18	0.64	0.42	0.30	0.35	0.50	0.42	0.30	0.58	0.23
R Peak Hip Extension	Treadmill	-0.17	0.65	-0.04	0.91	0.09	0.81	0.16	0.68	0.17	0.68	0.10	0.86	-0.16	0.70	-0.12	0.83
	Combined	0.75	0.02	0.24	0.54	0.18	0.65	0.06	0.88	0.08	0.85	0.19	0.71	0.09	0.83	0.15	0.78
R Peak Hip Flexion	Treadmill	0.03	0.93	-0.08	0.83	0.00	0.99	0.28	0.46	-0.01	0.98	0.03	0.95	-0.10	0.81	-0.09	0.87
	Combined	0.36	0.35	0.14	0.73	0.40	0.29	0.21	0.59	0.25	0.56	0.27	0.60	0.46	0.25	0.56	0.24
R Peak Plantarflexion	Treadmill	-0.50	0.17	0.14	0.72	-0.26	0.50	-0.35	0.36	-0.24	0.56	-0.58	0.23	-0.74	0.04	-0.87	0.02
	Combined	-0.22	0.58	-0.21	0.59	-0.48	0.19	-0.25	0.52	-0.41	0.31	-0.32	0.53	-0.65	0.08	-0.77	0.07
R Peak Dorsiflexion	Treadmill	-0.24	0.53	-0.04	0.93	-0.40	0.28	-0.25	0.52	-0.56	0.15	-0.80	0.05	-0.58	0.13	-0.79	0.06
	Combined	-0.23	0.55	0.06	0.87	0.61	0.08	0.08	0.83	0.47	0.24	0.51	0.30	0.58	0.13	0.79	0.06