

Original Article

The acute effects of whole-body vibration on gait parameters in adults with cerebral palsy

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Abstract

Objectives: As adults with cerebral palsy (CP) are surviving longer^{1,2}, interventions are needed to reduce spasticity and increase strength to improve mobility and life quality. Adults with CP are lacking a form of independent exercise that allows them to maintain or improve their ambulation skills^{1,2}. A new approach to increase muscle strength and flexibility called whole-body vibration (WBV) was assessed. **Methods:** Using an individualized frequency (I-Freq) approach to WBV therapy the acute effects on gait in adults with CP was measured. In this study, eight adults with CP (age 20-51 years, two female) participated in two testing sessions: session one determined each individual's I-Freq; and session two included a 3D gait analysis before and after a WBV treatment. The WBV was administered in five, one minute bouts of vibration followed by one minute of rest. **Results:** Following WBV exposure subjects experienced a significant increase in walking speed ($P=0.047$), stride length ($P=0.017$) and dynamic ankle range of motion ($P=0.042$). **Conclusions:** These data show that acute WBV treatments at I-Freq can improve measures of gait and mobility in adults with CP, however, future should assess potential long-term improvements.

Keywords: Individualized Frequency Vibration, Gait Analysis, Diplegia, Hemiplegia, Range of Motion

Introduction

Cerebral palsy (CP) results from damage to the developing central nervous system while *in utero*, during delivery, or during the first two years of life³. The most common signs of the disorder are spasticity, rigidity, muscle weakness, ataxia, and movement disorders^{4,5}. The extent of the disorder can depend on the scale, degree, and location of the damage that occurs in the spinal cord, brain stem, or brain³. The motor skills of the children affected by cerebral palsy do improve as they age and grow; however, the skills never match those of neurotypically developed children³. Due to advances made in neonatal technologies, more children diagnosed with cerebral palsy (CP) are experiencing longer life spans^{2,6}. However, as a result of the increased life expectancy these individuals continue to ex-

perience the effect of CP but are limited in the availability of resources to effectively deal with the symptoms².

One of the biggest problems associated with movement for individuals diagnosed with cerebral palsy is spasticity because of the associated pain, contractures and subluxation^{3,4}. Currently, there are many options for the treatment of spasticity including physical modalities, oral pharmacologic agents, peripheral injectables, intrathecal agents, and surgical interventions², however, the basic and most common form of treatment is physical therapy⁷. Unfortunately, for adults diagnosed with CP there is a reported lack of attention and availability of care^{2,8}. This may be in part to the beliefs of therapists who feel that they can have a larger impact on younger patients with CP^{2,7} or to limitations in health care coverage⁹. By decreasing the amount of therapy, these adults begin to lose their range of motion (ROM), flexibility, and strength^{6,9,10}.

As a result of the spasticity experienced by individuals with CP, impairments in gait are often manifested and identified as a problem⁴. Gait analysis can be a very helpful tool for describing and diagnosing motor control problems specifically in locomotion¹¹. A gait analysis allows surgeons to look at many motor problems involved with locomotion concurrently allowing for a more complete and successful course of treatment⁸. The components measured in a typical gait analysis include: kinematics, kinetics and electromyographic data⁸. Abnormal

The authors have no conflict of interest.

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Edited by: F. Rauch

Accepted 30 January 2013

Subject #	Gender	Age	Diagnoses	Height (cm)	Weight (kg)	I-Freq (Hz)	Protocol
1	F	20	hemiplegic-L	160.78	96.7	40	2 day
2	M	28	diplegic	161	87.4	30	2 day
3	M	25	hemiplegic-R	182	81.1	50	1 day
4	M	26	diplegic	165.5	77.4	40	2 day
5	M	51	diplegic	168	68.9	30	2 day
6	M	22	hemiplegic-L	183.5	73.2	40	2 day
7	F	35	hemiplegic- L	156	61.6	35	1 day
8	M	35	diplegic	180	82.6	35	1 day

Diagnoses were either diplegic or hemiplegic cerebral palsy; R= right side affected, L=left side affected; I-Freq= Individualized frequency of vibration measured in hertz.

Table 1. Summary of subject characteristics of study participants.

gait in patients with CP is often due to the extensive damage to the central nervous system including the loss of selective muscle control, abnormal muscle tone, relative imbalance between muscle agonists and antagonists across joints, and deficient equilibrium reactions⁸.

It is vital to keep adults with CP active and walking since higher survival rates have been found in those adults with increased functional levels⁶. Rimmer et al. reported that regular exercise improves functional status, decreases the level of required assistance, and reduces the incidence of secondary conditions in adults with disabilities¹². For many therapists, maintaining or improving gait in adults with CP is one of the major goals^{7,13}. Even though it is clear that a lot of emphasis is put on maintaining gait for adults with CP, they are still lacking a method to improve their ambulation skills independently.

Muscle weakness is another large contributor to gait problems experienced by adults with CP^{13,14}. A new technique for increasing muscle strength and ROM is that of “whole-body vibration” (WBV)¹³⁻¹⁶. The application of WBV is typically applied while standing on a vertically oscillating platform that displaces the individual and alters the gravitational forces experienced on the body. Vibration therapy is said to stimulate the body’s natural stretch reflex and consequently causes muscle contractions¹⁷. More specifically, vibration of a muscle is suggested to stimulate the primary endings of the muscle spindle (Ia afferent), which excites alpha motor neurons, causing contraction of homonymous motor units which results in a tonic contraction of the muscle¹⁸. The effects resulting from WBV have included strengthened muscles^{19,20}, increased flexibility¹⁵, increase power output^{19,21}, and improved postural control²². All of these effects could help to improve gait function. Although the exact mechanism is unknown, it is suggested that WBV improves both the sensitivity and responsiveness of the muscle spindle, thereby improving both its ability to respond to a perturbation and to respond more vigorously^{23,24}. Two studies in particular have used vibration as a long-term intervention for patients with CP and the results have shown a decrease in spasticity²⁵ and an increase in walking speed¹³. However, the acute effects of WBV on adults with CP or the effect of WBV on a full 3D kinematic gait analysis have not been assessed.

While some studies have shown positive effects of vibration, others have shown a decrease in force production, rate of force development, and EMG activity²⁶⁻³⁰. One possible reason for the equivocal findings may stem from each individual, and even each muscle, having an individualized vibration frequency to which it responds most vigorously^{31,32}. Applying the idea of individualized frequency to any population using WBV may show a more effective change in the variables being studied. By finding that WBV improves walking in adults with CP, a more feasible and cost effective therapy alternative may be available. With lack of support from insurance and therapy facilities, adults with CP would have the means to increase strength and decrease spasticity on their own.

Therefore, the goal of the current study was to determine the acute effects of using an individualized frequency approach to WBV on gait in adults with CP. It was hypothesized that the subject’s gait would have a greater ROM in the knee and ankle allowing for an increased speed, and increased step length as a result of the WBV.

Materials and Methods

Subjects. Eight individuals with CP (mean age 30.25±10.0 years) participated in this study and were recruited from facilities that aid adults with special needs across the state of Indiana. Participants ranged in age from 20-51 years and were classified as a rank CP5-8 in the CP-IRSA Functional Classification System³³, indicating that they were independently mobile for a short distance without aids or assistive devices. All participants were diagnosed with primary spastic diplegic or hemiplegic CP and only one had received Botox injection in the past (11 years prior to study), and no participants had undergone surgery in the past two years (Table 1).

Treatment Protocol. Subjects reported to a biomechanics laboratory and answered a set of screening questions to ensure that they met the eligibility requirements. All individuals were required to visit the laboratory on two separate visits which were conducted with a minimum of two hours between the first and second visit, but could be scheduled up to a week

apart. Each visit lasted approximately 1.5-2 hours. After the explanation, the subject was asked to sign a university approved informed consent document and fill out a health history questionnaire.

For individuals that completed the assessments on two separate days (two day protocol), the first visit entailed a short vibration exposure to determine each subject's individualized frequency. This frequency coincides with the maximal responsiveness of the lower body muscles, which was then used for the second portion of the study. The overall vibration exposure during the individualized frequency protocol was approximately 70 seconds (seven, ten second exposures with a four minute rest interval between each exposure)^{31,32}. The second visit began with a pre-vibration gait analysis, the vibration treatment (detailed below), and a post-vibration gait analysis. For individuals that completed the assessments on the same day (one day protocol), the pre-vibration gait analysis was performed prior to the individualized vibration exposure to ensure there were no effects on the subject's pre vibration gait assessed during the second visit. Once the pre-vibration gait analysis was complete, the individualized frequency was determined, followed by a two hour break to reduce fatigue as well as residual vibration effects. Following the break, the vibration treatment was administered and the post-gait analysis was performed. Five subjects completed the two day protocol while three subjects performed the one day protocol.

Individualized Frequency. Prior to the vibration exposure and gait assessment, the subjects were prepped by shaving and lightly abrading with fine sandpaper, followed by cleaning the muscles of interest on both the right and left legs with alcohol (i.e., rectus femoris, bicep femoris, semitendinosus, tibialis anterior, and gastrocnemius). Muscle activation was monitored using DelSys surface electrodes (DelSys DE-2.1 Single Differential EMG Electrode) (inter-electrode distance: 1cm) placed centrally on the muscles of interest³⁴, and were attached using double stick tape. A reference electrode, in the form of a dispersive pad, was placed over the patella of the right knee. During the vibration exposure subjects stood wearing socks with knees bent at 15 degrees on a 0.82 x 1.02 m Pneu-Vibe Pro synchronous vibrating platform (Pneumex, Sandpoint, ID). A goniometer was used to ensure 15 degrees of flexion between the thigh and shank segments and the position was monitored using a laser level to help maintain this position throughout the entire protocol. The vibration protocol consisted of a series of vibrations ranging from 20 Hz (1.61 g) to 50 Hz (10.06g) in 5 Hz increments, with peak-to-peak amplitude of 2 mm in a randomized order (vibration frequency and the absence of platform skidding was verified prior to the current study). To reduce the chance of residual effects, a four minute resting period was used between the vibration sets³². At each vibration level, a static trial was collected with no vibration for ten seconds followed by a ten second trial at the set vibration frequency. This data was collected and processed using a Butterworth notch filter +/- 2 Hz of the trial frequency. The individualized frequency used in this study was that of the bicep femoris of the affected (or more affected) leg. To deter-

mine muscle activation levels the root mean square of the signal was used to find the specific frequency that most excited the muscle.

Gait Analysis. The data collection recorded kinematic data during gait. Subject measurements were taken for height, weight, joint girths (ankle and knee), leg length, anterior superior iliac spine distance, shoulder offset, elbow and wrist width and hand thickness. Following subject measurements, reflective markers were placed on the subject's bony landmarks following the full-body Plug-In-Gait Model (Vicon, Oxford, UK). Subjects performed ten gait trials by walking across a 10 m walkway and a minimum of five gait cycles were used in each analysis. The subjects were provided no other instructions other than to walk naturally across the walkway at a self-selected pace. A 12 camera Vicon MX system was used to collect kinematic data during gait trials and was sampled at 60 Hz.

Whole-Body Vibration (WBV). The WBV treatment protocol consisted of a series of one minute of vibration followed by one minute of rest, repeated five times, for a total of five minutes of vibration. During the vibration exposure subjects were required to maintain a semi-squat position at the set individualized frequency, with the knees flexed to approximately 15 degrees. This position was used to help increase activation of the hamstrings during WBV.

Passive Range of Motion. A passive ROM in flexion and extension was measured at the knee and ankle using a goniometer by a certified athletic trainer. The participant was tested in a supine relaxed position as described by Rothstein et al.³⁵. This measurement was taken both pre and post vibration treatment to assess ROM about each joint³⁶. Both passive and dynamic ROM during gait was assessed to obtain a more thorough assessment of the effect of ROM both prior to and following vibration exposure.

Outcome Measures. The variables that were measured included joint angle measures as well as temporal and spatial parameters. The dynamic ROM about the knee joint was measured between the thigh and shank segments such that full extension was zero and a positive value indicates flexion. The ankle angle was measured between the foot and shank segments where a positive value indicated dorsiflexion and a negative value indicated plantar flexion. Both angle measurements were taken at initial contact and at toe-off and reported in degrees. Step and stride time were calculated and measured in seconds. Due to the importance of initial contact and toe-off during the gait cycle, the knee and ankle angles were obtained at these specific points. Once the knee and ankle angles were graphed, the minimum and maximum angles were extracted and subtracted to find the absolute range of motion about that joint (Figure 1).

The speed of the subject was measured as the average horizontal speed of the individuals COG along the plane of movement³⁷ and was measured in meters/second. The cadence was defined as step frequency and was measured in steps/minute. Finally, step length and stride length were also obtained. The step length was defined as the distance from initial contact of one foot to initial contact of the opposite foot and the stride

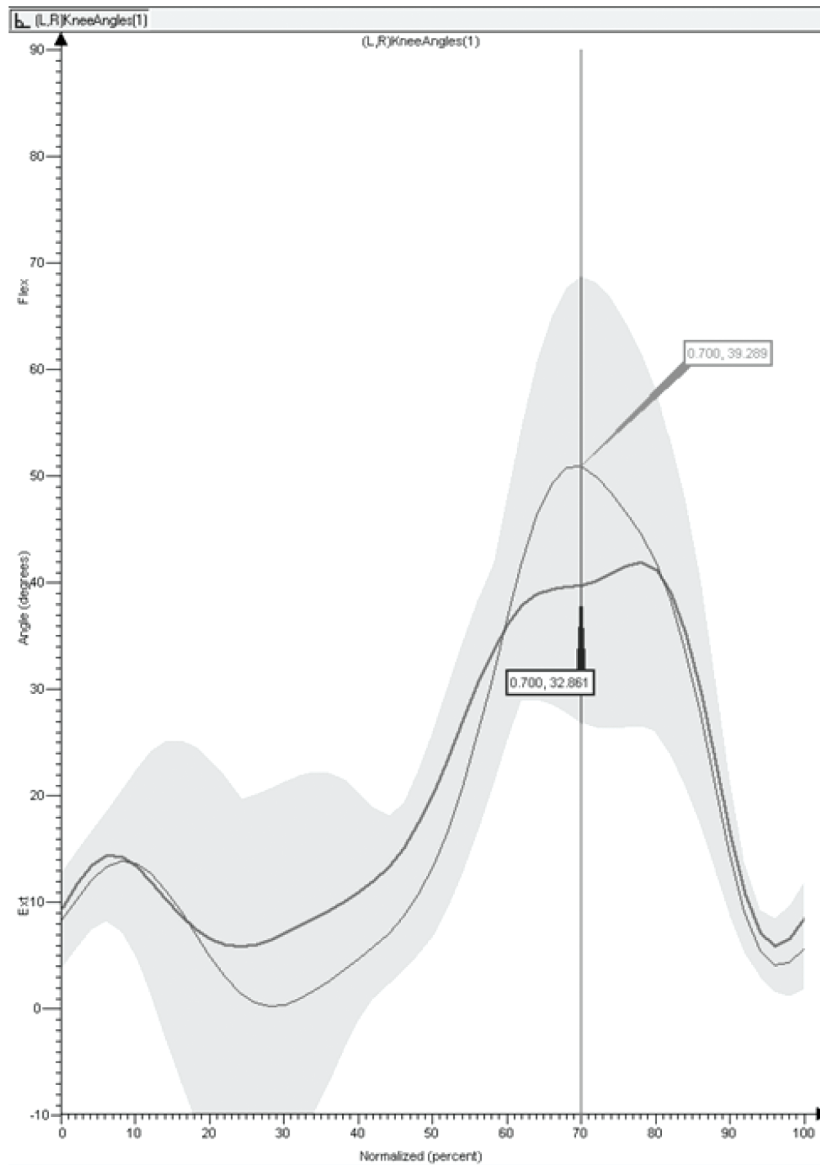


Figure 1. Exemplar graph depicting knee angle across the gait cycle. The maximum and minimum angles were abstracted to calculate the absolute knee range of motion in degrees.

length was defined as the distance between initial contact of one foot to initial contact of that same foot⁸.

With CP being an umbrella term and presenting itself differently in every affected individual, we compared the affected limb for subjects diagnosed with hemiplegic CP and took the average of both limbs for subjects diagnosed with diplegic CP as had been similarly done in a previous study¹⁶.

Statistical Analysis. Through SPSS (IBM, Somers, NY), the variables were compared using Repeated Measures Analyses of Variance to compare the data pre and post vibration. More specifically, the variables included walking speed, cadence, step length, stride length, step time, stride time, ankle angle and knee angle at initial contact and toe off, passive and dy-

namic ROM as a function of the independent variable of vibration status (i.e., no vibration, individualized frequency vibration). For all tests the alpha level was set at $p \leq 0.05$.

Results

All eight subjects completed all visits and protocols and the results can be seen in Tables 2 & 3. The comparisons from pre to post WBV revealed significant changes in three of the main variables: walking speed ($F_{(1,7)}=5.764$, $P=0.047$; $\eta^2=0.452$), stride length ($F_{(1,7)}=9.757$, $P=0.017$, $\eta^2=0.582$) and dynamic ankle ROM ($F_{(1,7)}=6.185$, $P=0.042$; $\eta^2=0.469$). Although there were small changes in each of the other variables there were

Variables	Pre Vibration	Post Vibration	Cohen's d
Walking Speed (m/s)*	0.961 (0.121)	0.993 (0.128)	0.257
Cadence (steps/min)	109.489 (7.011)	111.375 (6.723)	0.271
Step Length (m)	0.526 (0.062)	0.526 (0.062)	0.010
Stride Length (m)*	1.046 (0.130)	1.069 (0.139)	0.182
Step Time(s)	0.560 (0.029)	0.554 (0.0252)	-0.191
Stride Time(s)	1.096 (0.075)	1.081 (0.0637)	0.210
Knee Angle @ IC	19.669 (9.511)	18.522 (9.053)	-0.128
Ankle Angle @ IC	-5.704 (2.822)	-6.179 (2.144)	-0.063
Knee Angle @ TO	41.934 (9.151)	41.400 (8.459)	-0.195
Ankle Angle @TO	-6.317 (4.750)	-6.813 (4.967)	-0.105

Numbers represent mean scores with values in parentheses indicating the standard deviation. Angles were measured in degrees. For the knee, full extension=0 deg and for the ankle, positive values indicate dorsi flexion and negative values indicate plantar flexion. *Significant differences from pre to post ($p<0.05$).

Table 2. Mean values of the measures of interest for pre and post vibration intervention for all participants.

ROM	Pre Vibration	Post Vibration
Passive		
Knee ROM	128.21 (18.17)	126.07 (15.82)
Ankle ROM	55.286 (10.22)	57.07 (8.62)
Dynamic		
Knee ROM	39.545 (14.402)	36.858 (14.169)
Ankle ROM	20.170 (7.044)	21.631 (5.978)*

Numbers represent mean scores with values in parentheses indicating the standard deviation. The ROM is the total degrees of flexion and extension that a joint can go through passively. *Significant differences from pre to post ($p<0.05$).

Table 3. Mean values for the range of motion about the knee and ankle pre and post vibration intervention.

no other significant effects assessed in this study. Additionally, there were small differences between the 1 Day and 2 Day Protocol but with the small number of subjects in each group no statistical analyses were performed. The mean results for the two groups can be seen in Figures 2-4.

The average individualized frequency for all of the subjects was 38.13 ± 8.52 Hz. The average time from the end of the vibration protocol to the beginning of the first gait trial was 66 seconds (range 45s to 100 seconds). The average time from end of vibration protocol to the end of the post-vibration gait collection was 392 seconds (range 243s to 483s). Previous studies have determined that the effects of WBV can persist for 20-60 minutes following the exposure^{22,38}.

Discussion

The goal of this study was to determine the acute effects of WBV on gait speed, cadence, step length, stride length, step time, stride time, ankle angle and knee angle at initial contact

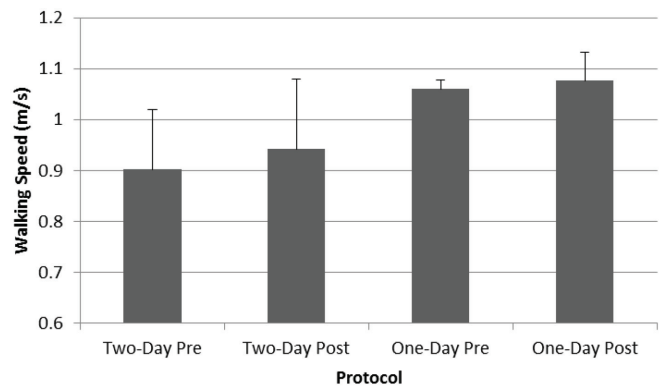


Figure 2. Comparison of Walking Speed (m/s) between subject's means for the One-Day Protocol and the Two-Day Protocol.

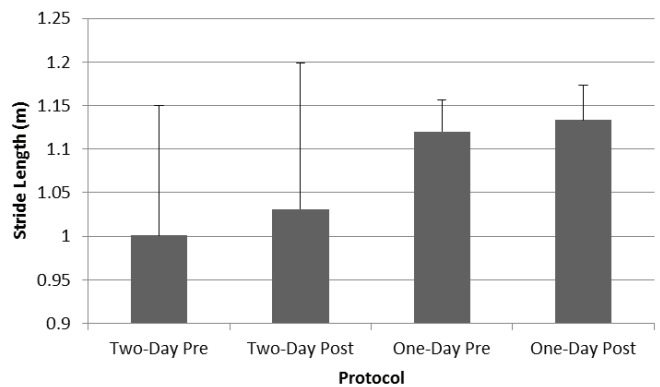


Figure 3. Comparison of Dynamic Ankle Range of Motion (deg) between subject's means for the One-Day Protocol and the Two-Day Protocol.

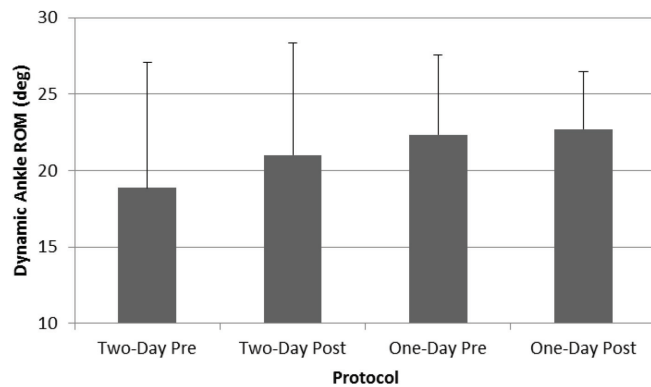


Figure 4. Comparison of Stride Length (m) between subject's means for the One-Day Protocol and the Two-Day Protocol.

and toe-off, and joint ROM during gait in adults with CP. Dynamic ankle ROM, stride length and walking speed were found to significantly increase following an acute bout of WBV. Hypothesized significant changes in knee ROM and step length were not found, however, there were increasing trends noticed.

From the joint angle results, it could be suggested that the WBV exposure resulted in an increased ROM at the ankle which could have been the results of changes in overall muscle length. The short bout of WBV used in this study may have caused the muscle to become suppler, allowing for a change in length to occur during gait. There was a significant increase in the dynamic ankle ROM ($21.63^{\circ} \pm 5.978^{\circ}$) which could have resulted from a relaxation of the triceps surae allowing the ankle to go through a greater range of dorsiflexion movement. This increased ROM about the ankle (following WBV) more closely resembles a typical and more energy efficient gait pattern (ankle ROM 25°). Although recent studies have suggested a minimum detectable change of 1.87° for sagittal plane ankle ROM³⁹, the current study produced a change of 1.46° following only one vibration session. Given the relationship between increased ROM and gait efficiency in individuals with CP⁴⁰ it is worth investigating the underlying cause. Another alternative to the changes in ROM elicited in this study is the position (15° hip flexion) held while standing on the vibrating platform. Assuming a flexed hip position during the vibration exposures may have facilitated the increased ROM, or may have contributed to the changes in ROM. Regardless of the cause, any reasonable means to increase overall muscle length should be encouraged, as a muscle with spasticity can impair ROM and lead to pain in joints; following an acute bout of WBV, in the current study, there was an increase in ROM which could suggest a decrease in spasticity.

An increased ROM in the knee and ankle occurred at both initial contact and toe-off. At both phases of the gait cycle, there was a decrease in knee angle indicating that the knee was closer to full extension. This suggests that the hamstring muscle in addition to the gastrocnemius could be more relaxed allowing for an increased ROM and greater degree of knee

extension. Given that these muscles are often times spastic in individuals with CP the increased ROM following the acute bout of WBV appears to have resulted in more elongated muscle which could be the result of a reduction in overall spasticity. Although the current study attempted to elucidate the current and past¹³ findings of improved gait speed following WBV, future studies should assess the overall levels of spasticity in the muscles to determine the nature of the increased ROM following WBV.

With the increased ROM demonstrated following the individualized WBV exposure participants were able to achieve greater degree of knee extension. As the individual moves closer to full extension the limb becomes more rigid allowing the body to propel itself over its base of support and forward. Without the full extension at initial contact, the pivotal action of the “heel rocker” is reduced which results in decreased momentum, reduced stride length and decreased speed⁴¹. With the trends experienced in both the ankle and knee ROM reaching closer to typical gait this could explain the significant increase in stride length.

Another result of the increased ROM is that the subjects were able to reach further during their strides. It is worth noting that there was not a significant change in the step length ($P=0.905$), which was determined based on the diagnosis of each subject, but there was the significant change in stride length ($P=0.017$). Although the current study's changes of 2.3 cm were larger than the mean variability reported by Stolze and colleagues⁴², caution should be taken in the interpretation of this significant finding albeit promising for those with CP. For the subjects diagnosed as hemiplegic CP, the affected side's step length was used for comparison. For those diagnosed diplegic CP the data from both the right and the left sides were averaged to get a value. Since stride length is measured using both the right and left step for all subjects, it seems that there was a compensatory action occurring. This change could be a result of an increase in step length of the unaffected side. This effect might also be explained through the averaging performed on the diplegic subjects' data. These subjects could have had an imbalance between their affected sides that might have been obscured as a result of the data averaging across affected sides. Future studies using a larger sample size and more homogenous group of individuals with diplegic CP might be able to discern a clearer distinction between sides.

The significant increase in stride length may account for the increase in walking speed observed in this study. Increased walking speed following acute WBV is consistent with results from a previous study¹³. Utilizing a longitudinal WBV training protocol similar changes in walking speeds were elicited using a vibration protocol similar to the current study. Subjects in the previous study received nine minutes of vibration therapy per day over six months and increased their average walking speed in the ten meter walk by a median of 0.18 m/s ¹³. These results, compared to the results of the current study, show that a longer duration of vibration may produce a greater magnitude of change in the subjects. Using an acute exposure of only five minutes with an individualized vibration exposure, the

adults with CP were also able to walk faster across the ten meter gait platform. In the previous study the specific gait parameters were not assessed, but the results from this study suggest that the increase in walking speed following WBV may be the result of increased ROM throughout the knee and ankle. This implies that WBV may allow adults with CP to walk more effectively with increased speed which could lead to increased daily exercise as a result of improved mobility. It is important to note that the WBV protocol used in the current investigation was that of an individualized protocol (vibration frequencies ranged from 30-50 Hz resulting in peak acceleration valued of 3.6g to 10.1 g, respectively), since the previous study utilized a 12-18 Hz frequency (peak acceleration of 2.6 g) protocol it would be interesting to determine if the effects are different based on the different vibration settings.

Summary

Findings from the current study indicated that improvements in walking speed, stride length and dynamic ankle ROM may be elicited through the use of single session of an individualized frequency WBV exposure in adults with CP. Using an acute exposure the current study was able to achieve an improvement in three measures of gait, while also attempting to determine the cause(s) for improved gait speed reported in previous investigations. For the individual with CP, WBV could be performed daily on the patient's own schedule since there would be no need for a therapist to be present during the WBV. This intervention is cost effective when compared to the rising cost of health insurance and physical therapy sessions. This also allows for adults with CP to be more independent and in control of improving or maintaining their ambulation skills. Physical therapists and orthopedists alike could also use this as a fairly inexpensive intervention that produces immediate results.

Acknowledgements

Special thanks to the all of the participants in this study for their time and effort. Additional thanks to Ball State Universities ASPiRE Grant for funding to provide participants with a small stipend.

References

- Murphy KP. The adult with cerebral palsy. *Orthop Clin North Am* 2010;41(4):595-605.
- Koman LA, Paterson SB, Balkrishnan R. Spasticity associated with cerebral palsy in children: guidelines for the use of botulinum A toxin. *Paediatr Drugs* 2003;5(1):11-23.
- Koman LA, Smith BP, Shilt JS. Cerebral palsy. *Lancet* 2004;363(9421):1619-31.
- Flett PJ. Rehabilitation of spasticity and related problems in childhood cerebral palsy. *J Paediatr Child Health* 2003;39(1):6-14.
- Sutherland DH. *Gait disorders in childhood and adolescence*. 1984.
- Bottos M, Feliciangeli A, Sciuto L, Gericke C, Vianello A. Functional status of adults with cerebral palsy and implications for treatment of children. *Dev Med Child Neurol* 2001;43(8):516-28.
- Webb D, Tuttle RH, Baksh M. Pendular activity of human upper limbs during slow and normal walking. *Am J Phys Anthropol* 1994;93(4):477-89.
- Gage JR, DeLuca PA, Renshaw TS. Gait analysis: principle and applications with emphasis on its use in cerebral palsy. *Instr Course Lect* 1996;45:491-507.
- Donkervoort M, Roebroek M, Wiegerink D, van dH-M, Stam H. Determinants of functioning of adolescents and young adults with cerebral palsy. *Disabil Rehabil* 2007;29(6):453-63.
- Andersson C, Mattsson E. Adults with cerebral palsy: a survey describing problems, needs, and resources, with special emphasis on locomotion. *Dev Med Child Neurol* 2001;43(2):76-82.
- Liptak GS. Health and well being of adults with cerebral palsy. *Curr Opin Neurol* 2008;21(2):136-42.
- Rimmer JH. Health promotion for people with disabilities: the emerging paradigm shift from disability prevention to prevention of secondary conditions. *Phys Ther* 1999;79(5):495-502.
- Ruck J, Chabot G, Rauch F. Vibration treatment in cerebral palsy: A randomized controlled pilot study. *J Musculoskelet Neuronal Interact* 2010;10(1):77-83.
- Rauch F. Vibration therapy. *Dev Med Child Neurol* 2009;51(Suppl.4):166-8.
- Sands WA, McNeal JR, Stone MH, Russell EM, Jemni M. Flexibility enhancement with vibration: Acute and long-term. *Med Sci Sports Exerc* 2006;38(4):720-5.
- Wren TA, Lee DC, Hara R, Rethlefsen SA, Kay RM, Dorey FJ, Gilsanz V. Effect of high-frequency, low-magnitude vibration on bone and muscle in children with cerebral palsy. *J Pediatr Orthop* 2010;30(7):732-8.
- Marin PJ, Bunker D, Rhea MR, Ayllon FN. Neuromuscular activity during whole-body vibration of different amplitudes and footwear conditions: implications for prescription of vibratory stimulation. *J Strength Cond Res* 2009;23(8):2311-6.
- Cochrane DJ. Vibration exercise: the potential benefits. *Int J Sports Med* 2011 February;32(2):75-99.
- Cochrane DJ, Stannard SR. Acute whole body vibration training increases vertical jump and flexibility performance in elite female field hockey players. *Br J Sports Med* 2005;39(11):860-5.
- Delecluse C, Roelants M, Verschueren S. Strength increase after whole-body vibration compared with resistance training. *Med Sci Sports Exerc* 2003;35(6):1033-41.
- Bosco C, Colli R, Introini E, Cardinale M, Tarpela O, Madella A, Tihanyi J, Viru A. Adaptive responses of human skeletal muscle to vibration exposure. *Clin Physiol* 1999;19(2):183-7.
- Dickin DC, McClain MA, Hubble RP, Doan JB, Sessford D. Changes in postural sway frequency and complexity in altered sensory environments following whole body vi-

- brations. *Hum Mov Sci* 2012; April 17.
23. Burke D, Hagbarth KE, Lofstedt L, Wallin BG. The responses of human muscle spindle endings to vibration during isometric contraction. *J Physiol* 1976;261(3):695-711.
24. Cardinale M, Bosco C. The use of vibration as an exercise intervention. *Exerc Sport Sci Rev* 2003;31(1):3-7.
25. Ahlborg L, Andersson C, Julin P. Whole-body vibration training compared with resistance training: effect on spasticity, muscle strength and motor performance in adults with cerebral palsy. *J Rehabil Med* 2006;38(5):302-8.
26. Bongiovanni LG, Hagbarth KE, Stjernberg L. Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man. *J Physiol* 1990;423:15-26.
27. de Ruiter CJ, Van Raak SM, Schilperoort JV, Hollander AP, de HA. The effects of 11 weeks whole body vibration training on jump height, contractile properties and activation of human knee extensors. *Eur J Appl Physiol* 2003; 90(5-6):595-600.
28. Humphries B, Warman G, Purton J, Doyle TLA, Dugan E. The influence of vibration on muscle activation and rate of force development during maximal isometric contractions. *Journal of Sports Science and Medicine* 2004;3(1):16-22.
29. Jackson SW, Turner DL. Prolonged muscle vibration reduces maximal voluntary knee extension performance in both the ipsilateral and the contralateral limb in man. *Eur J Appl Physiol* 2003;88(4-5):380-6.
30. Torvinen S, Sievanen H, Jarvinen TA, Pasanen M, Kontulainen S, Kannus P. Effect of 4-min vertical whole body vibration on muscle performance and body balance: a randomized cross-over study. *Int J Sports Med* 2002; 23(5):374-9.
31. Cardinale M, Lim J. Electromyography activity of vastus lateralis muscle during whole-body vibrations of different frequencies. *J Strength Cond Res* 2003;17(3):621-4.
32. Di GR, Tihanyi J, Safar S, Scrimaglio R. The effects of vibration on explosive and reactive strength when applying individualized vibration frequencies. *J Sports Sci* 2009; 27(2):169-77.
33. Auxter D. Principles and methods of adapted physical education and recreation. 11th ed ed. New York: McGraw-Hill Higher Education; 2010.
34. Criswell E, Cram JR. Cram's introduction to surface electromyography. 2nd ed ed. Sudbury, MA: Jones and Bartlett; 2011.
35. Rothstein JM, Miller PJ, Roettger RF. Goniometric reliability in a clinical setting. Elbow and knee measurements. *Phys Ther* 1983;63(10):1611-5.
36. Andersson C, Grooten W, Hellsten M, Kaping K, Mattsson E. Adults with cerebral palsy: walking ability after progressive strength training. *Dev Med Child Neurol* 2003;45(4):220-8.
37. Hamill J, Knutzen K. Biomechanical basis of human movement. 3rd ed ed. Philadelphia: Wolters Kluwer Health/Lippincott Williams and Wilkins; 2009.
38. Bosco C, Colli R, Introini E, Cardinale M, Tarpela O, Madella A, Tihanyi J, Viru A. Adaptive responses of human skeletal muscle to vibration exposure. *Clinical Physiology* 1999;19(2):183-7.
39. Wilken JM, Rodriguez KM, Brawner M, Darter BJ. Reliability and Minimal Detectable Change values for gait kinematics and kinetics in healthy adults. *Gait Posture* 2012;35(2):301-7.
40. Ballaz L, Plamondon S, Lemay M. Ankle range of motion is key to gait efficiency in adolescents with cerebral palsy. *Clin Biomech (Bristol, Avon)* 2010;25(9):944-8.
41. Nolan KJ, Yarossi M. Preservation of the first rocker is related to increases in gait speed in individuals with hemiplegia and AFO. *Clin Biomech (Bristol, Avon)* 2011; 26(6):655-60.
42. Stolze H, Kuhtz-Buschbeck JP, Mondwurf C, Johnk K, Friege L. Retest reliability of spatiotemporal gait parameters in children and adults. *Gait Posture* 1998;7(2):125-30.