12-2020

Neuromuscular response to a single session of whole-body vibration in children with cerebral palsy: A pilot study

Huaqing (Virginia) Liang

Gena Henderson

Jianhua Wu

Highlights:

- A single session of whole-body vibration benefits children with cerebral palsy.
- Both high- and low-amplitude vibration reduce leg muscle spasticity.
- Both vibration sessions improve long-range correlation of standing posture.
- Both vibration sessions reduce muscle activity of tibialis anterior during walking.
- Only high-amplitude vibration increases the ankle range of motion during walking.

Neuromuscular response to a single session of whole-body vibration in children with cerebral palsy: A pilot study

Virginia Liang [a], Gena Henderson [b], Jianhua Wu [b,c]*

[a] Department of Physical Therapy, University of Illinois, Chicago, IL, USA

[b] Department of Kinesiology and Health, Georgia State University, Atlanta, GA, USA

[c] Center for Movement & Rehabilitation Research, Georgia State University, Atlanta, GA, USA

* Corresponding author:

Jianhua Wu, Ph.D.

Department of Kinesiology and Health, Center for Movement & Rehabilitation Research,

Georgia State University. 125 Decatur Street, Atlanta, GA 30302, USA.

Email: jwu11@gsu.edu

Word count for Abstract: 247

Word count for Main Text: 3,996

Number of Tables: 5

Number of Figures: 1

This manuscript is submitted as an Original Article.

Neuromuscular response to a single session of whole-body vibration in children with cerebral palsy: A pilot study

Abstract

Background: Whole-body vibration (WBV) is a relative new intervention paradigm that could reduce spasticity and improve motor function in children with cerebral palsy (CP). We investigated neuromuscular response to a single session of side-alternating WBV with different amplitudes in children with CP.

Methods: Ten children with spastic CP aged 7-17 years at GMFCS level I-III participated in this pilot study. Participants received two sessions of side-alternating WBV with the same frequency (20Hz) but different amplitudes (low-amplitude: 1mm and high-amplitude: 2mm). Each session included six sets of 90 seconds of WBV and 90 seconds of rest. Before and after each WBV session, we used (a) the modified Ashworth scale to evaluate the spasticity of the participants' leg muscles, (b) a quiet standing task to analyze center-of-pressure (CoP) pattern and postural control, and (c) overground walking trials to assess spatiotemporal gait parameters and joint range-of-motion (RoM).

Results: Both WBV sessions similarly reduced the spasticity of the ankle plantarflexors, improved long-range correlation of CoP profile during standing, and reduced muscle activity of tibialis anterior during walking. The high-amplitude WBV further increased ankle RoM during walking.

Conclusions: This study demonstrates that a single session of WBV with either a low or a high amplitude can reduce spasticity, enhance standing posture, and improve gait patterns in children with CP. It suggests that low-amplitude WBV may induce similar neuromuscular response as high-amplitude WBV in children with spastic CP and can provide positive outcomes for those who are not able to tolerate stronger vibration.

Keywords:

Spasticity; side-alternating; gait; kinematics; electromyography.

1. Introduction

Cerebral palsy (CP) is the most common motor disability in childhood with prevalence ranging from 1.5 to more than 4 per 1000 live births in the United States.[1] Children with CP often display neuromuscular impairments such as spasticity and loss of selective muscle control starting in early infancy.[2] Spasticity is a type of abnormal muscle tone characterized by a velocity-dependent increase of involuntary muscle activation while being stretched. It is related to hyper-excitability and poor descending supraspinal modulation of the stretch reflex.[3,4] Spasticity is common in children with CP: more than three quarters of them are diagnosed with spastic CP.[1] Currently, there is a lack of effective non-pharmacological method of controlling spasticity in children with CP.

Children with CP often develop secondary neuromuscular complications such as abnormal gait patterns and poor postural control.[2] Children with CP typically show a greater velocity and a greater sway area of center-of-pressure (CoP) movement than typically developing (TD) children during quiet standing.[5] Their poor balance control results in restricted daily activities and a higher risk of falls in children with CP.[6] In terms of locomotion, children with CP generally display limited walking ability characterized by a shorter step length, a slower walking speed, a longer stance time, and higher step-to-step variability compared to their TD peers.[7,8] To improve motor function of children with CP, many intervention strategies such as passive stretching have been studied; however, the benefits have been limited thus far and may not be translated into functional locomotion activities such as overground walking.[9]

Whole-body vibration (WBV) is an innovative rehabilitation paradigm and may be able to reduce spasticity in children with CP. One possible mechanism of WBV is that it increases excitation of muscle spindles of agonist muscles, which increases their force and power production, and inhibits antagonists through the reciprocal Ia inhibition pathway.[10,11] Months-long WBV training at a frequency of 18-25Hz and with an amplitude of 1-4mm has been shown to reduce spasticity of the leg muscles and improve gait parameters by increasing stride length and dynamic ankle range-of-motion (RoM) in children with CP.[12-14] It was noted that two types of WBV platforms have been used in previous studies: synchronous (i.e., the platform moving up and down in a linear motion) and side-alternating (i.e., the platform rotating about its center and acting like a seesaw board). Compared to synchronous WBV where the whole body moves up and down simultaneously, side-alternating WBV utilizes the depression and elevation of the pelvis in the frontal plane to reduce the transmission of vertical acceleration from the lower legs to the trunk and head, resulting in safer training effects.[15,16]

Similar to months-long WBV training, a single session of WBV at a frequency of 20Hz and an amplitude of 2mm could temporarily reduce the spasticity of the leg muscles and increase both active and passive RoM of the ankle in children with CP.[14,17,18] Furthermore, a single session of synchronous WBV session was found to improve long-range correlation of CoP profile during standing in TD children, suggesting improvement of postural stability.[19] However, these previous studies only examined one combination of a certain frequency and amplitude of WBV. To our knowledge, little study has been conducted to understand neuromuscular response of children with CP to a single session of side-alternating WBV with different frequencies and amplitudes. Although leg muscle activity increases with both WBV frequency (from 15 to 25Hz) and amplitude (from 2.5 to 5.5mm), doubling the amplitude could increase leg muscle activity to a greater extent than increasing the frequency by 5-10 Hz in healthy young adults.[20,21] Given a small range of WBV frequency tolerable in children with CP but a relatively wider range of WBV amplitude, it seems logical to investigate neuromuscular response to a single session of WBV with different amplitudes.

The purpose of this study was to evaluate neuromuscular response immediately after a single session of WBV with different amplitudes in children with CP. Two WBV sessions were presented with the same frequency (20Hz) but different amplitudes: low-amplitude at 1mm and high-amplitude at 2mm. Neuromuscular response was evaluated immediately after each WBV session. Assessments included (a) spasticity of the leg muscles, (b) CoP variables during quiet standing, and (c) gait patterns during overground walking. Our hypothesis was that both WBV sessions would reduce spasticity, enhance postural control, and improve gait spatiotemporal parameters and leg muscle activation patterns. Furthermore, we hypothesized that between the two WBV sessions, the high-amplitude WBV would elicit better neuromuscular responses than the low-amplitude WBV in children with CP.

2. Methodology

2.1. Participants

Ten children with spastic CP (7M/3F) aged 7-17 years participated in this study (Table 1). We recruited participants through flyers and from local pediatric physical therapy clinics in the greater Atlanta area. The inclusion criteria were that a child (a) had a diagnosis of CP, (b) had a Gross Motor Function Classification System (GMFCS) level of I-III, (c) was able to walk without an assistive device for five meters, (d) was able to stand with or without holding a handrail for three minutes, (e) was able to understand verbal instructions, and (f) had a consistent dosage of Baclofen for the past three months if it was being used. The exclusion criteria included the presence of any other progressive neurological, metabolic, or balance disorders not typically associated with CP, Botox injections within the past three months, or any other contraindications to the WBV. This study was approved by the institutional review board at the hosting university. Prior to participation, a parent permission form was signed by the parent, and a verbal or a written assent was obtained from participants aged 6-10 or 11-17 years, respectively. Data collection was mostly at physical therapy clinics except one in a Biomechanics lab.

2.2. Experimental protocol

A Galileo Med-L WBV platform (StimDesigns LLC, Carmel, CA) was used to provide side-alternating WBV. This study consisted of two sessions: both having the same frequency at 20 Hz but with either a low amplitude (LA) of 1mm or a high amplitude (HA) of 2mm, resulting in a peak vertical acceleration of 1.6*g* and 3.2*g*, respectively (*g* is gravitational acceleration and equal to 9.81m/s^2). The LA condition was presented first to all the participants to minimize possible intolerance of the HA condition. For each condition, participants completed six bouts of vibration, with each bout involving 90 seconds of vibration and 90 seconds of rest. Participants stood barefoot on the platform with knees flexed to about 30°.[17] The WBV platform has line marks for different vibration amplitudes. Participants aligned the middle of their feet with the 1mm or 2mm line marks for the desired vibration amplitudes. Two researchers pulled the participants’ heel down, if necessary, to maintain their heels on the platform during vibration. Participants held the front handle (not leaning on it) to aid their standing posture, so that the vibration transmission was majorly in the vertical direction. There was a 30-minute washout period between the LA and HA sessions.[19,22,23]

Before and immediately after each session, assessments included muscle spasticity at the ankle and knee, postural control during quiet standing, and the gait patterns during overground walking. Therefore, there were three conditions: *Pre* (pre-WBV), *LA-Post* (post low-amplitude WBV), and *HA-Post* (post high-amplitude WBV). The spasticity was assessed using the modified Ashworth scale (MAS) for ankle plantarflexors with the knee extended and flexed, knee extensors, and knee flexors. The MAS uses a rating system of 0 (normal tone) to 4 (rigidity) with an additional 1+ score.[24] During quiet standing, a portable Kistler force plate (Kistler, Amherst, NY) was used to collect kinetic data at a frequency of 1000Hz at clinics and an AMTI force plate (AMTI, Watertown, MA) embedded in the floor was used to collect data in the Biomechanics lab. Participants stood barefoot on the force plate for one 60-second trial with the feet hip-width apart, the hands placed on their hips, and the trunk as straight as possible.

For gait data collection at the clinics, a Nikon D90 camera (Nikon, Japan) was placed in the middle of a 5-meter level walkway to record the motion of lower legs in the sagittal plane at a frequency of 24 Hz. For gait data collected in the biomechanics lab, 16 reflective markers were placed bilaterally on the participant’s anterior superior iliac spine, posterior superior iliac spine, thigh, knee, shank, ankle, heel, and toe based on the Vicon Plug-in-Gait lower-body model.[25,26] An 8-camera Vicon motion capture system (Vicon, Centennial, CO) was used to collect the kinematic data at a frequency of 100 Hz. In addition, a portable Delsys Trigno wireless EMG system (Delsys, Natick, MA) was used at all locations to register muscle activity at a frequency of 4000 Hz. Four EMG sensors were placed on the muscle belly of the lateral gastrocnemius (LG), tibalis anterior (TA), vastus lateralis (VL), and biceps femoris (BF) of the tested leg following the SENIAM recommendation for skin preparation and electrodes placement.[27] For participants with hemiplegic CP, the tested leg was the affected leg. For participants with diplegic CP, the tested leg was the less-affected leg as this leg supports the majority of body weight and might benefit more from WBV. Additionally, inertial measurement units (IMU) within the EMG sensors collected acceleration data along three axes at a frequency of 296 Hz.

2.3. Data analysis and outcome measures

2.3.1. COP parameters

For the quiet standing task, raw kinetic data were smoothed with a low-pass filter at a cut-off frequency of 6 Hz. Due to unintentional body movements in most of the participants, 30 seconds of the data were selected with the minimum unintentional body movements from the original 60-second data for further analysis. This 30-second data were generally taken from the first 30 seconds of a trial. The AP and ML CoP movement data were processed separately, and the mean value was removed before further calculation.[28] A customized MATLAB program was used to calculate average velocity and root-mean-square (RMS) of the CoP in the AP and ML directions separately. Furthermore, detrended fluctuation analysis (DFA) was applied in the AP and ML directions separately to assess the long-range correlation of the CoP movement (see Supplement Material A for the details). DFA is generally used to assess the long-range correlation in biological time series [29,30] and the scaling exponent estimates the correlation between current movement and its previous movements [31]. DFA analysis reveals that CoP movement typically shows a non-linear persistent feature in adults and TD children during quiet standing.[19,31]

2.3.2. Gait parameters during overground walking

Kinovea (Kinovea, France) and Vicon Nexus (Vicon, Centennial, CO) were used to process the marker data collected at clinics and in the biomechanics lab, respectively. The use of a 2D video system to assess gait parameters has been deemed to be accurate and reliable compared to the golden standard 3D motion capture system.[32] Foot strike was defined when either the heel or forefoot contacted the floor. Toe-off was defined when the toe was lifted off the floor. Stride length was calculated as the anterior-posterior (AP) distance between successive foot strikes of the tested leg. Stride velocity was equal to stride length divided by stride time. Double support time was the duration from ipsilateral foot strike to contralateral toe-off of a gait cycle. Double support percentage was the ratio of double support time to stride time.[33-36]

Joint angles were identified in the sagittal plane for each gait cycle. Ankle angle was the angle between the shank and foot segments subtracted from 90 degrees, and knee angle was the angle between the extension line of the thigh and the shank. Dynamic RoM was the difference between peak flexion and extension of the ankle and knee joints, separately.

2.3.3. Muscle activation during overground walking

EMGworks (Delsys, Natick, MA) was used to export the EMG and acceleration data during overground walking and a custom-written MATLAB (Mathworks, Natick, MA) program was used to calculate EMG variables. The EMG data were initially processed with a 6th-order zero-phase Butterworth band-pass filter of 20-500 Hz and the mean was removed for further analysis.[37] The signal was then processed with a full-wave rectification and the RMS value was calculated using a RMS envelope with a window length of 100ms for each gait cycle.[37] Peak vertical acceleration of IMU sensor on TA was used to detect the foot strike of the walking data collected at clinics.[38,39] For the data collected in the biomechanics lab, ground reaction force was used to determine the timing of foot strike. Foot strike determined by the peak vertical acceleration of the TA sensor was consistently 0.02 second later than that determined by the ground reaction force. Thus, adjustments were made to the data collected at clinics. The integrated EMG area was calculated for each muscle within a gait cycle and the average integrated area across gait cycles was computed for each participant.

2.4. Statistical analysis

For the MAS scores, a grade of 1+ was recorded as 1.5 and non-parametric Friedman test was conducted on the mean ranks of the three conditions, followed by Wilcoxon signed ranks test for pairwise comparisons when appropriate. Furthermore, a series of one-way (3 condition) ANOVAs with repeated measures were conducted on the CoP variables during quiet standing, and gait spatiotemporal parameters, joint RoM, and integrated EMG areas during overground walking. Post-hoc pairwise comparisons with Bonferroni adjustments were conducted when appropriate. SAS 9.4 software (SAS, Cary, NC) was used for statistical analysis. All significance levels were set at $\alpha=0.05$.

3. Results

3.1. Modified Ashworth scale (MAS)

No participant increased spasticity in any leg muscles after either a LA or a HA vibration session. Both sessions had a similar effect on the reduction of spasticity (Table 2). Results of the Friedman test showed reduced spasticity of the plantarflexors with the knee extended ($\chi^2(2)=9.33$, $P<0.05$) and flexed ($\chi^2(2)=11.47$, $P<0.05$) after vibration sessions. Further Wilcoxon signed ranks tests revealed that both *LA-Post* and *HA-Post* reduced the spasticity of the plantarflexors with the knee extended and flexed compared to *Pre* condition, but no difference between *LA-Post* and *HA-Post* conditions. Specifically, of the seven participants who had spasticity in their plantarflexors with the knee extended at baseline, five reduced the MAS score by 0.5-2 points. Of the seven participants who had spasticity in their plantarflexors with the knee flexed at baseline, six reduced the MAS score by 0.5-1.5 points.

3.2. COP variables

Children with CP displayed a similar average velocity and RMS of CoP across the three conditions. The DFA scaling exponent increased in the AP direction, but not in the ML direction, after both vibration sessions (Table 3). Statistical analysis showed that there was a condition effect for the DFA-AP (F(2,16)=6.26, $P<0.05$). Post-hoc analysis revealed that this value was greater at both *LA-Post* and *HA-Post* than *Pre* condition (Cohen's d=1.27 and 1.09, respectively).

3.3. Gait parameters

Four participants displayed apparent toe-walking patterns at the *Pre* condition, but improved toward a heel-strike gait pattern after either a LA or a HA vibration session. However, only the ankle RoM increased substantially after the HA session (Table 4). Statistical analysis showed that there was a condition effect for the ankle RoM (F(2,16)=4.49, $P<0.05$). Post-hoc analysis revealed that the ankle RoM was larger at *HA-Post* than *Pre* condition (Cohen's d=0.84). The individual spatiotemporal data are presented in Supplement Material B.

3.4. Muscle activation during overground walking

The EMG signals of the LG and TA displayed constant activation before WBV with unidentifiable phasic bursts for most participants (Fig. 1a), which is a common pattern observed in children with CP.[40] After both WBV sessions, the constant EMG activation pattern of the LG and TA decreased (Fig. 1b and 1c) and consequently, the integrated EMG area decreased (Table 5). Statistical analysis showed a condition effect on the integrated EMG area of the TA

(F(2,15)=6.77, $P<0.05$). Post-hoc analysis revealed that the integrated area was smaller at both *LA-Post* and *HA-Post* than *Pre* condition (Cohen's d=0.34 and 0.47, respectively).

4. Discussion

Overall, our results showed that WBV with either a LA or a HA can be tolerated by most children with CP. Most participants displayed reduced spasticity and decreased integrated EMG area of the TA during overground walking after both WBV sessions. Further, the HA vibration session significantly increased ankle RoM during overground walking.

4.1. Response in spasticity to a single session of WBV

Our results showed that most children with CP reduced spasticity of the ankle plantarflexors following both WBV sessions. These results are consistent with previous studies that reported an average decrease of the MAS score of the ankle plantarflexors by 0.5-1.5 points after a WBV session.[14] This confirms that a single session of side-alternating WBV (for a total vibration duration of less than ten minutes) can have an acute effect on reducing spasticity in children with CP. However, a single session of the HA vibration, despite having a peak vertical acceleration twofold of that in the LA vibration, did not elicit further reduction in spasticity. This finding is contrary to our hypothesis in favor of the HA vibration. However, we deem that this finding has its clinical implications such that if some children with CP are not able to tolerate WBV with a higher amplitude, they may still receive WBV with a relatively lower amplitude to obtain similar neuromuscular benefits in reduction of spasticity.

4.2 Response in standing posture to a single session of WBV

Our results of DFA-AP partially support our hypothesis that long-range correlation of CoP profile would improve after WBV. Similar to previous studies in young adults and TD children during quiet standing,[19,41] the DFA scaling exponent were between the range of 1.0 and 1.5 in children with CP, indicating a non-stationary persistent feature of CoP movement during quiet standing. After a WBV session, an increase of scaling exponent towards 1.5 (Brownian noise) in the AP direction suggests an intrinsic improvement in postural control with less frequent direction change and an overall smoother movement in children with CP. Furthermore, significant results using the DFA analysis but not in time-domain measures suggest that the DFA method may be more sensitive to WBV with different amplitudes and help reveal intrinsic features of postural control in children with CP.

4.3 Response in gait patterns to a single session of WBV

Our study was the first to examine the effect of a single session of WBV with different amplitudes on leg muscle activities during walking. Our findings indicate that the reduction in spasticity can result in better control of the leg muscles and improved gait patterns during walking. Previous literature suggested that abnormal gait patterns in children with spastic CP are primarily due to the spasticity and contracture of the hip and knee flexors and the ankle plantarflexors.[42] Previous study showed that WBV could cause a delay in the stretch reflex activation of the soleus muscle in children with CP.[43] In this study, we observed a reduced activation of the TA and LG throughout gait cycles (Fig. 1), suggesting a reduction of the spasticity of the lower leg muscles via decreased hyperactive stretch reflex responses. Compared to children with TD, children with CP often increase activation of the TA during the swing phase to compensate for the spastic plantarflexor muscles.[44] Our results of the decreased integrated EMG area of the TA after WBV might suggest that less activation of the TA was required to maintain the ankle position; the reduction of plantarflexor activity throughout the gait cycle may have necessitated decreased compensatory strategies to achieve toe clearance.

Previous study showed that higher muscle activation was observed in the lower leg muscles (LG and TA) than the thigh muscles (VL and BF) during WBV.[20] The lack of change in thigh muscle spasticity and activation during walking could be the result of damping and absorption of energy occurred primarily below the knee during WBV. Additionally, there were four participants with apparent toe-walking patterns at the *Pre* condition. All of them started to show a typical heel-strike gait pattern after either WBV session. This observation suggests an increased activation of the TA around foot strike, which might be masked by the reduction of overall activity originally caused by the continuous contraction of the muscle.

4.4 Inter-participant variability in their neuromuscular responses

During the data collection, we observed that some participants had a better response to WBV intervention and displayed prominent improvement in gait patterns after either WBV session, while other participants did not show much change (see Supplement Material B). Participants with low neuromuscular response such as CP09 and CP10 had a more or less typical gait pattern at baseline such that their stride velocity was comparable to that of TD children (1.07 m/s)[45]. In contrast, participants with high neuromuscular response such as CP01, CP03, and CP08 substantially increased stride length and decreased double support percentage. These results suggest that a single session of WBV with different amplitudes might induce larger improvement in gait patterns for children with CP who have more atypical gait patterns at baseline. For children with CP who have a more typical gait pattern at baseline, further investigation is warranted to examine if WBV with a higher frequency and a greater amplitude may lead to better improvements.

4.5 Limitations

We acknowledge that adding a control group with asymptomatic children to our study design may facilitate the interpretation of our results. However, our rationale of not including a control group was that these children have no spasticity and display normal walking patterns, so they may hardly benefit from WBV intervention. This speculation was supported by the observation that some of our participants who had higher motor functions showed limited gait improvement in this study.

One limitation of this study was that the same order of WBV was used for all participants. Since WBV was a novel neuromuscular experience for our participants, we deemed that without a familiarization session, most participants might not be able to tolerate stronger WBV, potentially causing incompletion of data collection. Since the residual effects of WBV are thought to last for 10-15 minutes[19,22,23] and there were at least 30-minute washout period between two vibration exposures, we believe that the increased ankle RoM after the HA session was primarily due to the effect of high amplitude. However, since we intended to complete the whole data collection within 2 hours to limit fatigue and to reduce dropout rate, we did not evaluate the long-term effect (after several hours or days) of a single-session of WBV. Future studies are warranted to examine the residual and long-term effects of a single WBV session on spasticity and motor function in children with CP.

Another limitation was that only one frequency (20Hz) and one intervention duration (90 seconds * 6 bouts) were tested. It is possible that a change in these two parameters would have an impact on neuromuscular response to WBV. Further research is warranted to examine the effect of different WBV frequencies on spasticity and motor function in children with CP. However, from this pilot study we deem that a substantial longer duration for a single-session WBV intervention may probably increase the chance of muscle fatigue and reduce the tolerance in children with CP. Even though our participants have varying body masses, all the participants received the same magnitudes of vertical accelerations from the WBV platform. Although vertical force transmitted to the participant was different, it was proportional to the participant's body mass. Therefore, we postulate that body size is not a factor for different neuromuscular responses.

Although the benefit of a single session of WBV seems to be transient, our findings suggest that it has the potential to temporarily reduce spasticity and improve motor function in children with CP. Future studies are warranted to explore the long-term effects of a single-session and weeks-long WBV intervention with different frequencies and amplitudes. Additionally, our results suggest that WBV can be an effective modality for children with spastic CP with different levels of sensorimotor dysfunctions. Physical therapists may use WBV at the beginning of the rehabilitation session to help reduce the spasticity of leg muscles and potentially maximize the training outcomes of other therapeutic activities such as treadmill walking.

Acknowledgements

The authors are thankful to all the participants and their families for their participation in this study. This study was supported in part by the College of Education and Human Development Dissertation Support Grant at Georgia State University.

References

1. CDC. Data & Statistics for Cerebral Palsy. https://www.cdc.gov/ncbddd/cp/data.html. Published 2018. Accessed September 10, 2018.
2. Novacheck TF, Gage JR. Orthopedic management of spasticity in cerebral palsy. *Childs Nerv Syst.* 2007;23(9):1015-1031.
3. Lance JW, Burke D. Mechanisms of spasticity. *Arch Phys Med Rehabil.* 1974;55(8):332-337.
4. Pandyan AD, Gregoric M, Barnes MP, et al. Spasticity: clinical perceptions, neurological realities and meaningful measurement. *Disabil Rehabil.* 2005;27(1-2):2-6.
5. Donker SF, Ledebt A, Roerdink M, Savelsbergh GJ, Beek PJ. Children with cerebral palsy exhibit greater and more regular postural sway than typically developing children. *Exp Brain Res.* 2008;184(3):363-370.
6. El-Shamy SM. Effect of whole-body vibration on muscle strength and balance in diplegic cerebral palsy: a randomized controlled trial. *Am J Phys Med Rehabil.* 2014;93(2):114-121.
7. Bell KJ, Ounpuu S, DeLuca PA, Romness MJ. Natural progression of gait in children with cerebral palsy. *J Pediatr Orthop.* 2002;22(5):677-682.
8. Skrotzky K. Gait analysis in cerebral palsied and nonhandicapped children. *Arch Phys Med Rehabil.* 1983;64(7):291-295.
9. Pin T, Dyke P, Chan M. The effectiveness of passive stretching in children with cerebral palsy. *Dev Med Child Neurol.* 2006;48(10):855-862.
10. Cochrane DJ. The potential neural mechanisms of acute indirect vibration. *J Sports Sci Med.* 2011;10(1):19-30.

11. Ritzmann R, Krause A, Freyler K, Gollhofer A. Acute whole-body vibration increases reciprocal inhibition. *Hum Mov Sci.* 2018;60:191-201.

12. Gusso S, Munns CF, Colle P, et al. Effects of whole-body vibration training on physical function, bone and muscle mass in adolescents and young adults with cerebral palsy. *Sci Rep.* 2016;6:22518.

13. Lee BK, Chon SC. Effect of whole body vibration training on mobility in children with cerebral palsy: a randomized controlled experimenter-blinded study. *Clin Rehabil.* 2013;27(7):599-607.

14. Tupimai T, Peungsuwan P, Prasertnoo J, Yamauchi J. Effect of combining passive muscle stretching and whole body vibration on spasticity and physical performance of children and adolescents with cerebral palsy. *Journal of physical therapy science.* 2016;28(1):7-13.

15. Abercromby AF, Amonette WE, Layne CS, McFarlin BK, Hinman MR, Paloski WH. Variation in neuromuscular responses during acute whole-body vibration exercise. *Med Sci Sports Exerc.* 2007;39(9):1642-1650.

16. Rittweger J. Vibration as an exercise modality: how it may work, and what its potential might be. *Eur J Appl Physiol.* 2010;108(5):877-904.

17. Cheng HY, Ju YY, Chen CL, Chuang LL, Cheng CH. Effects of whole body vibration on spasticity and lower extremity function in children with cerebral palsy. *Hum Mov Sci.* 2015;39:65-72.

18. Park C, Park ES, Choi JY, Cho Y, Rha DW. Immediate Effect of a Single Session of Whole Body Vibration on Spasticity in Children With Cerebral Palsy. *Annals of rehabilitation medicine.* 2017;41(2):273-278.

19. Liang H, Beerse M, Ke X, Wu J. Effect of whole-body vibration on center-of-mass movement during standing in children and young adults. *Gait Posture.* 2017;54:148-153.

20. Pollock RD, Woledge RC, Mills KR, Martin FC, Newham DJ. Muscle activity and acceleration during whole body vibration: effect of frequency and amplitude. *Clin Biomech (Bristol, Avon).* 2010;25(8):840-846.

21. Hazell TJ, Jakobi JM, Kenno KA. The effects of whole-body vibration on upper- and lower-body EMG during static and dynamic contractions. *Appl Physiol Nutr Metab.* 2007;32(6):1156-1163.

22. Cochrane DJ, Stannard SR, Firth EC, Rittweger J. Acute whole-body vibration elicits post-activation potentiation. *Eur J Appl Physiol.* 2010;108(2):311-319.

23. Dickin DC, Heath JE. Additive effect of repeated bouts of individualized frequency whole body vibration on postural stability in young adults. *J Appl Biomech.* 2014;30(4):529-533.

24. Bohannon RW, Smith MB. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Physical therapy.* 1987;67(2):206-207.

25. Davis Iii RB, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. *Hum Mov Sci.* 1991;10(5):575-587.

26. Gutierrez-Farewik EM, Bartonek Å, Saraste H. Comparison and evaluation of two common methods to measure center of mass displacement in three dimensions during gait. *Hum Mov Sci.* 2006;25(2):238-256.

27. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol.* 2000;10(5):361-374.

28. Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng.* 1996;43(9):956-966.

29. Peng CK, Havlin S, Stanley HE, Goldberger AL. Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. *Chaos.* 1995;5(1):82-87.

30. Eke A, Herman P, Bassingthwaighte JB, et al. Physiological time series: distinguishing fractal noises from motions. *Pflugers Arch.* 2000;439(4):403-415.

31. Delignieres D, Deschamps T, Legros A, Caillou N. A methodological note on nonlinear time series analysis: is the open- and closed-loop model of Collins and De Luca (1993) a statistical artifact? *Journal of motor behavior.* 2003;35(1):86-97.

32. Zult T, Allsop J, Tabernero J, Pardhan S. A low-cost 2-D video system can accurately and reliably assess adaptive gait kinematics in healthy and low vision subjects. *Sci Rep.* 2019;9(1):18385.

33. Murray MP. Gait as a total pattern of movement. *Am J Phys Med.* 1967;46(1):290-333.

34. Beerse M, Henderson G, Liang H, Ajisafe T, Wu J. Variability of spatiotemporal gait parameters in children with and without Down syndrome during treadmill walking. *Gait Posture.* 2019;68:207-212.

35. Henderson G, Beerse M, Liang H, Ferreira D, Wu J. Improvement in Overground Walking After Treadmill-Based Gait Training in a Child With Agenesis of the Corpus Callosum. *Phys Ther.* 2019.

36. Wu J, Beerse M, Ajisafe T, Liang H. Walking Dynamics in Preadolescents with and without Down Syndrome. *Phys Ther.* 2015;95:740-749.

37. De Luca CJ. The Use of Surface Electromyography in Biomechanics. *J Appl Biomech.* 1997;13(2):135-163.

38. Mitschke C, Heß T, Milani T. Which Method Detects Foot Strike in Rearfoot and Forefoot Runners Accurately when Using an Inertial Measurement Unit? *Applied Sciences.* 2017;7(9):959.

39. Selles RW, Formanoy MA, Bussmann JB, Janssens PJ, Stam HJ. Automated estimation of initial and terminal contact timing using accelerometers; development and validation in transtibial amputees and controls. *IEEE Trans Neural Syst Rehabil Eng.* 2005;13(1):81-88.

40. Wakeling, Delaney, Dudkiewicz. A method for quantifying dynamic muscle dysfunction in children and young adults with cerebral palsy. *Gait Posture.* 2007;25(4):580-589.

41. Duarte M, Sternad D. Complexity of human postural control in young and older adults during prolonged standing. *Exp Brain Res.* 2008;191(3):265-276.

42. Rodda JM, Graham HK, Carson L, Galea MP, Wolfe R. Sagittal gait patterns in spastic diplegia. *J Bone Joint Surg Br.* 2004;86(2):251-258.

43. Krause A, Schonau E, Gollhofer A, et al. 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.* 2017;8:416.

44. Fox AS, Carty CP, Modenese L, Barber LA, Lichtwark GA. Simulating the effect of muscle weakness and contracture on neuromuscular control of normal gait in children. *Gait Posture.* 2018;61:169-175.

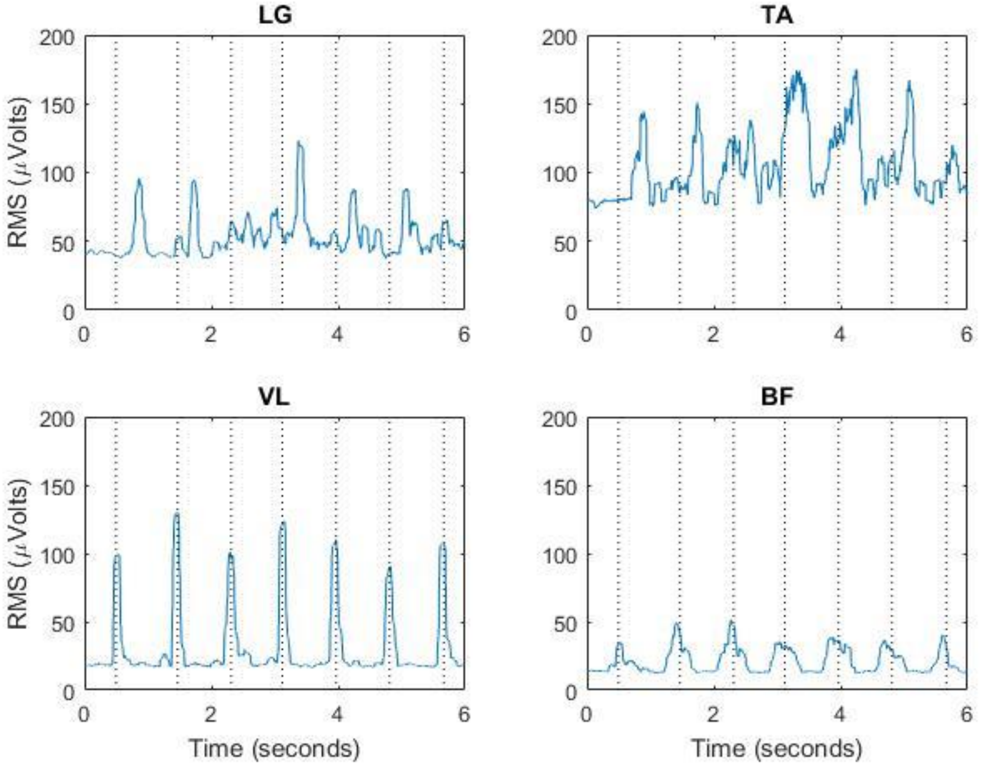
45. Kim CJ, Son SM. Comparison of Spatiotemporal Gait Parameters between Children with Normal Development and Children with Diplegic Cerebral Palsy. *Journal of physical therapy science.* 2014;26(9):1317-1319.

Figure captions

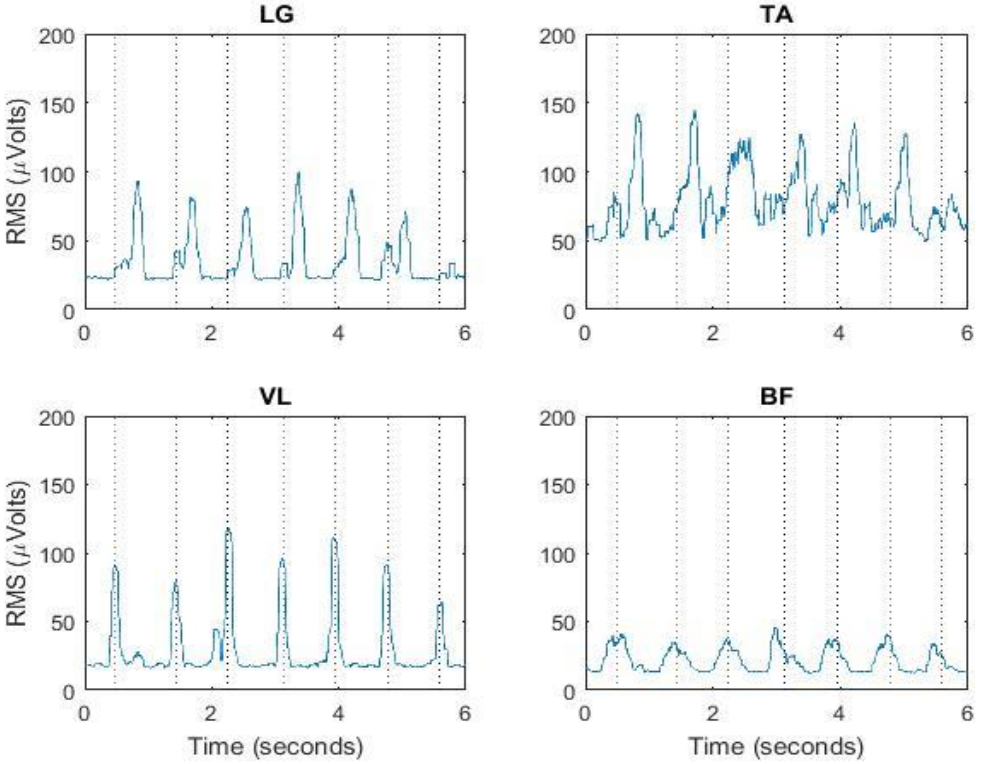
Figure 1: Representative plots of EMG RMS signals of the LG, TA, VL, and BF during an overground walking trial from one participant. (a) Before intervention (*Pre*), (b) after low-amplitude WBV (*LA-post*), and (c) after high-amplitude WBV (*HA-post*). The EMG signal was filtered and rectified before calculating RMS values. The dotted lines represent foot strikes and six full gait cycles are presented in each graph. Note that the values of LG and TA signals remained high throughout gait cycles, particularly in the *Pre* condition. Also note that the scale for BF in (c) is greater than the others. LG: lateral gastrocnemius; TA: tibialis anterior; VL: vastus lateralis; BF: bicep femoris.

Figure 1

(a)


LG
TA
VL
BF
RMS (μVolts)
Time (seconds)
0
50
100
150
200
0
2
4
6

(b)


LG
TA
VL
BF
RMS (μVolts)
Time (seconds)
0
50
100
150
200
0
2
4
6

(c)

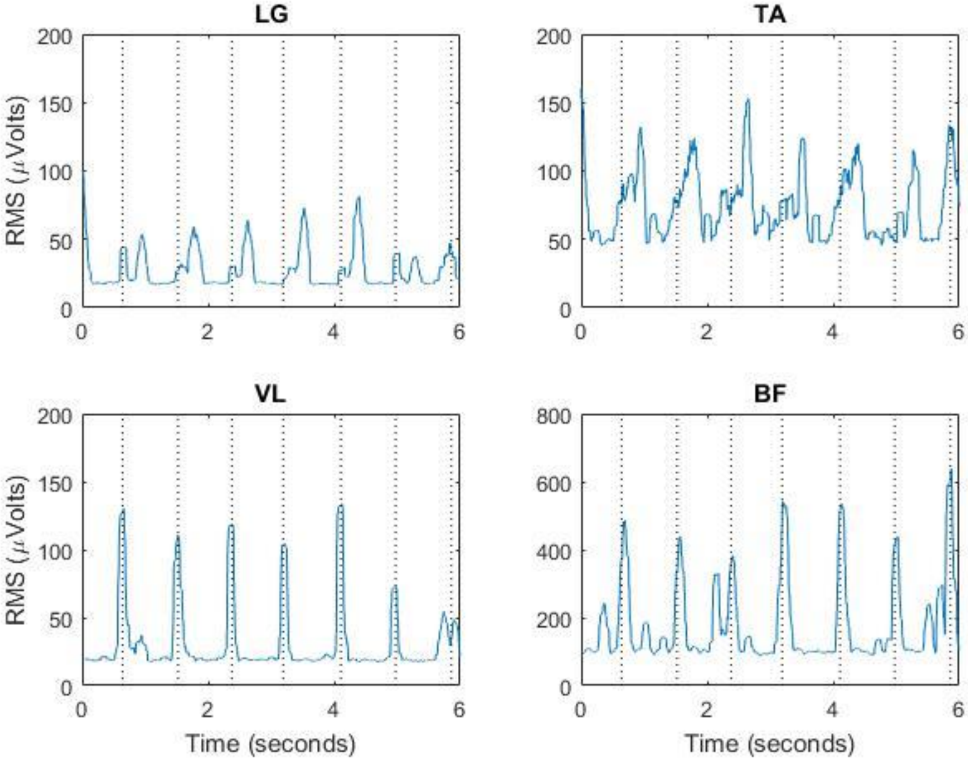

LG
TA
VL
BF
RMS (μVolts)
RMS (μVolts)
200
150
100
50
0
800
600
400
200
0
0
2
4
6
Time (seconds)
Time (seconds)

Table 1. Physical characteristics of the participants

ID	Diagnosis	GMFCS	Gender	Age (yrs)	Height (cm)	Mass (kg)
CP01	Diplegia	II	M	15	167	67.1
CP02	Diplegia	I	F	10	144	41
CP03	Diplegia	II	M	8	118	23.2
CP04	Diplegia	I	M	10	140.5	25.6
CP05	Left hemiplegia	I	M	10	144	26.2
CP06	Diplegia	I	F	17	151	45.9
CP07	Diplegia	III	M	7	107.5	21.7
CP08	Left hemiplegia	II	M	10	129	26.4
CP09	Left hemiplegia	I	M	7	114	25.3
CP10	Diplegia	I	F	7	123.5	26.1
	Mean (SD)			10.1 (3.4)	133.9 (18.6)	32.9 (14.4)

Table 2. Mean (SD) ratings of the modified Ashworth scale

Muscle groups	N	Pre	LA-Post	HA-Post
Ankle plantarflexors with the knee extended	7	1.71 (0.39)	1.14 (0.80)	0.79 (0.81)
Ankle plantarflexors with the knee flexed	7	1.57 (0.45)	0.79 (0.76)	0.93 (0.67)
Knee extensors	4	1.38 (0.48)	0.88 (0.63)	1.00 (0.00)
Knee flexors	3	1.67 (0.58)	0.33 (0.58)	1.33 (0.58)

N: number of participants who showed spasticity before WBV, defined as modified Ashworth scale scores greater than zero. Note that not every participant had spasticity in every muscle group measured in this study. Pre: pre-WBV; LA-Post: post-low amplitude (LA) WBV; HA-post: post-high amplitude (HA) WBV. Note that none of the participants in this study increased spasticity as measured by the modified Ashworth scales after either WBV session.

Table 3. Mean (SD) of the time-domain center of pressure (COP) variables during quiet standing.

Condition	RMS-AP (mm^2)	RMS-ML (mm^2)	Velocity-AP (mm/s)	Velocity-ML (mm/s)	DFA-AP	DFA-ML
Pre	10.9 (6.1)	10.1 (5.2)	19.8 (9.5)	17.7 (9.8)	1.33 (0.10)	1.35 (0.11)
LA-Post	11.9 (6.4)	11.4 (6.1)	16.6 (8.5)	16.6 (10.0)	1.46 (0.10)*	1.43 (0.11)
HA-Post	10.9 (5.4)	12.6 (7.7)	15.9 (8.5)	17.7 (9.5)	1.46 (0.13)*	1.35 (0.11)

Pre: pre-WBV; LA-Post: post-low amplitude (LA) WBV; HA-post: post-high amplitude (HA) WBV. RMS: root mean square; DFA: detrended fluctuation analysis; AP: anterior-posterior; ML: medial-lateral. A symbol * denotes a significant difference from the Pre condition at a significant level of $\alpha=0.05$.

Table 4. Mean (SD) of spatiotemporal gait parameters and joints kinematic variables during overground walking

Condition	Stride length (m)	Stride velocity (m/s)	Double support percentage (% of gait cycle)	Ankle ROM (deg)	Knee ROM (deg)
Pre	0.81 (0.31)	0.83 (0.38)	30.5 (12.6)	23.6 (8.2)	47.0 (10.3)
LA-Post	0.80 (0.31)	0.91 (0.40)	29.5 (12.2)	26.8 (9.4)	46.9 (11.4)
HA-Post	0.84 (0.28)	0.88 (0.38)	28.8 (10.7)	30.6 (8.3)*	50.9 (9.5)

ROM: range-of-motion; Pre: pre-WBV; LA-Post: post-low amplitude (LA) WBV; HA-post: post-high amplitude (HA) WBV. A symbol * denotes a significant difference from the Pre condition at a significance level of α=0.05.

Table 5. Mean (SD) of the EMG integrated area during overground walking.

Condition	LG (μV·s)	TA (μV·s)	VL (μV·s)	BF (μV·s)
Pre	52.5 (28.9)	64.6 (26.6)	35.6 (24.1)	27.0 (11.4)
LA-Post	49.8 (23.8)	55.9 (24.1)*	34.8 (24.7)	26.0 (11.4)
HA-Post	49.5 (25.5)	53.8 (17.9)*	40.0 (21.3)	19.8 (3.9)

Pre: pre-WBV; LA-Post: post-low amplitude (LA) WBV; HA-post: post-high amplitude (HA) WBV. LG: lateral gastrocnemius; TA: tibialis anterior; VL: vastus lateralis; BF: bicep femoris. A symbol * denotes a significant difference from the Pre condition at a significance level of α=0.05.

Conflicts of Interest Statement

There were no conflicts of interest when completing this study.

Author contribution

Huaqing Liang contributed to Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Software; Validation; Visualization; Original draft writing; Review and editing.

Gena Henderson contributed to Data curation; Investigation; Methodology; Original draft writing; Review and editing.

Jianhua Wu contributed to Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Original draft writing; Review and editing.

supplemental materials