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Effects of Plantar Vibratory Stimulation on Posture Control in Children with Cerebral Palsy

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Abstract

Introduction: Cerebral palsy is characterized by a group of posture and movement disorder which can be aggravated. Children with cerebral palsy are lacking plantar cutaneous afferent which provides information to control upright posture. A new approach to induce postural response by plantar vibratory stimulation was suggested for children with cerebral palsy.

Methods: Seven children with cerebral palsy, five boys and two girls, aged 11.41 (1.97) years with diagnoses of spastic diplegia, participated in this study. The participants stood barefooted, with their vision and auditory perception blocked, on the standing frame placed on the force plate. Twelve vibration conditions under three frequencies (20, 60 and 100 Hz) and four locations (left forefoot, right forefoot, left rear foot and right rear foot) were tested for every participant. Center of pressure coordinates were collected at a sampling rate of 200 Hz for a period of 44s.

Results: The height of standing frame had negligible effect on the center of pressure. The postural adjustments were significantly direction-specific when the vibration was applied on different plantar surfaces. Vibration on the rear foot resulted in a forward body tilt while the vibration on the forefoot resulted in a backward body tilt. The postural response was oriented to the right when the left foot was vibrated and to the left when the right foot was vibrated. There were significant differences across frequencies of stimulation on every location (P<0.001).

Conclusion: Plantar vibratory stimulation can produce direction-specific body tilts in children with cerebral palsy. Applying appropriate vibration stimulation on plantar surface is suggested to be a new rehabilitation training method for cerebral palsy rehabilitation to promote balance and posture control.

Keywords: Cerebral palsy; Plantar vibration; Center of pressure; Postural response

Abbreviation: CP: Cerebral Palsy; WBV: Whole Body Vibration; CoP: Center of Pressure; GMFCS: Gross Motor Function Classification System; AP: Anterior-Posterior; ML: Medial-Lateral; LFF: Left Forefoot; RFF: Right Forefoot; LRF: Left Rear foot; RRF: Right Rearfoot

Introduction

Cerebral palsy (CP) is the most common cause of severe physical disability in childhood [1], characterized by a group of posture and movement disorder which can be aggravated. CP prevalence was 1.8-6 per 1000 live births in China [2]. The prevalence of CP was 1.98–2.25 per 1000 live births in the world, and has remained constant in recent years [3].

It has been an important aspect to promote the postural control and motor skills of cerebral palsy. With the application of vibration stimulation in clinical practice, the positive effects of vibration stimulation or training on people with CP were reported. Researchers found either a short-term whole body vibration (WBV) for a few minutes [4,5] or a long-term WBV for a few weeks [6-13] could significantly increase the gross motor function, joint range of motion, gait speed, stride length, build strength, and decrease spasticity. However there were some differences in the selection of vibration frequency, amplitude, intensity, and time among these studies. To a certain extent, these factors limit the application of WBV in the rehabilitation of cerebral palsy.

That plantar sole vibration induced the directionally specific body tilts in healthy people has been confirmed [14-17]. Plantar vibration of different locations resulted in different directions of body leaning, which oriented in the direction opposite to the vibrated site (e.g. vibration of the heel resulted in a forward body tilt). However, Thompson [17] reported that the application of forefoot vibration alone did not produce the expected backward whole-body leaning. The author thought the vibration frequency used in the experiment might have stimulated more the toes and intrinsic foot muscle receptors than the plantar cutaneous receptors, thus not provoking any postural reactions. Kavounoudias [14] thought vibration-induced body sways were frequency dependent and the amplitude of the postural responses increased with the vibration frequency.

Multisensory (such as vestibular, visual or muscular sensory) inputs are involved in the organization and control of human upright posture. Cutaneous afferent information plays an important role in controlling balance because the human skin has developed sensory structures (mechanoreceptors) that are responsible for different modalities of mechanosensitivity like touch, vibration, and pressure sensation [18]. Cutaneous receptors from the plantar soles are sensitive to vibration and are believed to represent a "pressure distribution map" [14]. Vibration of particular regions of the plantar soles would simulate

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an increased pressure under that area, compensated by leaning in the direction opposite to the stimulated site. Plantar cutaneous afferents provide information which is likely processed by the CNS to control upright balance and posture. Specific postural adjustment of vibration-induced can be applied in balance control training.

The postural responses under different plantar vibration conditions (amplitude, frequency and area) have been proved in normal subjects. However, the effects of vibration on patients with neurological disease (e.g. cerebral palsy) have not been well documented.

The present study was designed to investigate whether plantar cutaneous afferents contribute to balance control for children with CP. It was hypothesized that specific body tilts occur when plantar vibratory stimulation is applied to the foot sole of children with CP. It was hoped that the finds of this study would assist the selection of a new rehabilitation method to improve the postural control of children with CP.

Materials and Method

Participants

Seven children with CP, five boys and two girls, aged 11.41 (1.97) years with diagnoses of spastic diplegia, were recruited from a local rehabilitation center. The criteria for inclusion in this study were either level Ⅰ (N=4) or level Ⅱ (N=3) in the Gross Motor Function Classification System (GMFCS) [19]. Participants had the ability to independently walk without assistive mobility devices and the ability to respond commands. No participants had undergone lower extremity surgery in the past one year, and nerve block or botulinum toxin injection within the past 6 months. The Institutional Review Board for Human Studies of Beijing College of Social Administration approved this protocol. Written informed consents were obtained from all seven participants and their legal guardians.

Equipment

Figure 1 illustrates the essential features of equipment and apparatus which were constructed in the Biomechanics Laboratory at the Department of Orthopaedics and Rehabilitation in the Beijing College of Social administration.

The equipment utilized in this study included vibration exciter type 4808 (Brüel & Kjær, Nærum, Denmark), force plate type BP400600 (Advanced Mechanical Technology, Inc., Watertown, USA), function/arbitrary waveform generator type DG1032Z (Beijing RIGOL Technology Co., Ltd., China), and Laser range finder type ZLDS102-50-25-RS485-I-IN-AL-CG-4(ZSY Group Ltd, London, UK). The vibratory stimulation was delivered through brass probes, their location shown in Figure 2, that were driven vertically into the plantar surface by the power magnetic vibration exciter (Type 4808). The peak to peak amplitude (0-1 mm in this study) of the vibratory stimulation was controlled by the power amplifier type 2719 (Brüel & Kjær, Nærum, Denmark) and was measured by the laser range sensor, accurate to 25 μm, to display on the screen in real-time. Different frequencies of the vibratory stimulation were provided by the signal generator.

Protocol

All participants were assessed in the Biomechanics Laboratory. The feet outlines, the positions of the heel, the first and fifth metatarsal heads were marked to determine the locations of vibrating probes.

During testing, the participants stood barefoot on the standing frame with the center of heels apart at 10 cm width, with their eyes

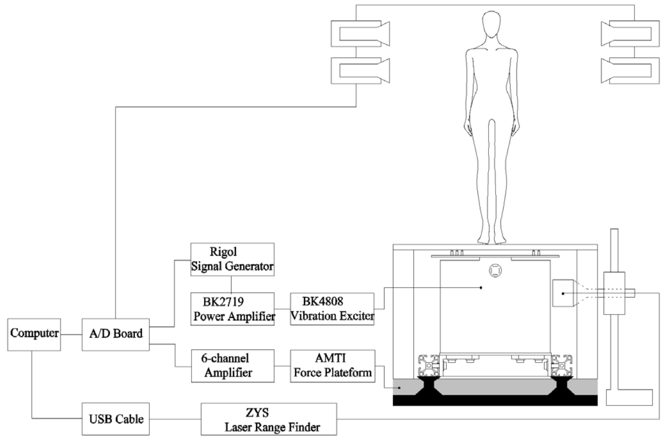

Figure 1: Schematic diagram of test system for plantar vibration.

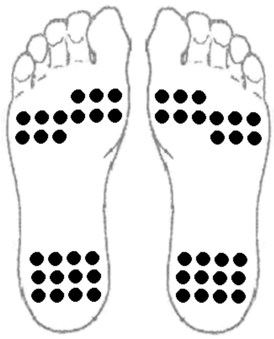

Figure 2: Locations of probes indenting the rearfoot and/or forefoot.

and ears blocked to eliminate the visual and vestibular inputs [20], as shown in Figure 3. The participants were asked to keep upright posture naturally, not to resist vibration-induced postural reaction. Protection is necessary when the participant had intent to fall [14].

Twelve vibration conditions under three frequencies (20, 60 and 100 Hz) and four locations [left forefoot (LFF), right forefoot (RFF), left rear foot (LRF) and right rear foot (RRF)] were tested in this study. In each condition, the center of pressure (CoP) coordinates were obtained in 44s at a sampling rate of 200 Hz. Firstly, no vibration was applied for the first 4s, and then five cycles were recorded continuously in every condition. In each cycle, the vibration lasted for 3s then no vibration for 5s. The participants were instructed to rest for 3 minutes between every three conditions. It took about 20 minutes to finish the total protocol for one child.

The selection of every condition was randomized by the experimenter. An external trigger was applied to synchronously trigger the exciter and the data acquisition software (Qualisys Track Manager, QTM).

Data analysis

In this experiment, the subjects faced the positive direction of Y axis with the positive direction of X axis on the left in a Cartesian coordinate system.

The raw experimental data obtained were processed by the two order curve fitting and filtering (Figure 4). Subsequently, the value of CoP under every trial condition was zeroed to the average position in the anterior-posterior (AP) plane and in the medial-lateral (ML) plane for the first 4s. In this study, all the data of CoP across 50ms of the largest deviation of CoP

Figure 3: The actual testing picture of participant.

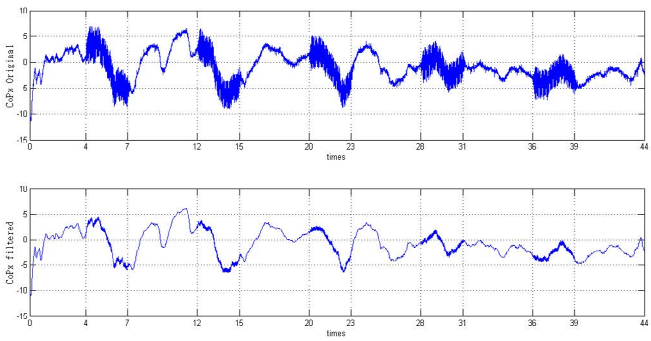

Figure 4: A representative CoP trajectory of one vibration condition from one participant (0-4s without vibration, 4-7s, 12-15s, 20-23s, 28-31s, 36-39s with vibration, 7-12s, 15-20s, 23-28s, 31-36s, 39-44s without vibration). (Top) raw CoP trace. (Bottom) CoP trace after filtering and fitting.

were averaged as the peak excursion (maximum or minimum) used as an index of postural control. The peak response amplitude was either positive or negative while stimulating the plantar skin.

The point of foot sole contact was raised 253 mm above the surface of the force plate in virtue of the standing frame. To verify the effect of the height of standing frame on the value of CoP, we compared the experiment value of CoP (CoPx and CoPy) output from the data acquisition software named QTM with the theoretical value of CoP (CoPtx and CoPty) obtained upon a corrected equation(shown below). Besides the CoPx and CoPy, forces (Fx, Fy and Fz) and moments (Mx, My and Mz) were recorded by the AMTI force plate and output by the QTM software in the x, y and z planes.

$$CoPty = ((Mx)-(0.253^{*}Fy))/Fz, \quad CoPtx = ((0.253^{*}Fx)-(My))/Fz$$

IBM SPSS version 22.0 statistical software was used in this study. The relationship between experimental value and theoretical value of CoP was examined by correlation analysis. Descriptive statistics were used to calculate participants' demographics. The influence of different frequencies and sites of vibration on the amplitude of the postural sway was tested using a two-way repeated measure ANOVA (3 frequency × 2 site). The alpha level was set at 0.05.

Results

1) The effect of the height of standing frame on the value of CoP:

Twelve frames of experimental data randomly selected from one subject were compared to find that the experimental values and theoretical ones of CoP were significant linear correlation (Pearson correlation coefficient of CoP was respectively 0.997, 0.996 in X, Y direction), as Table 1 shows.

In this experimental study, the maximum error rate of CoP value due to the height of standing frame was not more than 5%. The height of standing frame had negligible effect on CoP, and the sway of subjects standing on the standing frame could be described by the experimental value output from the QTM software.

2) Effects of plantar vibration stimulation on postural response for children with CP:

A significant effect was found for site of stimulation on the direction of CoP excursion (Figure 5). The mean value of CoP was negative when the left foot was vibrated, which meant the postural responses were oriented to the right, and the mean value of CoP was positive when the right foot was stimulated, which meant the body tilted the left. Likewise, the postural responses were directed backwards owing to the negative value of CoP when stimulating the anterior part of plantar sole, and forwards due to the positive value of CoP when vibrating on the rear foot.

The largest CoP excursion (-9.53 ± 0.14 mm) occurred on the location of LRF at 20 Hz and the smallest one (-0.99 ± 0.39 mm) on the LFF at 20 Hz in the ML direction, as shown in Table 2. The highest postural response (14.19 ± 0.10 mm) occurred on the LRF at 100 Hz and the smallest one (1.36 ± 0.22 mm) on the RRF at 60 Hz in the AP direction, as shown in Table 3. Interestingly, the absolute

Data number	CoPx (mm)	CoPtx (mm)	CoPy (mm)	CoPty (mm)	Error rate of CoPx (%)	Error rate of CoPy (%)
1	-44.42	-43.93	57.05	59.23	1.12	3.68
2	-34.18	-33.67	57.94	58.73	1.52	1.34
3	-39.88	-38.81	65.52	66.65	2.75	1.70
4	-32.24	-30.84	56.11	56.51	4.55	0.70
5	-38.16	-36.90	55.78	57.15	3.42	2.39
6	-33.38	-32.01	54.89	55.43	4.28	0.97
7	-37.32	-36.28	48.44	50.09	2.85	3.29
8	-35.61	-34.30	53.71	54.56	3.82	1.56
9	-35.07	-33.79	53.31	54.39	3.78	1.99
10	-37.94	-36.65	49.93	50.84	3.51	1.78
11	-38.43	-37.34	46.57	47.91	2.93	2.79
12	-38.53	-37.49	46.82	48.39	2.77	3.24
Mean value	-37.097	-36.001	53.839	54.988	3.108	2.12

Note: Error rate of CoPx was $\left|\frac{CoPx-CoPtx}{CoPtx}\right|\times 100$, Error rate of CoPy was $\left|\frac{CoPy-CoPty}{CoPty}\right|\times 100$

Table 1: Comparison between experimental value and theoretical value of CoP.

Frequency Position	LFF (mm)	RFF (mm)	LRF (mm)	RRF (mm)
20	-0.99 ± 0.39	4.70 ± 0.21	-9.53 ± 0.14	7.87 ± 0.07
60	-8.45 ± 0.07	8.02 ± 0.20	-6.14 ± 0.16	6.46 ± 0.21
100	-4.27 ± 0.03	8.84 ± 0.05	-3.47 ± 0.14	2.75 ± 0.16

Table 2: CoP response amplitudes in the ML direction (mean ± SD).

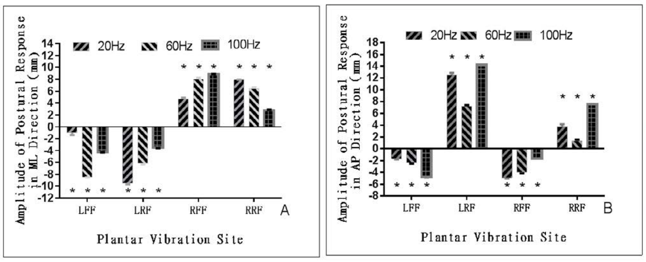

Figure 5: CoP displacements induced by separate stimulation of four different sites at 20, 60 and 100 Hz. (A) All subjects' mean peak-peak ML CoP amplitude. (B) All subjects' mean peak-peak AP CoP amplitude. All data are mean ± SEM. *P<0.001.

Frequency Position	LFF (mm)	RFF (mm)	LRF (mm)	RRF (mm)
20 Hz	-1.72 ± 0.07	-4.86 ± 0.19	12.49 ± 0.38	3.73 ± 0.41
60 Hz	-2.41 ± 0.10	-3.99 ± 0.17	7.23 ± 0.17	1.36 ± 0.22
100 Hz	-4.81 ± 0.07	-1.67 ± 0.01	14.19 ± 0.10	7.54 ± 0.06

Table 3: CoP response amplitudes in the AP direction (mean ± SD).

CoP excursion increased with the increase of the frequency in the ML direction and declined with the increase of the frequency in the AP direction when the RFF was stimulating.

Discussion

The oriented postural responses of children with CP were observed when vibratory stimulation was applied to the plantar skin in this study. Vibration of the left plantar sole induced a rightward body tilt while vibration of the right plantar sole induced a leftward body tilt (Figure 5A). Vibration of the rear of the plantar sole induced a forward body tilt while vibration of the fore of the plantar sole induced a backward body tilt (Figure 5B). This reaction was in accord with the result from Kavounoudias [14,15] who considered the foot sole as a 'dynamometric map' equipped with numerous sensors able to spatially code every pressure exerted against the sole.

Kavounoudias found rear foot stimulation evoked larger amplitude responses than did forefoot stimulation. Christopher [21] found also the similar results from their research. Vibration on the LRF produced larger amplitude responses than did LFF stimulation in our study; however this result didn't occur in the right foot. The reason possibly was the plantar condition of right foot was different from the left foot, because there were more abnormal status (inversion, little heel-off) in the right foot for most of participates with CP.

There were significant differences between the amplitudes of postural adjustments across frequencies of stimulation at each site (P<0.001). This result was consistent with that reported by Kavounoudias [14,15]. However the amplitudes of postural response were not proportional to the frequencies of vibration.

Our results provide new evidence about the benefits of vibration stimulation in CP individuals. The stimulating of vibration on the plantar skin could allow the CNS to constantly extract body position information and trigger appropriate responses to reduce the gap between the body position and the equilibrium position. The specific postural response of vibration-induced can be applied as a rehabilitation method for children with CP to train them to keep balance.

However, a few samples with CP and a few indicators of posture control were taken into account in the present study. In addition, it is not clear whether the immediate postural adjustment could help to improve postural control in the long term. We will make further efforts to optimize the whole experimental process, including increasing larger sample sizes, making the acquisition of electromyogram (EMG) and electroencephalography (EEG), and stimulating more locations.

Conclusion

This study confirmed that plantar vibratory stimulation can produce direction-specific body tilts in children with CP. This clearly demonstrated that cutaneous afferent could contribute to balance control for children with CP. Applying appropriate vibration stimulation on plantar surface to induce specific body tilts is proposed as a new rehabilitation training method for CP to improve postural control. The study addressing these issues can be a promising field for further research on postural control for children with CP.

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