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Site-specific transmission of a floor-based, high-frequency, low-magnitude vibration stimulus in children with spastic cerebral palsy

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Abstract

Objective—To determine the degree to which a high-frequency, low-magnitude vibration (HLV) signal emitted by a floor-based platform transmits to the distal tibia and distal femur of children with spastic cerebral palsy (CP) during standing.

Design—Cross-sectional study

Setting—University research laboratory

Participants—4 to 12 year-old children with spastic CP who could stand independently (n=18) and typically developing children (n=10) participated in the study.

Intervention—Not applicable

Main outcome measures—The vibration signal at the HLV platform (~33 *Hz* and 0.3 *g*), distal tibia and distal femur was measured using accelerometers. Degree of plantar flexor spasticity was assessed using the Modified Ashworth Scale.

Results—The HLV signal was greater ($p<0.001$) at the distal tibia than at the platform in children with CP (0.36±0.06 vs. 0.29±0.05 *g*) and controls (0.40 ± 0.09 vs. 0.24 ± 0.07 *g*). Although the HLV signal was also higher at the distal femur (0.35±0.09 *g*, $p<0.001$) than at the

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platform in controls, it was lower in children with CP (0.20±0.07 *g*, $p<0.001$). The degree of spasticity was negatively related to the HLV signal transmitted to the distal tibia ($r_s=-0.547$) and distal femur ($r_s=-0.566$) in children with CP (both $p<0.05$).

Conclusions—An HLV signal from a floor-based platform was amplified at the distal tibia, attenuated at the distal femur and inversely related to the degree of muscle spasticity in children with spastic CP. Whether this transmission pattern affects the adaptation of their bones to HLV requires further investigation.

Keywords

cerebral palsy; muscle spasticity; vibration; bone

Introduction

Children with physical disabilities such as cerebral palsy (CP) have reduced muscle[1] and bone[2, 3] mass and quality, especially in the lower extremities. This musculoskeletal deficiency in children with CP is associated with less force generating capacity of the muscles[4] and a higher incidence of low-energy fractures in the lower extremities.[5] Because children with CP have difficulty participating in physical activities[6] leading to reduced mechanical loading on their skeletal system, identifying alternate nonpharmacologic treatments is of interest.[7]

Studies have shown that a floor based, high-frequency, low-magnitude vibration (HLV) signal has an anabolic effect on bone in various populations[8, 9] including children with CP.[10, 11] There are also studies showing no effect of HLV on bone[12, 13] or an inconsistent effect across sites.[14, 15] It is plausible that the effectiveness of HLV is dictated by the degree to which the HLV signal is transmitted to a particular bone site, similar to the site-specific effects of exercise.[16] The tibia and femur are of interest in children with CP because they are the most commonly fractured bones and the distal femur is the most commonly fractured site.[5] Unfortunately, the transmission of HLV to key bone sites in children with CP has not been studied.

The primary aim of this study was to determine the degree to which an HLV signal emitted by a floor-based platform transmits to the distal tibia and distal femur of children with spastic CP during standing. An amplification of vibration at the ankle and an attenuation at the knee has been observed in typically developing children.[17] Whether a similar profile is exhibited in children with spastic CP is unknown. Toe-standing, which is common in children with spastic CP, has been shown to attenuate vibration at the ankle and the knee.[18] Therefore, we hypothesized that the HLV transmission would be lower in children with spastic CP than typically developing children. We also hypothesized that there would be an inverse relationship between the degree of spasticity and HLV transmission in children with CP.

Methods

Participants

Children with spastic CP, 4–12 years of age, at the level of I to III using the Gross Motor Function Classification System (GMFCS) were recruited from the AI duPont Hospital for Children, Wilmington, DE. Children were excluded if they were unable to stand independently, if they had any metal rods in their thigh or leg, or if they had a surgery involving the musculoskeletal system or any anti-spastic medication, such as botulinum toxin, within the past year. Eighteen children with CP were tested. Eight of the children had one of more previous surgeries which include: adductor lengthening (n=1), adductor tenotomy (n=1), adductor release (n=1), hamstring lengthening (n=6), tendoachilles lengthening (n=1), gastrocnemius recession/lengthening (n=4) and botulinum toxin (n=8). Thirteen of the children had equinus deformity and walked on their toes. Five of the children were taking antiepileptic medication. Typically developing children (n=10) in the same age range as the children with CP, between the 5^{th} and 95^{th} percentiles for height and body mass and without a history of chronic medication use were recruited from the Newark, DE community to serve as controls. This study was approved by the AI duPont Hospital for Children and the University of Delaware Institutional Review Boards. Participants and their parents gave written assent and consent, respectively, before testing.

Study Design and Procedures

A within-subject and between-group comparison design was used. Anthropometrics, pubertal development, degree of spasticity, gross motor function, and vibration transmission were assessed during a single visit at the University of Delaware.

Anthropometrics

Height and body mass were measured while the children were wearing minimal clothing and were without shoes or braces. Height was measured to the nearest 0.1 cm using a stadiometer (Seca 217).[a] Body mass was measured to the nearest 0.1 kg using a weighing scale (Detecto D1130).[b]

Tanner Staging

Tanner staging was conducted by a physician assistant to assess sexual maturity of each participant. The Tanner stage rating scale ranges from I to V, with I indicating no sign of sexual maturity and V indicating full sexual maturity.[19, 20]

Modified Ashworth Scale (MAS)

Ankle plantar flexor tightness was assessed in children with CP while the participant was lying on a table in a supine position using the MAS. The grading system ranges from 0 to 4, with 0 indicating presence of normal tone and 4 indicating muscle rigidity in flexion/extension.[21] The grade for each limb was based on an average grade of three trials. The

[a]**Suppliers**
Seca Medical Measuring Systems and Scales, Hammer Steindamm 9 – 25, Hamburg, Germany 22089
[b]Detecto, 203 East Daugherty Ave, Webb City, MO 64870

reliability of spasticity assessment of the plantar flexors using the MAS was determined by evaluating 12 children with CP (4–11 years) on two different days one month apart. A Cohen's Kappa=0.71 (p<0.001) indicates good reliability.

GMFCS

Gross motor function was assessed using the GMFCS, which ranges from I to V. Only those children who were GMFCS level I (walks without restrictions), II (walks without assistive device; limitations walking outdoors and in the community) or III (walks with assistive mobility device; limitations walking outdoors and in the community)[22] participated in our study. The reliability of GMFCS was determined by evaluating 12 children with CP (4–11 years) on two different days one month apart. A Cohen's Kappa=0.74 (p<0.001) indicates good reliability.

Vibration Transmission

Participants stood on an HLV platform (Juvent 1000 Motion Therapy System)[c] for three consecutive conditions (pre-HLV, HLV and post-HLV) of 30 seconds per condition. The HLV platform delivered a sinusoidal vertical vibration signal of approximately 0.3 *g* at a frequency of 30–37 *Hz*. No HLV was transmitted during the pre-HLV and post-HLV conditions, which were immediately before and immediately after the HLV condition, respectively. The platform was divided into right and left halves and the center of each foot was placed in the center of the respective half. The participants stood on the platform without shoes, socks or braces. They were instructed to stand on the platform as still as possible in a relaxed positon and were encouraged to stand without support. Although all children were able to stand without assistance, poor balance is an issue associated with CP which can be exacerbated by antiepileptic medications.[23] Therefore, as a precaution, a standard wooden chair was placed in front of the HLV platform to allow intermittent support, if needed, and a spotter stood on each side of the participant to prevent falls. Only data collected during independent standing was used for the analysis. The same HLV platform was used for all participants.

To quantify the amount of vibration emitted by the HLV platform, a uniaxial accelerometer (model 3711B1110G)[d] was secured to the center of the platform using double-sided tape, as per recommendations by Rauch et al.,[24] and further secured with single-sided tape over the top of the accelerometer. To quantify the transmission of HLV signal to the distal tibia and the distal femur, triaxial accelerometers (model 3713B1113G),[d] were secured to the skin immediately above the medial malleolus of the distal tibia and at the lateral condyle of the distal femur to the limit of the participant's comfort using a self-adhesive elastic bandage. The placement of all accelerometers was done by a single research assistant for all participants. All accelerometers were calibrated prior to each data collection session. The same accelerometers were used at the same sites for all participants. The data collection setup is displayed in Figure 1.

[c]Juvent Inc, 2000 Avenue P, Ste 14, Riviera Beach, FL 33404
[d]PCB Piezotronics, 3425 Walden Avenue, Depew, NY 14043

A 12-bit AD converter data acquisition device (model USB-1208FS)[e] was used to collect the vibration data at a sampling frequency of 2 *kHz* using DASYLab® (version 11.0).[e] Spike 2 (version 7.10)[f] was used to analyze the data after it was filtered using custom MATLAB[g] coding. Peak-to-peak voltage values (mV) were converted to *g* force per the sensitivity for each respective axis. The resultant *g* was calculated for the triaxial accelerometers at the distal tibia and the distal femur using the following equation: $R = \sqrt{(V_g^2 + ML_g^2 + AP_g^2)}$ with V_g, ML_g, AP_g representing *g* forces in the vertical, mediolateral, and anteroposterior directions. A 5 second period within each 30 second condition (pre-HLV, HLV and post-HLV) was chosen to calculate amplitude and frequency of HLV signals. HLV transmission was defined as the difference in HLV signals at the platform vs. the distal tibia and the distal femur.

The reliability of acceleration measurement at the platform, distal tibia and distal femur was determined by assessing 6 children with CP and 9 typically developing children (4–11 years) on two different days one month apart. Intraclass correlations = 0.89, 0.91 and 0.95, respectively, in the combined sample (all $p<0.05$) indicate excellent reliability.

Statistical analysis

Data were analyzed using SPSS (version 22.0).[i] Data were assessed for normality using skewness, kurtosis, and the Shapiro-Wilk test. Group differences in physical characteristics were assessed using independent t-tests. The Chi-square test of independence was used to determine if there group differences in Tanner stage. Paired t-tests were used to determine if pre-HLV and post-HLV signals were different. If they were not different, the pre-HLV condition was used for comparison to the HLV condition. A two-way ANOVA (group × site) with repeated measures on site was used to determine if there were group differences and an interaction effect in HLV transmission at the platform, distal tibia, and distal femur. If a group-by-site interaction was detected, simple contrasts were used to identify specific differences. A Bonferroni adjustment was made for multiple comparisons. Spearman correlation (r_s) analysis was used to determine if there were relationships between MAS and the HLV signal transmission. Values are reported as mean±SD. The magnitude of effects of group differences was assessed by using Cohen's *d* (*d*), with 0.2, 0.5, and 0.8 demonstrating small, medium, and large effects.[25]

Results

Physical characteristics of the participants are reported in Table 1. All data were normally distributed except pubic hair and testicular-penile/breast Tanner stage. There were no group differences in age, Tanner stages, body mass, BMI or BMI percentile (all $p>0.20$). Children with CP had lower height and height percentile than controls ($p<0.05$). In addition, height in children with CP was lower than the 50th age-and sex-based percentile ($p<0.001$). Body mass percentile ($p=0.064$) was lower in children with CP than controls and body mass in

[e]Measurement Computing Corp., 10 Commerce Way, Norton, MA 02766
[f]Cambridge Electronic Design, 4 Cambridge Science Park, Milton Rd, Cambridge, Cambridgeshire, UK CB4 0FE
[g]The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760
[i]International Business Machines Corp., New Orchard Rd., Armonk, NY 10504.

children with CP was also lower than the 50th age-and sex-based percentile (p=0.059), although the differences were marginally insignificant. Height, body mass and BMI in controls were not different from the 50th age- and sex-based percentiles (p>0.380).

HLV data are reported in Figure 2. No differences in pre-HLV and post-HLV measures were observed at the platform (d=0.18, p=0.850), distal tibia (d=0.19, p=0.805), or distal femur (d=0.01, p=0.450) so the pre-HLV was used for comparison against the HLV condition. There was a significant group-by-site effect (d=1.49, p<0.001). Specifically, in children with CP, the HLV signal was significantly higher at the distal tibia (d=1.28, p<0.001) and lower at the distal femur (d=1.58, p<0.001) than at the platform. In controls, the HLV signal was significantly higher at the distal tibia (d=2.10, p<0.001) and higher at the distal femur (d=1.47, p<0.001) than at the platform. The same patterns were observed when only those children with CP who had equinus deformity (n=13) were compared to controls (p<0.05).

Scatter plots of MAS vs. HLV transmission, as indicated by the ratio of the vibration signal measured at the site (i.e., distal tibia or distal femur) to the vibration signal measured at the platform, in children with CP are depicted in Figure 3. MAS was moderately and negatively related to the transmission of HLV from the platform to the distal tibia (r_s=−0.547, p=0.019) and from the platform to the distal femur (r_s=−0.566, p=0.014).

Discussion

This is the first study to investigate the transmission of a floor-based HLV platform (i.e., transmits <1.0 g) across the lower extremity of ambulatory children with spastic CP. Relative to the signal generated at the platform, the signal at the distal tibia was amplified in children with CP and in typically developing children. The signal was also amplified at the distal femur in typically developing children but it was dampened in children with CP to ~70% of the signal emitted at the platform.

One factor that may have contributed to the different pattern of HLV signal transmission in children with CP vs. typically developing children is the spasticity in children with CP. There was an inverse relationship between MAS and the degree of HLV transmission to the distal femur. The reason for this relationship is unclear but it may be related to the effect of spasticity on posture. Some of the children with CP had equinus deformity (n=13 of 18). Therefore, they had difficulty limiting knee and ankle plantar flexion and had difficulty or were unable to place their feet completely flat on the HLV platform, which are common postures in children with spastic CP[26]. Previous studies have shown that increased knee flexion and toe standing leads to attenuation of a vibration signal at the knee.[18, 27] However, the pattern of the results in the present study was the same when only those with equinus deformity were included in the statistical analysis which suggests that other factors may have contributed to the dampened transmission of HLV to the distal femur. Another factor that may have contributed to the dampened transmission of HLV to the distal femur include unequal weight distribution in the lower extremities creating variable degrees of muscle tension or muscular force production. Increased muscular force production has been shown to dampen vibration.[28] The loss of HLV signal at the distal femur may also be related to mechanical filtering through altered soft tissue.[28] Individuals with CP have a high

concentration of fat within[29] and surrounding[30] their musculature, which might lead to attenuated HLV signals at the distal femur. However, the effect of leg adiposity on HLV transmission has not been investigated. Foot position on the HLV platform is another element that could affect vibration transmission and local site-specific resonance frequency.[24] For example, standing in the step position (i.e., standing with one foot behind the other) has been shown to give rise to local resonance at 12.5–25 *Hz* leading to amplified vibration transmission at the lateral epicondyle of the femur. The potential effect of foot position was minimized in the present study by having all participants placed their feet in the same place at the center of the platform.

The amplified HLV signal at the distal tibia in children with CP and in typically developing children is consistent with previous findings in adults.[17, 18, 31] It is also consistent with a study by Bressel et al.[17] who reported an amplification of vibration signal to the distal tibia in typically developing children during standing while using a higher magnitude vibration signal (~2.15–5.15 *g*) than used in the present study (~0.3 *g*) and not considered an HLV (i.e., not <1 *g*). The amplification of HLV signal can be attributed to many factors, chief being the resonant frequency. Resonance is the propensity of a structure to oscillate at a greater amplitude at some specific frequencies or over a range of frequencies. Previous studies have determined that the resonance frequency of the ankle lies between 10–63 *Hz* in healthy adults[18, 31] and between 28–33 *Hz* in children.[17] In the current study, a mean frequency of 33 *Hz* was used. Another factor that may contribute to the amplified HLV signal at the distal tibia is the lack of natural shock absorbers to attenuate the vibration signal at the foot.[32] The effect of an amplified signal on bone is unknown and requires further investigation.

The HLV signal at the distal femur of typically developing children was higher than the signal measured at the HLV platform (Figure 2). This is inconsistent with previous studies that have examined vibration transmission to the knee and showed a dampening of the signal.[17, 18, 31] However, previous studies have assessed vibration signals[18, 31] that were higher in magnitude or were at different sites, such as the lateral tibial tuberosity.[17, 31] In the present study, we assessed the transmission of a very low magnitude vibration signal (~0.3 *g*) at the lateral femoral condyle. There is evidence that the resonance frequency is different along the length of a bone,[33] which may partially account for our different results.

One strength of our study was the homogeneous nature of the participants. All the children with CP were able to stand independently and all had spasticity in their leg muscles. The pattern of findings remained the same when typically developing children were matched to a subgroup of 10 children with CP for age, sex, and race. Moreover, typically developing children were not different from the 50th age-based percentile for height, body mass and BMI. Another strength of this study is that the transmission of HLV was evaluated at key bone sites. More than 80 % of all fractures in children with CP occur in the lower extremities, with almost half of all fractures occurring at the distal femur.[5]

Study limitations

One of the limitations of this study is the lack of kinematic data. We did not collect any data related to posture of our participants. Skin-mounted accelerometers can overestimate the

acceleration signal by ~10%.[34] However, even when a 10% correction was made (not reported), the pattern of the findings remained the same.

Conclusions

The results from this study suggest that the HLV signal from a floor-based platform is amplified at the distal tibia but dampened at the distal femur in children with CP. The dampening of HLV is related to the degree of spasticity, with greater spasticity associated with less signal transmission. Future studies are needed to uncover the specific mechanisms underlying the relationship between spasticity and HLV signal transmission are needed. Studies are also needed to determine if the potential HLV-induced benefits to bone mass and architecture in children with CP are influenced by the degree of HLV transmission.

Acknowledgments

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Abbreviations

CP	Cerebral palsy
GMFCS	Gross motor function classification system
HLV	High-frequency, low-magnitude vibration
MAS	Modified Ashworth Scale

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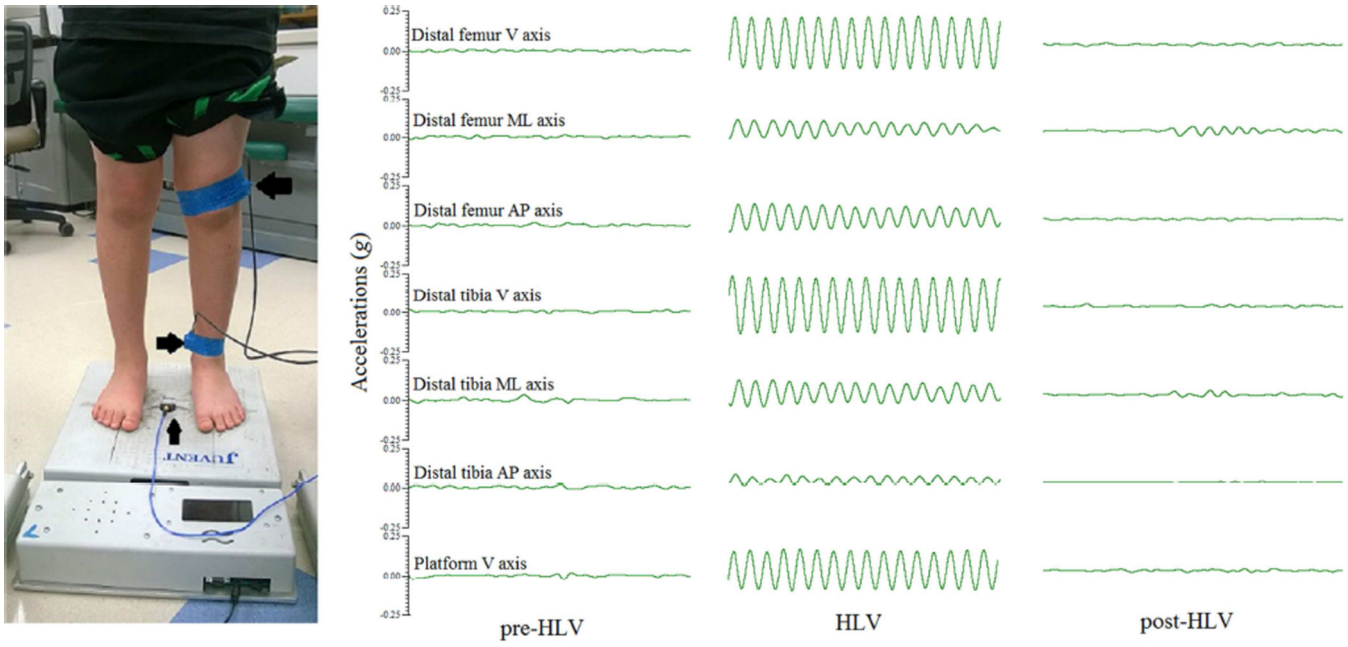

Figure 1.

On the left (A) is a participant with triaxial accelerometers secured to the distal femur (large arrow) and distal tibia (medium arrow) and a uniaxial accelerometer secured to a platform that emits a high-frequency, low-magnitude vibration (HLV) signal when turned on (small arrow). On the right (B) are sinusoidal waveforms showing signals at the HLV platform, distal tibia, and distal femur in the vertical (V), mediolateral (ML) and anteroposterior (AP) axis while standing before the HLV platform is turned on (pre-HLV), while it is on (HLV) and after it is turned off (post-HLV).

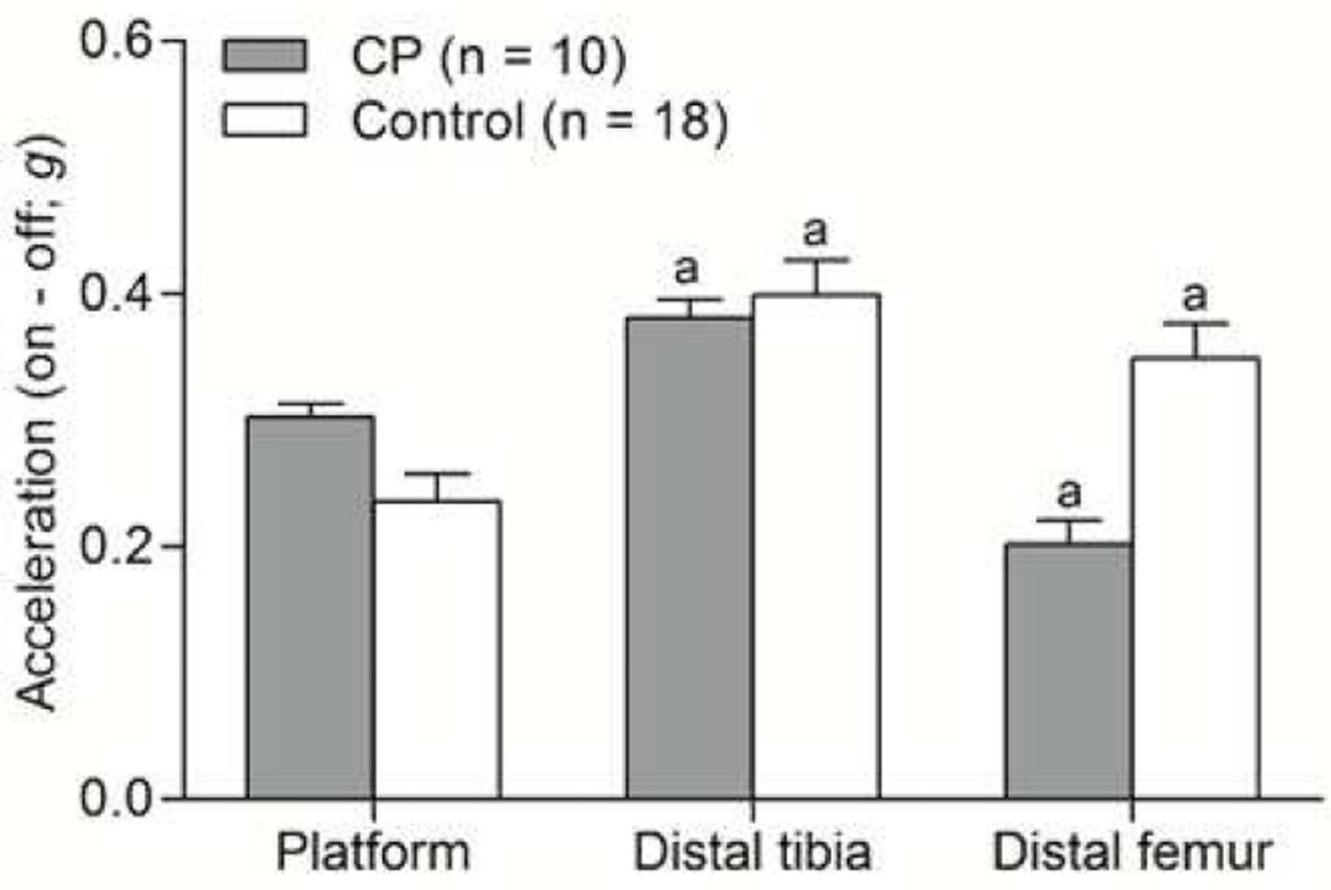

Figure 2.

Bar graphs showing transmission of the high-frequency, low-magnitude vibration (HLV) signal from the HLV platform to the distal tibia and the distal femur. The HLV signals are presented as values in the on condition (HLV) minus the off conditions (pre-HLV).[a]Different from the HLV signal values at the platform, $p < 0.05$.

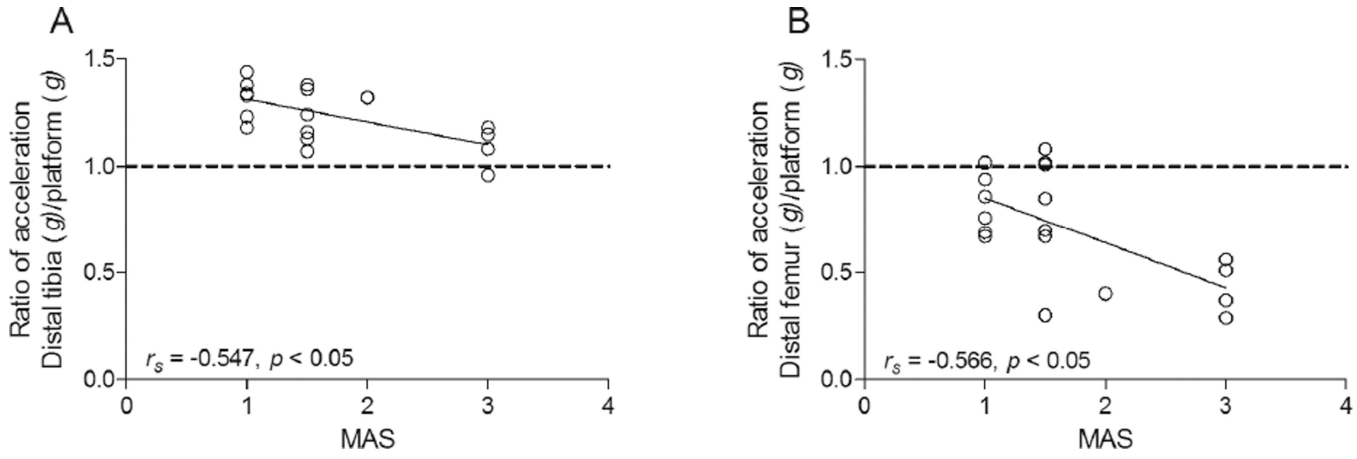

Figure 3.

Scatter plots show the relationship between spasticity estimated using the Modified Ashworth Scale (MAS) and the transmission of high-frequency, low-magnitude vibration (HLV) signals emitted from the HLV platform to (A) the distal tibia and (B) the distal femur in children with CP (n = 18). The transmission of HLV signal was expressed as the ratio of the acceleration measured at the bone site divided the acceleration measured at the HLV platform. A value of 1.0 (dotted line) indicates 100 % transmission. Values above 1.0 indicate an amplification of HLV signal and values below 1.0 indicate a loss of HLV signal.

Table 1

Physical characteristics of children with cerebral palsy (CP) and typically developing children (Control)

	CP (n = 18)	Control (n = 10)	*p*	*d*
Age (y)	8.0 ± 2.5	8.7 ± 1.7	0.413	0.33
Tanner stage (1/2/3)				
Pubic hair	13/4/1	9/1/0	0.261	0.47
Testicular-penile/breast	16/2/0	8/1/1	0.323	0.42
Height (m)	1.2 ± 0.12[a]	1.32 ± 0.07	0.011	1.11
Height (percentile)	21 ± 24[a,b]	56 ± 32	0.003	1.32
Body mass (kg)	25.7 ± 9.3	29.8 ± 6.7	0.231	0.49
Body mass (percentile)	35 ± 32	58 ± 27	0.064	0.77
BMI (kg/m^2)	17.3 ± 3.8	16.9 ± 2.9	0.786	0.11
BMI (percentile)	52 ± 37	48 ± 33	0.791	0.11
GMFCS (I/II/III)	10/7/1	-		
MAS (1/1.5/2/3)	6/7/1/4	-		

Values are means ± SD

[a] Group difference, $p < 0.05$

[b] Different from the 50th age-based percentile, $p < 0.05$

Gross motor function classification system (GMFCS)
Modified Ashworth Scale (MAS)