

Original Article

Hip Girdle Muscle Activation by Whole-Body Vibration to Achieve the Impact of Walking and Running: A Prospective Pilot Study in Healthy Children

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Abstract

Objectives: This prospective pilot study in healthy children aimed to evaluate the effect of whole-body vibration therapy (WBVT) on hip girdle muscle activation and identify the optimal amplitude and frequency settings that replicate the effects of walking or running without causing discomfort. **Methods:** A prospective pilot study involving 20 healthy children was conducted to evaluate muscle activation during WBVT at amplitudes of 1, 2, and 3 mm and frequencies of 5–20 Hz. Surface electromyography of the gluteus medius, tensor fascia lata, iliopsoas, and rectus femoris was recorded during walking, running, and WBVT trials, and steady-state 10-s epochs were extracted for analysis. **Results:** Although dose–response analyses showed no statistically significant increases beyond 10 Hz within WBVT conditions, the reported thresholds specify the vibration settings at which WBVT-induced activation exceeded the RMS values observed during walking or running, rather than indicating significant within-WBVT frequency differences. When “optimal setting” was defined as the highest activation within tolerable ranges, the 3 mm/ 10 Hz setting met these criteria. **Conclusions:** WBVT produced short-term increases in hip-girdle muscle activation under tolerable conditions. While not indicative of therapeutic benefit, these data provide hypothesis-generating insights for future clinical studies involving children with movement limitations.

Keywords: Healthy Child, Hip Girdle Muscles, Running, Whole-body Vibration Therapy, Walking

Introduction

The hip girdle muscles are essential for body stability and mobility. They are responsible for flexion, medial rotation, lateral rotation, abduction, and adduction.

These muscles enable various movements and maintain posture. In addition, they improve overall posture by supporting the pelvis during hip motions. The hip girdle

muscles are necessary for high-level sports activities, such as running, jumping, and kicking, as well as daily activities, such as walking, bending, and sitting¹.

Weight-bearing activities, such as walking and running, play vital roles in promoting bone and muscle development in children, these activities strengthen muscles, enhance joint and bone integrity, and improve coordination and balance²⁻⁴. Furthermore, these activities have been shown to positively influence bone growth in children and adolescents and, in some cases, contribute to changes in lean mass and fat distribution^{5,6}. However, children with severe disabilities, such as cerebral palsy (CP), who are unable to walk or run, may experience delayed bone and hip girdle muscle development. In addition, conditions such as acetabular dysplasia, coxa valga, and femoral anteversion may occur in these children, further increasing the risk of hip subluxation^{7,8}.

Hip subluxation and dislocation are the most common musculoskeletal complications in patients with severe CP.

The authors have no conflict of interest.

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The risk of dislocation increases with delayed standing or walking and prolonged periods of lying down⁸⁻¹⁰. Various conservative treatments, including assisted standing, sitting, and walking, are available for hip dislocation management in children with CP; however, each intervention has its limitations. For instance, standing aids provide limited transmission of weight through the pelvis, whereas sitting aids may not fully prevent femoral head displacement. Moreover, walking aids often lack adequate support and balance, limiting their effectiveness in preventing dislocation¹¹. Furthermore, these treatments do not provide sufficient hip joint stimulation to the extent that a typically developing child can walk or run; therefore, they are insufficient to prevent hip dislocation.

Whole-body vibration therapy (WBVT) is a therapeutic intervention that delivers mechanical stimulation while an individual stands on specialized equipment. Previous studies have shown that exercise routines combined with WBV improve muscular power and strength¹², muscle cross-sectional area^{13,14}, flexibility^{15,16}, bone mineral density¹⁷, and visceral fat¹⁸. WBVT can stimulate adaptive skeletal responses, particularly in prepubertal children, indicating that the growing skeleton is highly responsive to vibrations¹⁹. A growing body of research supports the use of WBV as an alternative training method for people who are unable to exercise²⁰. WBVT has been investigated as a treatment option for children with disabilities. Studies have reported that total-body bone mineral density increases within 6 months of WBVT, and improvements have been observed in femoral bone density, total-body BMD content, and lean mass²¹. Furthermore, WBVT is expected to induce reactive contractions in the hip girdle muscles of patients with severe CP who are unable to actively move, potentially mimicking the hip joint biomechanical effects of walking or running. Previous studies have shown that WBVT is more effective than conventional physical therapy in enhancing lower limb motor function in children with CP²²⁻²⁵. Despite these findings, no definitive evidence supports the effectiveness of WBVT in strengthening the hip girdle muscles or preventing hip dislocation in children with CP. This pilot study was designed as dose-finding physiological research in typically developing children, with the goal of identifying feasible vibration parameters that may guide future hypothesis-driven studies in children with neurodisabilities.

Methods

Study design

This single-center, prospective pilot study was conducted between December 2022 and September 2023.

Sample size

As this was a pilot feasibility study, a target sample size of 22 children was selected based on precision-based recommendations for pilot trials, which commonly range

from 12 to 30 participants. This sample size was deemed sufficient to estimate variability, assess tolerability, and inform the design of future adequately powered studies and the results should be interpreted as hypothesis-generating rather than confirmatory.

Participants

Participants were recruited through announcements, recruitment notices, and online platforms from a rehabilitation clinic at a university hospital. The inclusion criteria were as follows: (1) children between the ages of 5 and 15 years, (2) healthy and typically developing children, (3) children with stable vital signs, (4) children or their legal guardians who agreed to participate in the study, and (5) children who provided informed consent. The exclusion criteria were as follows: (1) children who could not follow one-step commands; (2) children with a history of developmental, neurological, or psychiatric conditions; (3) children who had allergic reactions to the electrodes; (4) children for whom participation was deemed difficult based on the research director's judgment; and (5) children with a recent medical history that may affect their exercise performance.

Interventions

All participants attended a single laboratory session. We attached eight S-EMGs electrodes to record activation of the gluteus medius (GM), tensor fascia lata (TFL), iliopsoas (IP), and rectus femoris (RF) muscles. The root mean square (RMS) value was measured through eight S-EMG channels for more than 10 s while walking and running in place. Walking was adjusted to a speed of 100 bpm using a metronome, and running was adjusted to 170 bpm. Pediatric gait and running-mechanics data were used to calculate the selected cadences, which were walking: 100 bpm, running: 170 bpm. RMS values were calculated using a 100-ms moving window after full-wave rectification. The raw EMG signals were processed with a 20–450 Hz band-pass filter and a 60 Hz notch filter. Data were sampled at 1,000 Hz. All EMG recordings were visually inspected, and any artifact-contaminated segments were removed prior to analysis. For each trial, RMS values were averaged across a steady-state 5-s epoch and standardized to percent change relative to walking RMS values.

Ahmedov et al.²⁶ discovered similar values in prepubertal cohorts, and Tudor-Locke et al.²⁷ observed average walking cadences of 120–140 steps/min in children aged 6–12 years. Despite the lack of a universal pediatric cadence standard for running, several biomechanical studies have shown that children adopt greater step frequencies than adults due to shorter limb lengths and stride mechanics^{27,28}. A practical, physiologically relevant cadence of 170 bpm was used to produce rhythmic hip girdle activation while maintaining tolerability. The lack of balance-shift dynamics and ground-reaction forces in in place walking and running limits their external validity.

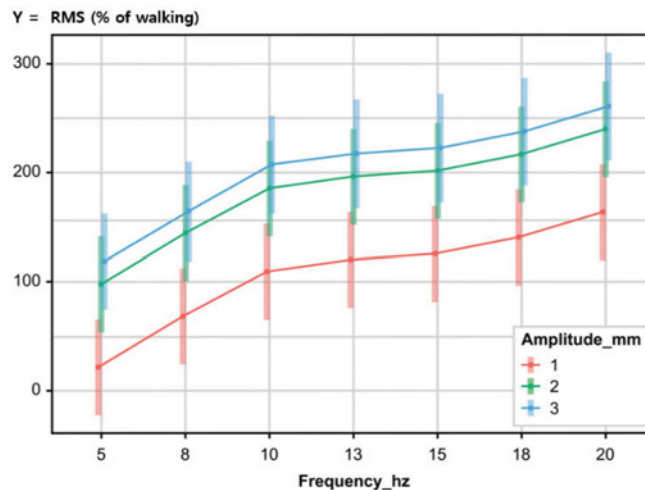


Figure 1. Changes in the RMS values of the muscles around the hip joint according to changes in WBVT frequency and amplitude. Apparent upward trend beyond 10 Hz was not statistically significant in pairwise LMM contrasts. Error bars show 95% CIs of model-based marginal means.

Surface electromyography (S-EMG) signal acquisition

A wireless S-EMG analysis system (BTS FREEEMG 1000 with an EMG-BTS EMG Analyzer; BTS Bioengineering Co., Milan, Italy) was used for the quantitative electrophysiological analysis to assess the degree of muscle contraction during walking, running, and WBVT. Data analysis was conducted using an EMG analyzer program on a laptop. S-EMG signals were received from eight channels, converted into digital signals, and wirelessly transmitted to a personal computer.

Eight channels were used in the four muscles (GM, TFL, IP, and RF muscles) around the hip joint, and the electrode attachment location was in accordance with the guideline for Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM). The channels for both sides and the attachment sites of the S-EMG electrodes are presented in Supplementary Figure 1.

For the pediatric participants, we clarified that electrode placement adhered to a modified SENIAM-based procedure. Surface EMG electrode placement followed modified SENIAM recommendations, including alignment with muscle fiber direction, standardized bipolar electrode spacing (~20 mm), and placement at the anatomically recommended sites for each hip girdle muscle. Skin preparation (alcohol cleansing, and drying) was also performed according to SENIAM guidelines. We additionally cited Jiroumaru et al.²⁹ to support the feasibility of using surface EMG to assess iliopsoas activity. They showed that with appropriate anatomical positioning, iliopsoas EMG can be reliably collected with low crosstalk from the sartorius. Furthermore, Juan et al.³⁰ showed that iliopsoas activation

peaks between 30° and 60° during hip flexion, which corresponds to the posture used during WBVT exposure. These results support the inclusion of iliopsoas EMG in this study.

The RMS, μV value, a quantitative index associated with muscle activity, was used to analyze and process the electrical signals recorded in the muscles. The RMS value was used as a parameter to reflect the motor unit's physiological activity during muscle contraction. The RMS was measured using S-EMG after the plateau state was confirmed for 5 s. As participants tended to exhibit abnormal muscle activation during the initial habituation process, the S-EMG signals during the initial 10 s were discarded, and the remaining S-EMG signals were used for analysis. The S-EMG measurements were conducted twice on both sides; and, the mean value was used.

WBVT

The participant was placed barefoot on the WBV device with the S-EMG electrodes attached (Galileo Med S; Novotech Inc., Germany). According to the manufacturer's displacement-position mapping, vibration amplitude increases linearly with lateral foot placement: 0 mm at the center, 1 mm at ~4 cm, 2 mm at ~8 cm, and 3 mm at ~12 cm from the midline. These positions were verified using the platform's built-in calibration ruler, and the device had undergone routine manufacturer calibration in 2022, which is within the standard 2-year interval preceding the 2023 study period. All amplitude settings (1, 2, and 3 mm) were applied using these calibrated position markers. Vibration

frequency was electronically controlled between 5 and 27 Hz with a resolution of 1 Hz, ensuring precise delivery of the programmed stimulus. They stood on the platform and had both feet placed side-by-side symmetrically, based on their second toes. Participants held a front-mounted safety bar to prevent falls and were instructed to face forward with both knees fully extended for the duration of the training. As the participants' feet moved farther from the center, the vibration amplitude increased. There are two WBVT indicators: amplitude and vibration frequency. The amplitude was adjusted to 1, 2, and 3 mm by placing the participants' feet on the vibration device at different marked widths, and all three amplitude settings were applied. In each amplitude setting, the vibration frequency started at 5 Hz and gradually increased to 20 Hz (5–8–10–13–15–18–and 20 Hz). To ensure safety and stability for pediatric participants, WBVT amplitudes were delivered in a fixed ascending order (1 mm → 2 mm → 3 mm). Within each amplitude block, frequencies also progressed sequentially from 5 to 20 Hz without randomization.

The duration of vibration was 3 min per amplitude set. Three sets (9 min) were applied, followed by a 3-min rest between each amplitude set to reduce fatigue accumulation. If the participants reported discomfort before reaching 20 Hz, the frequency was not increased further.

Safety and Tolerability Assessment

Clinical evaluations included a questionnaire assessment, such as the Visual Analog Scale and Numeric Rating Scale, to assess the presence of discomfort or pain in participants during vibration therapy. Discomfort was defined a priori as any of the following: (1) NRS ≥ 4 on a 0–10 scale (0 = no discomfort, 10 = intolerable discomfort), (2) dizziness, (3) plantar pain, or (4) visible anxiety or request to stop. A pediatric-appropriate NRS anchoring script was used before WBVT exposure. If any of these criteria were met, the vibration frequency was not increased further, and the trial was stopped if symptoms persisted. Safety was monitored continuously by a pediatric rehabilitation physician and research assistant. All adverse events—including dizziness, pain, and imbalance—were recorded.

Statistical Analysis

All analyses were performed using R version 4.2. Descriptive statistics are reported as mean \pm standard deviation. To model repeated measures across muscles, amplitudes, and frequencies within participants, we fitted a linear mixed-effects model (LMM). The fixed-effects structure included vibration amplitude (1, 2, 3 mm), frequency (5–20 Hz), muscle (GM, TFL, IP, RF), and side (left/right). Two-way interactions between frequency \times amplitude and frequency \times muscle were included based on the expected physiological coupling. The random-effects structure consisted of random intercepts for

Table 1. Participants' demographic data.

Characteristics	Total (n = 20)
Sex (male: female) N(%)	9 (45%): 11 (55%)
Age (years) Mean \pm SD	9.15 \pm 2.80
Height (cm) Mean \pm SD	137.83 \pm 17.44
Weight (kg) Mean \pm SD	34.02 \pm 13.49
BMI (kg/m ²) Mean \pm SD	17.16 \pm 3.01
<i>BMI = body mass index.</i>	

subjects, with muscles nested within subjects to account for repeated measurements. An unstructured covariance matrix was used for the within-subject repeated measures. Model estimation used restricted maximum likelihood (REML) with degrees of freedom calculated using the Satterthwaite approximation via the lmerTest package. To evaluate differences across WBVT, walking, and running, marginal means and 95% confidence intervals were estimated using the emmeans package. Standardized effect sizes were computed using semi-partial R^2 (partial η^2) derived from the F-statistic and denominator degrees of freedom for each fixed effect. The primary endpoint was prespecified as the change in normalized RMS between WBVT and gait. We hypothesized that WBVT, particularly at higher amplitudes and frequencies, would generate higher RMS activation than gait. To control for multiplicity, Bonferroni correction was applied to families of contrasts within amplitudes and within frequencies. A summary of all fixed-effect estimates, standard errors, degrees of freedom, t-values, p-values, and effect sizes is provided in Supplementary Tables 1 and 2.

Results

Participant Characteristics

A total of 22 participants were initially recruited for the study; however, two participants withdrew due to health concerns, resulting in a final sample size of 20 participants, 9 males and 11 females, with a mean age of 9.15 \pm 2.802 years (Supplementary Figure 2). Table 1 presents the demographic characteristics of the study population.

Influence of vibration amplitude on muscle activation

The RMS values of the hip muscles gradually increased as the WBVT amplitude increased from 1 to 3 mm. Increasing the vibration amplitude from 1 to 2 mm resulted in a statistically significant increase in the RMS values across all measured muscles ($p < 0.001$). However, no significant differences were observed when the amplitude was increased from 2 to 3 mm ($p = 0.796$) (Table 2).

Table 2. Comparison of RMS values of muscles around the hip joint between WBVT amplitudes or frequencies.

Contrast ^a	Estimate ^b	Standard error	Lower 95% CI	Upper 95% CI	p-value ^c
2mm-(1mm)	76.296	13.520	49.797	102.795	0.000***
3mm-(2mm)	20.608	16.302	-11.344	52.560	0.796
8Hz- (5Hz)	46.400	13.022	20.877	71.923	0.005**
10Hz-(8Hz)	41.954	13.092	16.294	67.614	0.015*
13Hz-(10Hz)	10.407	14.968	-18.930	39.744	0.990
15Hz-(13Hz)	5.587	15.813	-25.406	36.580	1.000
18Hz-(15Hz)	14.987	15.813	-16.006	45.980	0.945
20Hz-(18Hz)	23.019	15.813	-7.974	54.012	0.667

a. Contrast: RMS values between amplitudes within a frequency or between frequencies within an amplitude. Contrasts represent pooled main effects. b. Estimation: The estimated mean difference. c. *p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

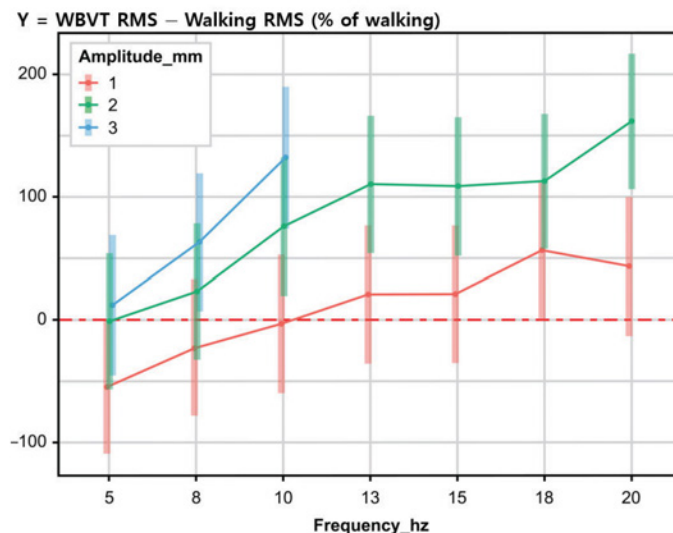


Figure 2. Changes in the difference between the RMS value of the muscles around the hip joint and the RMS value during walking according to WBVT frequency and amplitude changes. Error bars show 95% CIs of model-based marginal means. Dashed line = equality (0).

Effect of vibration frequency on muscle activation

The RMS values of the hip muscles gradually increased as the frequency increased from 5 to 20 Hz (Figure 1). These findings indicated that increasing the frequency from 5 to 8 Hz significantly increased muscle activation ($p = 0.005$). Further increases in frequency, particularly from 8 to 10 Hz, resulted in additional increases in muscle activation improvements ($p = 0.015$). However, no significant differences were observed in the RMS values beyond 10 Hz ($p > 0.05$). Furthermore, some participants reported discomfort at 20 Hz, which limited further testing at this frequency (Table 2).

WBVT settings resulted in the highest percentage of RMS values exceeding those measured during walking and running for each muscle

The WBVT settings that resulted in the highest percentage of RMS values exceeding those measured during walking were as follows: GM and TFL at an amplitude of 2 mm and a frequency of 20 Hz, IP at 2 mm and 18 Hz, and RF at 2 mm and 13 Hz (Supplementary Figure 3). In comparison, the WBVT settings that resulted in the highest percentage of RMS values exceeding those measured during running were GM at 2 or 3 mm and 10 Hz, TFL and IP at 2 mm and 20 Hz, and RF at 3 mm and 10 Hz (Supplementary Figure

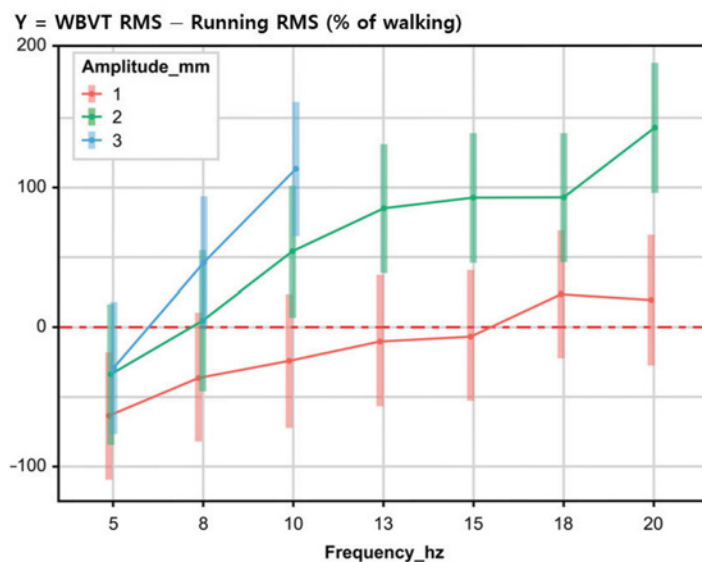


Figure 3. Changes in the difference between the RMS value of the muscles around the hip joint and the RMS value during running according to WBVT frequency and amplitude changes. Error bars show 95% CIs of model-based marginal means. Dashed line = equality (0).

4). The effectiveness of WBVT in inducing hip girdle muscle activation compared with walking and running was assessed by comparing the RMS values obtained under different vibration settings.

Comparison between WBVT and walking

WBVT elicited greater hip muscle activation than walking at frequencies of ≥ 13 Hz (1 mm amplitude), ≥ 8 Hz (2 mm), and ≥ 5 Hz (3 mm). The highest RMS values were observed at 2 mm and 20 Hz and at 3 mm and 10 Hz (Figure 2, Supplementary Table 3).

Comparison between WBVT and running

WBVT elicited greater hip muscle activation than running at frequencies of ≥ 18 Hz (1 mm amplitude) and ≥ 8 Hz (2 mm and 3 mm). The highest RMS values were observed at 2 mm and 20 Hz and at 3 mm and 10 Hz (Figure 3, Supplementary Table 4).

WBVT tolerability

All 20 participants reported discomfort, such as dizziness and fear, when the frequency exceeded 10 Hz at an amplitude of 3 mm and when it exceeded 20 Hz at an amplitude of 2 mm. No serious adverse events occurred.

Optimal setting (Settings yielding the highest observed activation within tolerable ranges)

We defined the optimal WBVT setting as the highest activation condition that remained tolerable (no reported discomfort) and produced RMS values above those of walking and running. Based on this definition, 3 mm / 10 Hz emerged as the optimal setting.

Discussion

This study investigated hip girdle muscle activation in typically developing children during walking, running, and WBVT at varying amplitudes and frequencies. These findings provide valuable insights into WBVT's neuromuscular effects and its potential applications in pediatric rehabilitation and musculoskeletal training.

All four hip girdle muscles analyzed—GM, TFL, IP, and RF—exhibited measurable activation during walking and running. Comparing the muscle activation levels between these two activities, running consistently elicited higher activation across all muscles than walking. This observation is consistent with previous findings that running requires greater neuromuscular engagement because of the increased demand for stability, force production, and coordination in the lower extremities³¹⁻³³.

WBVT is a popular clinical preventative and rehabilitation

tool in physical medicine and neurorehabilitation. WBV has been found to have a significant effect on increasing neuromuscular performance, improving muscular strength, balance, gait mechanics, and quality of life³⁴. Currently, vibratory training is a studied modality that can improve proxies of musculoskeletal function and joint stability in certain contexts. Evidence for disease prevention (e.g., osteoporosis, osteoarthritis, sarcopenia) remains mixed, and the present study evaluates acute muscle activation and tolerability rather than clinical outcomes^{35,36}.

The LMM analysis confirmed that increasing the WBVT amplitude from 1 to 2 and 3 mm, as well as increasing the frequency from 5 to 10 Hz, was associated with progressively higher muscle activation. However, beyond 10 Hz, the rate of increase in the RMS values became less pronounced, suggesting that a threshold frequency may exist at which neuromuscular adaptation occurs, beyond which further increments produce diminishing returns³⁷. Notably, the comparison of the RMS values between the 1 and 2 mm amplitude settings showed a statistically significant difference, whereas the difference between the 2 and 3 mm amplitudes was not significant. This finding suggests the existence of a mechanical saturation point beyond which increasing amplitude no longer enhances neuromuscular activation. A similar effect has been reported in studies examining muscle responses to mechanical stimulation, in which increasing the WBVT amplitude beyond a certain threshold failed to produce additional benefits in muscle activation^{38,39}.

At 2 mm amplitude, a gradual increase in frequency was initially observed, resulting in greater RMS values; however, the RMS values began to decline for certain muscles once the frequency exceeded 18–20 Hz. This may indicate that excessive vibration forces trigger the compensatory activation of stabilizing muscles, such as those in the core and trunk, which may counterbalance postural instability rather than directly recruiting the hip girdle muscles. Previous studies have made similar observations, indicating that excessive WBVT frequencies may result in altered neuromuscular responses, as the body prioritizes stabilization over targeted muscle engagement^{35,40}.

Children appeared to achieve comparable or even greater neuromuscular activation at relatively lower WBVT settings than adults. Although effective training in adults generally requires higher frequencies and amplitudes, owing to their greater muscle mass, stiffer connective tissues, and reduced neuromuscular responsiveness^{41–43}, children show heightened sensitivity to mechanical stimuli, possibly because of increased proprioceptive feedback and greater motor unit excitability. Moreover, vibration transmissibility to the hip and ankle joints has been found to be significantly greater in children than in adults, particularly at frequencies of 18–20 Hz compared with around 33 Hz in adults, indicating a more effective mechanical energy transfer in the pediatric musculoskeletal system⁴⁴. Furthermore, WBVT tolerance in children may be lower at higher intensities. All participants reported dizziness and discomfort when

exposed to frequencies above 20 Hz, particularly at higher amplitudes. Notably, adverse sensations emerged at frequencies as low as 10 Hz at an amplitude of 3 mm, resulting in the early termination of these trials. In adult studies, low-frequency (10–50 Hz) and low-amplitude (<10 mm) vibrations have shown beneficial effects, especially in therapeutic applications⁴⁵, whereas high-frequency (>100 Hz) and high-intensity (>10 mm) vibrations can cause musculoskeletal impairment^{46,47}.

These observations highlight the importance of carefully balancing therapeutic effectiveness with participant comfort and safety.

When the amplitude was set to 1 mm, a frequency ≥ 13 Hz was required to surpass the muscle activation levels observed during walking. At a 2-mm amplitude, a frequency ≥ 8 Hz was required, and at a 3-mm amplitude, a frequency of ≥ 5 Hz was sufficient to elicit greater muscle activation than walking. A more intense vibration setting was required to exceed the activation levels observed during running. At the 1-mm amplitude, a frequency of ≥ 18 Hz was required, while at the 2-mm and 3-mm amplitudes, a frequency of ≥ 8 Hz was sufficient to induce higher RMS values than running. These findings suggest that WBVT is an effective alternative intervention for individuals with neuromotor impairments who cannot engage in conventional weight-bearing activities.

The optimal WBVT settings identified in this study for maximizing muscle activation while maintaining participant comfort were a 3-mm amplitude at 10 Hz. These settings resulted in the highest levels of hip muscle activation without causing significant discomfort, indicating their potential application in rehabilitation programs.

The effects of WBVT in children with neuromuscular disorders have been investigated in several studies. Research has shown that WBVT can improve lower limb muscle strength in children with CP, with significant gains observed in quadriceps and hamstring muscle force^{25,48}. Similarly, a systematic review of WBVT in children with Down syndrome revealed improvements in the hip flexor, hip extensor, knee flexor, and knee extensor strength^{49,50}.

In WBVT, the body receives a vibration stimulus through a vibrating platform, and the mechanical vibration signal activates the muscle spindle, which in turn activates α -motor neurons^{51,52}. The Golgi tendon organ's inhibitory response to motor neurons is also diminished by vibration, which results in the same muscular contraction as the tonic vibration reflex^{53–55}.

The safety of WBVT among children has been well established. A randomized controlled trial involving toddlers with CP showed that a 14-week WBVT intervention was feasible and safe, with no serious adverse effects reported⁵⁶. Additional studies on children with severe motor disabilities have shown that WBVT is well-tolerated across vibration intensities, further reinforcing its applicability⁵⁷. No serious adverse events occurred in this study, and the only reported discomfort was mild dizziness and anxiety at higher frequencies.

Despite its strengths, this study has some limitations. The small sample size limits the generalizability of the findings. Accordingly, the present findings should be interpreted as hypothesis-generating and may serve as preliminary data to support the design of subsequent larger-scale clinical trials. Future research should involve larger cohorts. Because gait tasks were performed in place, without ground-reaction forces or balance-shift dynamics, and no accelerometer/kinematic checks were available, the external validity of WBVT-to-gait comparisons is limited. Only four hip girdle muscles were analyzed, indicating that other important stabilizing muscles were not assessed. Iliopsoas surface EMG is prone to cross-talk and signal attenuation, especially in children due to anatomical variability; therefore, the accuracy of these recordings represents a limitation of the study. Furthermore, the study was limited to a single WBVT session, preventing the evaluation of long-term neuromuscular adaptations. The amplitude sets were fixed (1→2→3 mm), and the frequency was always raised from 5→20 Hz. Because vibration settings were not randomized, potential order effects (fatigue, habituation, anticipatory stabilization) were not controlled for and may have affected the dose–response findings. Order was not modeled as a covariate in the linear mixed-effects models, which may further contribute to residual bias in the within-WBVT contrasts.

Conclusion

WBV is a safe technique that enhances postural stability and muscle strength. This study found that WBVT can activate the muscles around the hip joints in children at levels comparable with those elicited during walking and running by adjusting the WBVT amplitude and frequency. The optimal WBVT parameters for achieving maximal activation of the hip girdle muscles are less in children than in adults. Further research, including large numbers of children, is needed to generalize the results among the pediatric population.

Ethics Approval

The study protocol was approved by the Institutional Review Board of Seoul National University Bundang Hospital, the affiliated research institution for this study (No. B-2212-801-305).

Consent to Participate

All participants, or their legal guardians, read and signed an informed consent form approved by the institution's ethics committee before taking part in the study.

Authors' contributions

Won-Jae Jo: Data curation, formal analysis, investigation, statistical analysis, visualization, writing—original draft preparation, writing—reviewing, and editing. Eunseo Choi: Data curation and investigation. Jee Hyun Suh: Supervision, writing, original draft preparation, reviewing, and editing. Jiwoon Lim: Conceptualization and Methodology. Ju Seok Ryu: Conceptualization, methodology,

project administration, resources, supervision, writing, reviewing, and editing. All authors have read and approved the final version of the manuscript.

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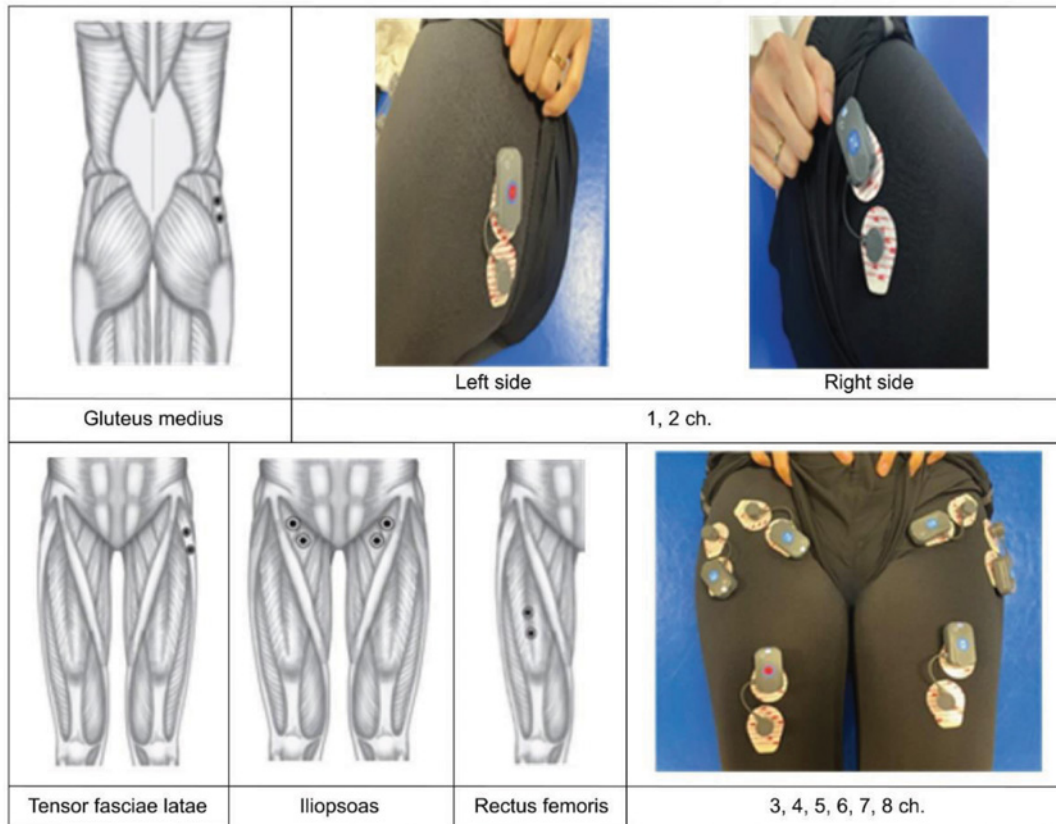
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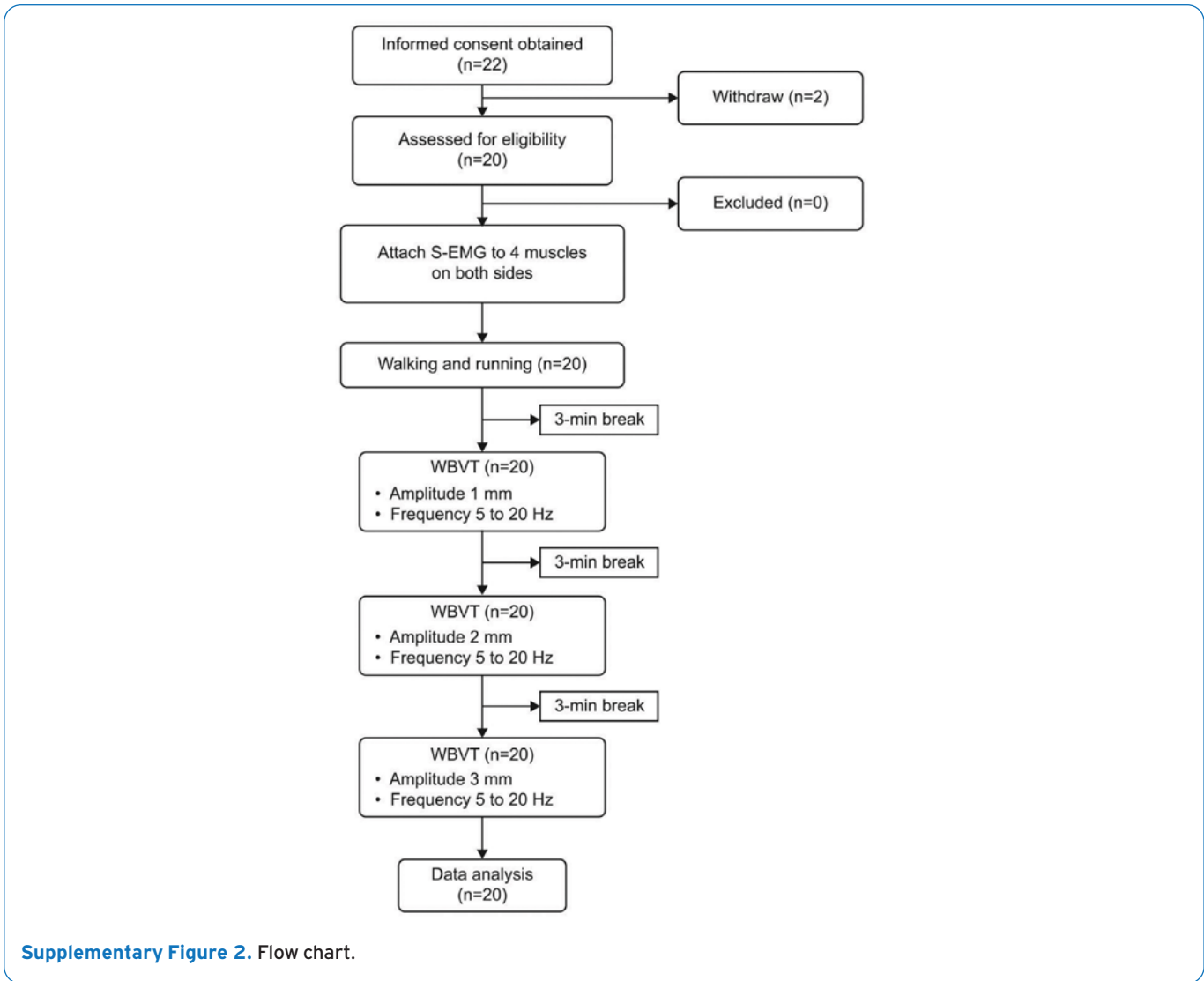
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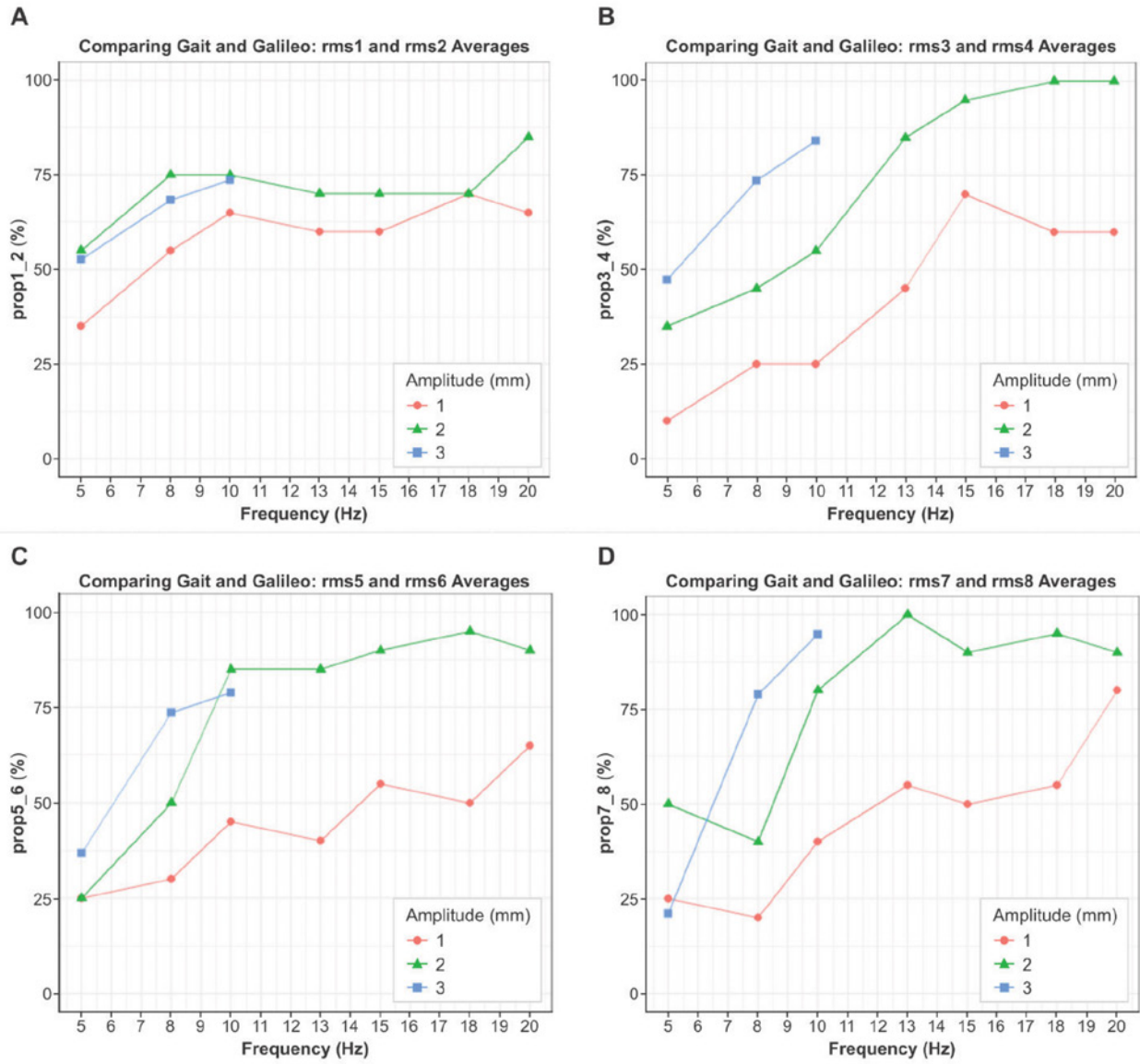
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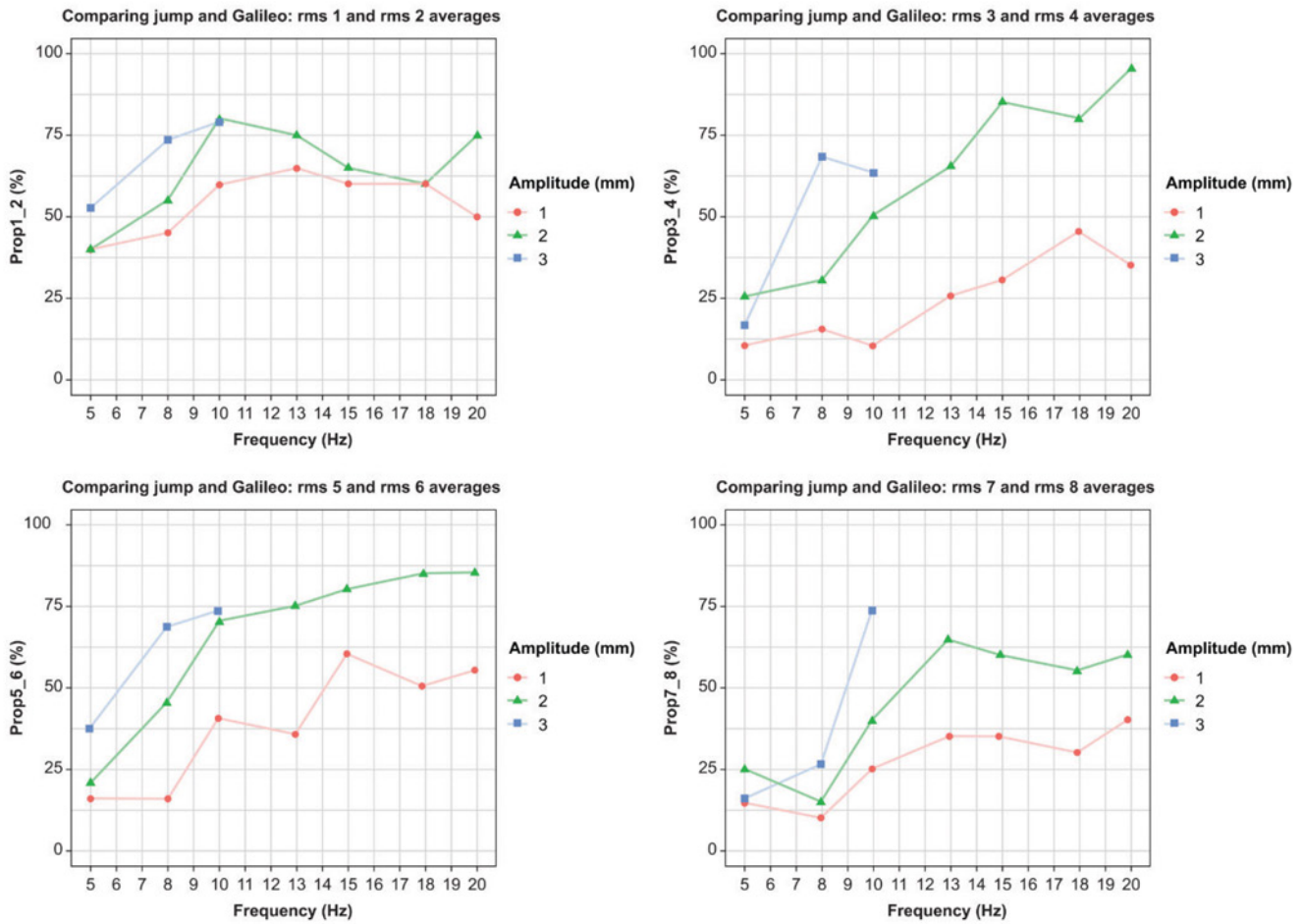
Supplementary Figure 1. Channels for both sides and the attachment site of the S-EMG electrodes according to the anatomical guideline. The GM muscle attachment site was the midpoint of the line connecting the iliac crest and trochanter (Rt.: 1 channel, Lt.: 2 channel). The attachment site of the TFL was 1/6 point toward the proximal area from the line connecting the anterior superior iliac spine (ASIS) and lateral epicondyle of the femur. (Rt.: 3 channel, Lt.: 4 channel). The attachment site of the IP muscle was attached 4 cm below the ASIS and next to the femoral artery. (Rt.: 5 channels, Lt.: 6 channels) The attachment site of the RF was attached to the midpoint of the line from the ASIS to the upper margin of the patella bone. (Rt.: 7 channels, Lt.: 8 channels)



Supplementary Figure 2. Flow chart.



Supplementary Figure 3. The percentage at which the RMS value is higher for each muscle under different WBVT settings compared with walking.



Supplementary Figure 4. The percentage at which the RMS value is higher for each muscle under different WBVT settings compared with running.

Supplementary Table 1. Fixed effects from the LMM(Outcome: Y = WBVT RMS – walking RMS) with semi-partial R² (partial η^2).

Effect	t	df	F	partial η^2	p-value ^a
frequency_hz8	1.28	2536.99	1.63	0.001	0.208
frequency_hz10	2.07	2536.99	4.26	0.002	0.064
frequency_hz13	3.04	2536.99	9.23	0.004	0.013*
frequency_hz15	3.04	2536.99	9.22	0.004	0.007**
frequency_hz18	4.47	2536.99	19.97	0.008	0.000***
frequency_hz20	3.96	2536.99	15.68	0.006	0.000***
amplitude_mm2	2.01	445.01	4.05	0.009	0.220
amplitude_mm3	2.48	439.11	6.13	0.014	0.157
freq8:amp2	-0.22	2536.99	0.05	0.000	0.689
freq10:amp2	0.72	2536.99	0.52	0.000	0.110
freq13:amp2	1.01	2536.99	1.03	0.000	0.030*
freq15:amp2	0.98	2536.99	0.96	0.000	0.023*
freq18:amp2	0.06	2536.99	0.00	0.000	0.197
freq20:amp2	1.82	2536.99	3.30	0.001	0.002**
freq8:amp3	0.54	2536.99	0.29	0.000	0.114
freq10:amp3	1.91	2549.42	3.64	0.001	0.001**

RMS (% of walking). All fixed-effect estimates reflect the change in normalized RMS relative to the reference condition, defined as frequency = 5 Hz and amplitude = 1 mm. a. *p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001.

Supplementary Table 2. Fixed effects from the LMM(Outcome: Y = WBVT RMS– running RMS) with semi-partial R² (partial η^2).

Effect	t	df	F	partial η^2	p-value ^a
frequency_hz8	1.26	2534.89	1.58	0.001	0.208
frequency_hz10	1.85	2534.89	3.44	0.001	0.064
frequency_hz13	2.49	2534.89	6.22	0.002	0.013*
frequency_hz15	2.68	2534.89	7.18	0.003	0.007**
frequency_hz18	4.08	2534.89	16.63	0.007	0.000***
frequency_hz20	3.87	2534.89	14.95	0.006	0.000***
amplitude_mm2	1.23	283.01	1.51	0.005	0.220
amplitude_mm3	1.42	280.11	2.03	0.007	0.157
freq8:amp2	0.40	2534.89	0.16	0.000	0.689
freq10:amp2	1.60	2534.89	2.56	0.001	0.110
freq13:amp2	2.17	2534.89	4.72	0.002	0.030*
freq15:amp2	2.28	2534.89	5.20	0.002	0.023*
freq18:amp2	1.29	2534.89	1.68	0.001	0.197
freq20:amp2	3.12	2534.89	9.73	0.004	0.002**
freq8:amp3	1.58	2534.89	2.49	0.001	0.114
freq10:amp3	3.32	2546.78	11.01	0.004	0.000***

RMS (% of walking). All fixed-effect estimates reflect the change in normalized RMS relative to the reference condition, defined as frequency = 5 Hz and amplitude = 1 mm. a. *p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001.

Supplementary Table 3. Differences in RMS activation between WBVT and walking across amplitude–frequency combinations.

Frequency	Amplitude	Contrast	Estimate	SE	Lower 95% CI	Upper 95% CI	df	t.ratio	p-value
5Hz	.	2mm- (1mm)	53.81	26.73	1.42	106.20	422.43	2.01	1.000
5Hz	.	3mm- (2mm)	13.32	27.12	-39.84	66.48	417.94	0.49	1.000
8Hz	.	2mm- (1mm)	45.82	26.73	-6.57	98.21	422.43	1.72	1.000
8Hz	.	3mm- (2mm)	40.64	27.12	-12.52	93.80	417.94	1.5	1.000
10Hz	.	2mm- (1mm)	79.56	26.73	27.17	131.95	422.43	2.98	0.098
10Hz	.	3mm- (2mm)	56.8	27.52	2.86	110.74	427.63	2.06	1.00
13Hz	.	2mm- (1mm)	89.81	26.73	37.42	142.20	422.43	3.36	0.027
13Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
15Hz	.	2mm- (1mm)	88.62	26.73	36.23	141.01	422.43	3.32	0.032
15Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
18Hz	.	2mm- (1mm)	55.93	26.73	3.54	108.32	422.43	2.09	1.000
18Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
20Hz	.	2mm- (1mm)	118.36	26.73	65.97	170.75	422.43	4.43	0.000
20Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
.	1mm	8Hz-(5Hz)	32.12	25.14	-17.15	81.39	598.73	1.28	1.000
.	1mm	10Hz- (8Hz)	19.79	25.14	-29.48	69.06	598.73	0.79	1.000
.	1mm	13Hz- (10Hz)	24.48	25.14	-24.79	73.75	598.73	0.97	1.000
.	1mm	15Hz- (13 Hz)	-0.05	25.14	-49.32	49.22	598.73	-0.0	1.000
.	1mm	18Hz- (15Hz)	36.0	25.14	-13.27	85.27	598.73	1.43	1.000
.	1mm	20Hz- (18Hz)	-12.79	25.14	-62.06	36.48	598.73	-0.51	1.000
.	2mm	8Hz-(5Hz)	24.14	25.14	-25.13	73.41	598.73	0.96	1.000
.	2mm	10Hz- (8Hz)	53.53	25.14	4.26	102.80	598.73	2.13	1.000
.	2mm	13Hz- (10Hz)	34.72	25.14	-14.55	83.99	598.73	1.38	1.000
.	2mm	15Hz- (13Hz)	-1.24	25.14	-50.51	48.03	598.73	-0.05	1.000
.	2mm	18Hz- (15Hz)	3.31	25.14	-45.96	52.58	598.73	0.13	1.000
.	2mm	20Hz- (18Hz)	49.65	25.14	0.38	98.92	598.73	1.98	1.000
.	3mm	8Hz-(5Hz)	51.45	25.8	0.88	102.02	598.73	1.99	1.000
.	3mm	10Hz- (8Hz)	69.69	26.22	18.30	121.08	604.9	2.66	0.258
.	3mm	13Hz- (10Hz)	NA	NA	NA	NA	NA	NA	NA
.	3mm	15Hz- (13Hz)	NA	NA	NA	NA	NA	NA	NA
.	3mm	18Hz- (15Hz)	NA	NA	NA	NA	NA	NA	NA
.	3mm	20Hz- (18Hz)	NA	NA	NA	NA	NA	NA	NA

RMS (% of walking). Reference levels (freq=5 Hz, amp=1 mm); CI definition (95%); Model-based marginal means (emmeans) with Bonferroni within-family adjustment.

Supplementary Table 4. Differences in RMS activation between WBVT and running across amplitude–frequency combinations.

Frequency	Amplitude	Contrast	Estimate	SE	Lower 95% CI	Upper 95% CI	df	t.ratio	p-value
5Hz	.	2mm- (1mm)	29.47	23.99	-17.55	76.49	269.97	1.23	1.000
5Hz	.	3mm- (2mm)	5.19	24.35	-42.54	52.92	267.67	0.21	1.000
8Hz	.	2mm- (1mm)	41.39	23.99	-5.63	88.41	269.97	1.73	1.000
8Hz	.	3mm- (2mm)	41.47	24.35	-6.26	89.20	267.67	1.70	1.000
10Hz	.	2mm- (1mm)	77.75	23.99	30.73	124.77	269.97	3.24	0.043
10Hz	.	3mm- (2mm)	59.27	24.70	10.86	107.68	276.41	2.40	0.546
13Hz	.	2mm- (1mm)	95.01	23.99	47.99	142.03	269.97	3.96	0.003
13Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
15Hz	.	2mm- (1mm)	98.31	23.99	51.29	145.33	269.97	4.10	0.002
15Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
18Hz	.	2mm- (1mm)	68.53	23.99	21.51	115.55	269.97	2.86	0.148
18Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
20Hz	.	2mm- (1mm)	123.60	23.99	76.58	170.62	269.97	5.15	0.000
20Hz	.	3mm- (2mm)	NA	NA	NA	NA	NA	NA	NA
.	1mm	8Hz-(5Hz)	26.83	21.34	-14.99	68.66	594.06	1.26	1.000
.	1mm	10Hz- (8Hz)	12.73	21.34	-29.10	54.56	594.06	0.60	1.000
.	1mm	13Hz- (10Hz)	13.68	21.34	-28.15	55.51	594.06	0.64	1.000
.	1mm	15Hz- (13Hz)	3.94	21.34	-37.89	45.77	594.06	0.18	1.000
.	1mm	18Hz- (15Hz)	29.88	21.34	-11.95	71.71	594.06	1.40	1.000
.	1mm	20Hz- (18Hz)	-4.51	21.34	-46.34	37.32	594.06	-0.21	1.000
.	2mm	8Hz-(5Hz)	38.76	21.34	-3.07	80.59	594.06	1.82	1.000
.	2mm	10Hz- (8Hz)	49.08	21.34	7.25	90.91	594.06	2.30	0.698
.	2mm	13Hz- (10Hz)	30.94	21.34	-10.89	72.77	594.06	1.45	1.000
.	2mm	15Hz- (13Hz)	7.24	21.34	-34.59	49.07	594.06	0.34	1.000
.	2mm	18Hz- (15Hz)	0.10	21.34	-46.42	37.24	594.06	0.01	1.000
.	2mm	20Hz- (18Hz)	50.55	21.34	-41.73	41.93	594.06	2.37	0.582
.	3mm	8Hz-(5Hz)	75.04	21.91	8.72	92.38	594.06	3.43	0.021
.	3mm	10Hz- (8Hz)	66.89	22.29	32.10	117.98	599.71	3.00	0.090
.	3mm	13Hz- (10Hz)	NA	NA	23.20	110.58	NA	NA	NA
.	3mm	15Hz- (13Hz)	NA	NA	NA	NA	NA	NA	NA
.	3mm	18Hz- (15Hz)	NA	NA	NA	NA	NA	NA	NA
.	3mm	20Hz- (18Hz)	NA	NA	NA	NA	NA	NA	NA

RMS (% of walking). Reference levels (freq=5 Hz, amp=1 mm); CI definition (95%); Model-based marginal means (emmeans) with Bonferroni within-family adjustment.