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ORIGINAL ARTICLE

Brief skin cooling modulates the reflexes generated by whole-body vibration

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Abstract

Background Whole-body vibration (WBV) is a popular exercise method known for its neuromuscular benefits, though the underlying mechanisms remain unclear. WBV activates distinct reflexes based on vibration amplitude and voluntary muscle activity: low-amplitude vibration or voluntary contraction typically triggers the tonic vibration reflex (TVR), whereas high-amplitude vibration or quiet standing activates the bone myoregulation reflex (BMR). Muscle spindles, which are sensitive to sympathetic input, may exhibit increased responsiveness to vibration during brief skin cooling.

Objectives This study investigated the reflex mechanisms activated by WBV during quiet standing and their modulation by skin cooling.

Methods Thirty healthy young adults participated. The latency of the soleus TVR, induced by Achilles tendon vibration, and the latency of the soleus BMR, induced by WBV, were measured. These assessments were repeated during the cold pressor test (CPT), involving left-hand immersion in cold water.

Results The soleus TVR latency was 36.2 ± 5.1 ms, while the soleus BMR latency was 40.4 ± 5.0 ms. During CPT, Achilles tendon vibration latency remained unchanged (36.2 ± 5.7 ms, $p = 0.319$). However, the WBV-induced reflex latency with CPT (36.0 ± 6.1 ms, $p < 0.0001$) was significantly shorter than the soleus BMR latency and aligned with the TVR latency ($p = 0.711$).

Conclusion WBV activates BMR in a quiet standing position, but with skin cooling, the TVR predominates, likely due to heightened spindle sensitivity. These findings offer valuable insights into developing targeted WBV programs.

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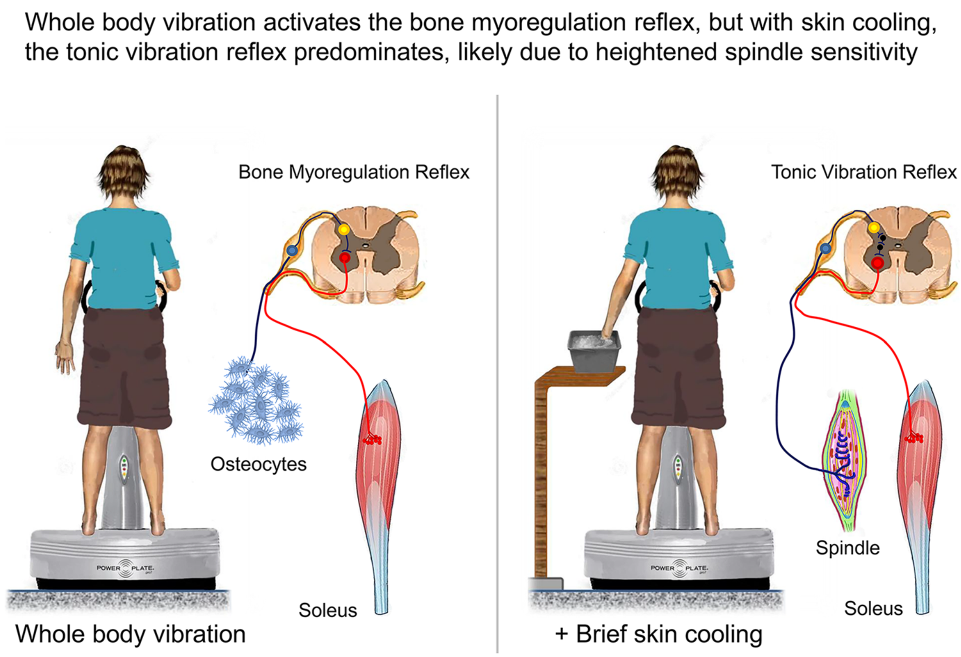
Graphical abstract



Keywords Cryotherapy · Exercise physiology · Motor facilitation · Strengthening exercise · Vibration

Abbreviations

Acc	Accelerometer
BMR	Bone myoregulation reflex
CPT	Cold pressor test
ms	Milliseconds
SE	Standard error
sEMG	Surface EMG
TV	Tendon vibration
TVR	Tonic vibration reflex
WBV	Whole-body vibration

Introduction

Whole-body vibration (WBV) has gained popularity as an exercise method in sports training and neurological rehabilitation due to its beneficial neuromuscular effects, including improvements in balance, postural stability, muscle activity, strength, and overall performance. (Alam et al. 2018; AlBaiti et al. 2024; Aydin et al. 2020; Cidem et al. 2014; De Meirelles et al. 2024; Monteiro-Oliveira et al. 2022; Rittweger 2020; van Heuvelen et al. 2021). Evidence suggests that these beneficial effects can be explained by two different neuromuscular mechanisms: the tonic vibration reflex (TVR) and the bone myoregulation reflex (BMR) (Aydin et al. 2020; Cakar et al. 2015; Kalaoğlu et al. 2023a; Kalaoğlu et al. 2023b; Karacan et al. 2017; Karacan and Türker 2024; Kvorning et al. 2006; Mester et al. 2006; Pollock et al. 2012; Ritzmann et al. 2010; Yang 2020; Yildirim et al. 2020).

TVR is a polysynaptic motor response believed to result from vibration-induced muscle spindle activation (Matthews 1966). However, despite widespread assumptions, limited publications confirm that muscle spindles are the primary receptors activated by WBV in a semi-squat position (Aydin et al. 2020; Kalaoğlu et al. 2023a). Experimental findings indicate that osteocytes, rather than muscle spindles, may act as the receptors activated by WBV, implicating the BMR when standing upright in a neutral position (Cakar et al. 2015; Kalaoğlu et al. 2023b; Karacan et al. 2017; Karacan and Türker 2024; Yildirim et al. 2020). WBV performed in an upright neutral position has been reported to increase knee flexor strength and hip adductor muscle activity (Cidem et al. 2014; Karamehmetoglu et al. 2014). A clear understanding of the conditions under which WBV stimulates specific receptor systems (i.e., muscle spindles, osteocytes) is crucial for the design rationale and, ultimately, the effectiveness of WBV training programs.

Muscle spindles are known to receive sympathetic innervation (Radovanovic et al. 2015). Brief skin cooling has been shown to increase sympathetic activity, enhance muscle spindle sensitivity, facilitate the stretch reflex, and improve voluntary contraction (Cetin et al. 2024; Kamibayashi et al. 2009). The modulation of muscle spindle sensitivity through sympathetic activity may provide an opportunity to characterize better the reflex response triggered during WBV. The increased muscle spindle sensitivity induced by brief local skin cooling could lead to a more pronounced and stronger TVR response during WBV.

This study is based on two primary hypotheses: first, that WBV induces the BMR in a quiet standing position (without voluntary contraction), with a longer latency compared to the TVR in the soleus muscle, and second, that when a cold pressor test (CPT) is applied to the left hand simultaneously with WBV in the same position, the TVR becomes the dominant reflex response. The objective of this study is to test these hypotheses.

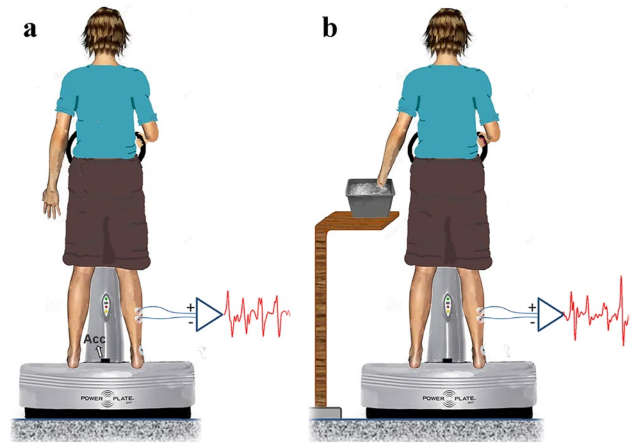


Fig. 1 Experimental design to determine vibration-induced soleus reflex latency. To assess WBV-induced soleus reflex responses, an accelerometer (Acc) was mounted on the WBV platform, and soleus sEMG recordings were simultaneously collected during WBV. **a** WBV was applied alone. **b** WBV was then applied in combination with CPT. Tendon vibration-induced soleus reflex responses were recorded via sEMG while the subject stood upright on the same platform in the same position. A custom-made local vibrator with an integrated accelerometer was attached to the Achilles tendon for tendon vibration

Methods

Participants

Thirty-three healthy young adult residents (20 males, 13 females) undergoing training at our institution were invited to participate in the study. Exclusion criteria included the presence of scars, dermatitis, or other skin conditions at the site where the surface EMG (sEMG) electrode would be placed, a history of kidney stones, intolerance to WBV during the familiarization protocol, and cold allergy. Participants had no prior experience with the WBV device but underwent a familiarization protocol to acclimate before the experiment. Three participants were excluded due to complaints of dizziness during WBV.

The local ethics committee approved the study protocol (approval no. 2022.06.136). Informed consent was obtained from all participants. The study was completed with 30 subjects. The participants had a mean age of 28.8 ± 5.8 years and an average height of 171.6 ± 9.2 cm. Their mean body mass index was 24.2 ± 3.3 kg/m^2.

Procedure

All subjects underwent WBV alone, followed by WBV combined with a CPT. Similarly, Achilles tendon vibration alone was followed by Achilles tendon vibration combined with a CPT. WBV and Achilles tendon vibration were applied randomly, with a 5-min rest period between applications (Fig. 1). During the CPT, subjects were instructed to immerse their left hand in ice water. sEMG recordings were taken from the soleus muscle during the mechanical vibration applications to evaluate reflex responses. Reflex latencies were calculated using the"Cumulative Average Method"(Karacan et al. 2014).

Cold pressor test

The participant's left hand, up to the wrist, was submerged in an ice-water bath (2–4 °C) for 3 min and then immediately dried. Between the tendon vibration test and the WBV test, the dorsum skin temperature of the hand was monitored until it returned to the baseline value. The experiment was resumed once temperature measurements confirmed that it had reached the baseline value. The laboratory temperature was maintained at approximately 24 °C throughout the experiments.

Whole-body vibration

WBV was applied using the PowerPlate® Pro5 WBV device (London, UK). Subjects were asked to stand upright on the vibrating platform with their lower extremity joints in a neutral position while holding onto the platform arms for support (Fig. 1). The mechanical vibration amplitude was set to 2 mm, and vibrations were applied at three different frequencies (30, 35, and 40 Hz). Each vibration session lasted 45 s, with a minute rest interval between frequencies. Different frequencies were used to pinpoint the effective stimulation time point on the mechanical vibration wave as explained in the legend of Fig. 2. A piezoelectric accelerometer (LIS344 ALH, full-scale of ± 6 g, linear accelerometer, ECOPACK®, Mansfield, TX, USA) was affixed to the WBV platform for reflex latency calculations.

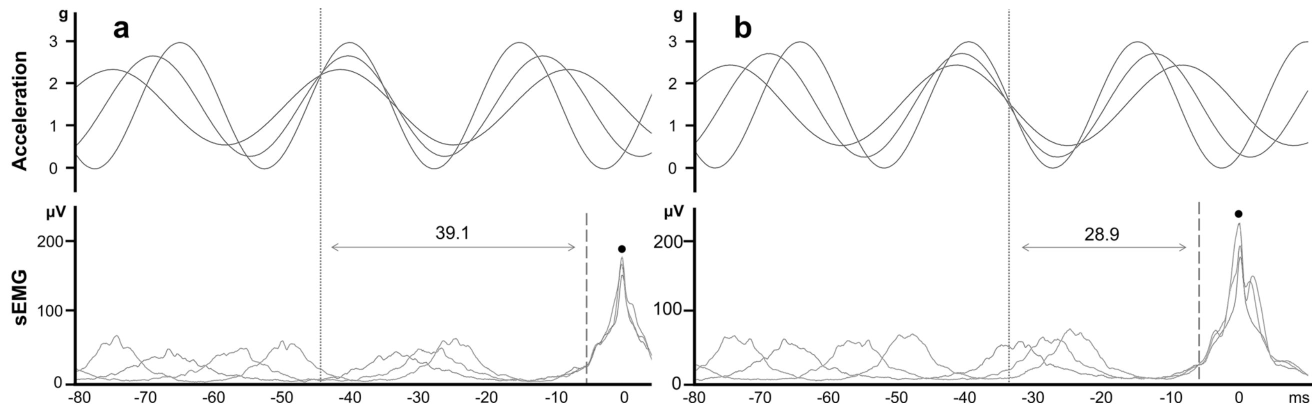


Fig. 2 Determination of WBV-induced reflex responses using the cumulative average method. **a** When WBV was applied alone, a BMR response was observed. **b** When simultaneous CPT was applied, WBV induced a reflex response with shorter latency. The filled solid circle marks the peaks, which serve as triggers in the filtered and rectified sEMG. To determine the onset of the vibration stimulus, peaks in the rectified EMG traces were first identified using LabChart 7, with solid circles marking these peaks in the filtered and rectified sEMG signals. Accelerometer data were averaged within time windows spanning 80 ms before and 10 ms after each peak. This process was performed separately for three WBV periods, each corresponding to a different vibration frequency (30, 35, and 40 Hz). The averaged accelerometer data for each frequency were then combined to generate a cumulative mean for each participant. The effective stimulus time point was defined as the moment when the standard error of the cumulative accelerometer data was at its lowest. In the acceleration recordings, this effective stimulus point is indicated by a dotted vertical line. A similar process was applied to EMG signals to determine the onset of the reflex response. Reflex latency was evaluated as the time interval between the effective stimulus time point and the onset of the reflex response in the EMG recordings

Achilles tendon vibration

To apply Achilles tendon vibration, subjects were asked to stand upright on the WBV platform as previously described. The mechanical vibration was delivered to the right Achilles tendon using a custom-made vibrator at three different frequencies (90, 100, and 110 Hz), each lasting 45 s. A piezoelectric accelerometer (LIS344 ALH, full-scale of ± 6 g, linear accelerometer, ECOPACK®, Mansfield, TX, USA) was affixed to the skin over the Achilles tendon to calculate the latency of the TVR.

Surface EMG recording

sEMG recordings were obtained from the right soleus muscle using the bipolar technique. Self-adhesive Ag/AgCl electrodes (Redline®, Istanbul, Turkey) were used for the recordings. The electrodes were positioned on the lateral soleus muscle belly, while the ground electrode was placed on the right lateral malleolus (Tucker and Turker 2005). Before attaching the electrodes, the skin was prepared by shaving hair and cleaning the area with alcohol-soaked cotton to remove the oil layer. ECG gel was applied to the electrode placement area to enhance skin conductivity.

sEMG and accelerometer recordings were acquired using a data acquisition system (Power1401 MK 2, Cambridge Electronic Design Limited, Cambridge, England) at a sampling rate of 20 kHz. The data were analyzed offline with LabChart7 Pro® software (version 7.3.8, ADInstrument, Oxford, UK).

Cumulative average method

The cumulative averaging method calculated reflex latencies induced by WBV and tendon vibration (Karacan et al. 2014; Kilic et al. 2023). The cumulative averaging method was used to calculate reflex latency by utilizing the electrical activity of the soleus muscle recorded with sEMG and the signals recorded by the accelerometer mounted on the vibrating platform for BMR or the accelerometer fixed on the skin above the Achilles tendon for TVR. sEMG recordings were first filtered and then rectified. For WBV recordings, a 60 Hz high-pass filter was applied, while a 120 Hz high-pass filter was used for tendon vibration recordings. Peaks in the rectified sEMG signal were identified and marked. Spike-triggered averaging was performed using these sEMG peaks as triggers and the acceleration data as the source. The averaging process included 80 ms (ms) of acceleration data preceding the trigger point and 10 ms following it. This process was repeated separately for each of the three vibration frequencies. Each frequency's resulting average acceleration curves were superimposed to generate a cumulative average curve. The standard errors (SEs) of the averaged acceleration data across the three vibration frequencies were calculated for each 1600 bins within the averaging window (− 80 ms to the trigger). The point with the lowest SE in the SE curve was identified as the"effective stimulation point"in the Cumulative average acceleration curve (Fig. 2).

A similar averaging procedure was applied to the sEMG recordings to determine the onset time of the reflex response. The point with the lowest SE in the cumulative average sEMG trace was considered the time at when reflex responses to the mechanical vibration were most synchronized, marking the onset of the reflex response.

The latency of the reflex response was calculated as the time difference between the effective mechanical stimulus point and the onset of the sEMG reflex muscle response. This latency was normalized to the participants'height and reported in milliseconds. Normalizing latency to height eliminates the effect of anatomical differences, such as axon lengths, on nerve conduction time. Since nerve conduction speed is constant, this process allows for a more objective evaluation of reflex mechanisms by removing these natural variations (Stetson et al. 1992).

Skin temperature measurement

Skin temperature was measured using an infrared thermometer (Bosch® UniversalTemp) at a pre-marked point on the back of the hand, both before and immediately after immersion in ice water during tendon vibration or whole-body vibration trials. The thermometer had a measurement accuracy of ±0.2 °C.

Statistical Analysis

The normality of the data distribution was evaluated using the Shapiro–Wilk test. Continuous variables were summarized as the arithmetic mean and standard deviation, while categorical variables were expressed as frequency (percentage). Latency means were compared using either a paired t test or the Wilcoxon test, depending on whether the data met the normality assumption. A p value < 0.05 was considered statistically significant. All analyses were conducted using PASW Statistics for Windows, Version 18.0 (SPSS Inc, Armonk, NY).

Results

When Achilles tendon vibration was applied, the TVR latency was 36.2 ±5.1 ms. During CPT, no significant difference was observed in the latency between the tendon vibration-induced reflex and the TVR ($p = 0.319$, Wilcoxon test) (Fig. 3). In contrast, when WBV was applied, the BMR latency was 40.4 ±5.0 ms. During CPT, the latency of the WBV-induced reflex (35.8 ±6.1 ms) was significantly shorter than that of the BMR ($p < 0.0001$, Cohen's d effect size: 0.77, paired t test) (Fig. 3). However, no significant difference was found in latency between the TVR and the reflex induced by WBV combined with CPT (36.0 ±6.1 ms) ($p = 0.711$, paired t test).

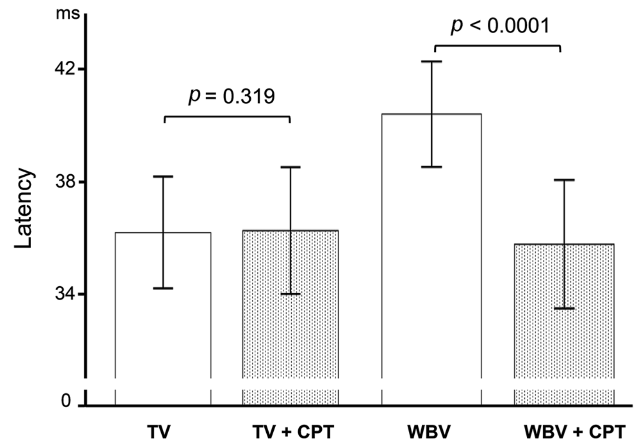


Fig. 3 Reflex latencies for WBV, tendon vibration (TV), and changes in latency values with the CPT for all cases. Error bars represent the 95% confidence interval

Skin temperature decreased from 31.5 ±2.3 °C to 10.8 ±1.6 °C in WBV tests and from 31.3 ±2.6 °C to 11.2 ±2.1 °C in Achilles tendon vibration tests after brief cooling.

Discussion

This study yielded two main findings that support both of our hypotheses. First, WBV activates the bone myoregulation reflex in a quiet standing position, as previously described (Cakar et al. 2015; Kalaoğlu et al. 2023b; Karacan et al. 2017; Karacan and Türker 2024; Yildirim et al. 2020). Second, when CPT and WBV are applied simultaneously, the TVR, which has a shorter latency, becomes the dominant reflex, possibly due to the increased sensitivity of the muscle spindles.

The bone myoregulation reflex

This reflex is a mechanism that explains the neuronal communication between bone and muscle. According to this concept, signals originating from mechanically loaded bone reflexively regulate skeletal muscle activity at the spinal cord level. In this reflex pathway, the mechanosensitive osteocytic network within the bone matrix functions as the receptor. Mechanical stimuli detected by this network are transmitted to the spinal cord via thick, myelinated afferent fibers. This information is then conveyed to skeletal muscles through alpha (motor) fibers, reflexively regulating muscle function (Karacan et al. 2009; Karacan and Türker 2024).

Osteocytes, the mechanosensitive cells of bone, constitute more than 90–95% of all bone cells in the adult skeleton. Living bones are susceptible to mechanical loads within the 15–30 Hz frequency range. Subjects standing upright on a vibrating platform are exposed to cyclic mechanical loading, potentially stimulating mechanosensitive osteocytes (de Oliveira et al. 2023; Karacan and Türker 2024). Sclerostin, a mechanosensitive protein secreted exclusively by osteocytes, has been shown to have serum levels associated with the soleus bone myoregulation reflex response (Cidem et al. 2014; Karamehmetoglu et al. 2014). Previous studies have reported that the mean latency of the soleus bone myoregulation reflex ranges between 40 and 44 ms (Cakar et al. 2015; Corum et al. 2022; Kalaoğlu et al. 2023a, b; Karacan et al. 2017; Yildirim et al. 2020). In this study, the latency of the reflex response activated during WBV was measured as 40.4 ± 5.0 ms and identified as the bone myoregulation reflex. When WBV was combined with brief skin cooling, a shorter latency soleus reflex response (36.0 ± 6.1 ms) was observed. This short-latency reflex was classified as TVR, as its latency matched that of the soleus reflex induced by Achilles tendon vibration.

Two possible explanations can account for the shorter-latency reflex response observed with CPT application. The first explanation is that muscle spindles, which remain inactive during WBV alone, become activated when combined with CPT, leading to a more pronounced TVR response that dominates over the BMR reflex. In this study, the reflex latency induced by WBV ranged from 15 to 20 ms, with a difference of approximately 4.5 ms observed between the latencies of TVR and BMR. Since the dominant TVR appears 4.5 ms earlier, it may mask the simultaneously occurring BMR reflex in EMG recordings.

The second explanation is that the BMR reflex may be inhibited during CPT. Mechanical vibration activates mechanoreceptors such as Piezo1 in the osteocyte membrane, triggering mechanotransduction—the process by which vibratory stimulus energy is converted into action potentials (Sá-Caputo et al. 2023). Osteocytes also express adrenergic receptors, making them responsive to sympathetic activity. Increased sympathetic activation influences intracellular and intercellular signaling pathways, including RANKL, sclerostin, and intracellular calcium, in ways that promote bone loss (Patel and Elefteriou 2007; Uchibori et al. 2020). This mechanism suggests that heightened sympathetic activity may reduce the mechanosensitivity of osteocytes. According to Frost's mechanostat theory, which explains how mechanosensitive osteocytes regulate bone modeling and remodeling in response to mechanical loading, a decrease in mechanosensitivity could contribute to bone loss (Frost 2001, 2004).

Tonic vibration reflex

It is well established that tendon vibration activates muscle spindles and the TVR (De Gail et al. 1966; Matthews 1966). Previous studies have reported that the mean latency of the soleus TVR ranges between 31 and 36 ms (Corum et al. 2022; Kalaoğlu et al. 2023a, b; Yildirim et al. 2020). In this study, TVR response with a latency of 36.2 ± 5.1 ms was found to be activated by Achilles tendon vibration.

Whole body vibration

It has been reported that WBV activates different neuromuscular mechanisms depending on the conditions. Specifically, the mechanical vibration amplitude determines whether WBV primarily activates the BMR or the TVR. Studies have shown that the TVR is triggered when the mechanical vibration amplitude is < 0.25 mm, while amplitudes > 1 mm activate the BMR (Karacan et al. 2017). In this study, a 2 mm amplitude vibration was applied, and the BMR, with a latency of 40.4 ms, was observed to be activated. Similarly, the muscle's voluntary activation status influences which mechanism WBV predominantly activates. During isometric contractions, such as a semisquat, WBV activates the TVR (Aydin et al. 2020; Kalaoğlu et al. 2023a). In contrast, in the absence of voluntary contraction, it activates the BMR (Cakar et al. 2015; Kalaoğlu et al. 2023b; Karacan et al. 2017; Karacan and Türker 2024; Yildirim et al. 2020). This study confirmed that WBV activates the BMR when subjects are standing quietly. Notably, it is the first to demonstrate that WBV can activate the TVR in the same quiet standing position when brief cold applications are administered.

Study limitations and strengths

This study has some limitation: first, activating the BMR requires the individual to stand upright; therefore, the findings are limited to WBV applied in an upright standing position. Second, sympatheticactivity was not directly assessed during the CPT. Previous studies have reported increased sympathetic activity and enhanced muscle spindle sensitivity in response to the CPT, and our findings were interpreted based on this existing literature (Cetin et al. 2024; Kamibayashi et al. 2009). A strength of this study is its exceptionally high statistical power, with post-hoc analyses revealing a power of 98.2%. Another strength lies in its provision of valuable insights into the spinal mechanisms underlying the neuromuscular effects of WBV, as well as offering new information for designing exercise programs tailored to specific conditions, such as muscle strengthening and spasticity resolution.

Conclusion

In conclusion, this study demonstrated that low-frequency WBV with a 2-mm amplitude activated the bone myoregulatory reflex in the quiet standing position, and triggered the tonic vibration reflex with shorter latency when combined with the CPT. Previously inactive muscle spindles may have been sensitized by the sympathetic activation during CPT, making them more responsive to low-frequency WBV. Given the modulatory effects of brief skin cooling on the neuromuscular mechanisms of WBV, future research cold focus on developing more effective strategies to enhance muscle strength and reduce spasticity.

Authors contribution EK: conceptualization, methodology, resources, validation, investigation, writing—original draft, visualization; OA, SS, MA: conceptualization, methodology, resources, investigation, writing—original draft; KST, IK: conceptualization, methodology, resources, formal analysis, investigation, writing—original draft, writing—review & editing, supervision.

Data availability Data are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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