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Review article

Effects of Whole Body Vibration on the Neuromuscular Amplitude of Vastus Lateralis Muscle

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Abstract
The aim of this study was to investigate the effects of whole-body vibration (WBV) on vastus lateralis (VL) surface electromyographic (sEMG) amplitude during an isometric semi-squat exercise, using two different frequencies, and to verify the influence of additional filters on the analyzed sEMG signal's characteristics. Forty physically active women were randomly divided into two groups with 20 members each: one group performed an isometric semi-squat exercise at 30 Hz – while the other group performed the same exercise protocol at 50 Hz. The sEMG amplitude of the VL muscle was recorded during the exercise protocols in two conditions: with and without vibration. After removing vibration-induced artifacts using digital filters, sEMG amplitude of VL increased significantly ($p < 0.05$) without differences between the frequencies. The results of this study suggest that WBV at 30 Hz and 50 Hz increased the sEMG amplitude of the VL muscle during an isometric semi-squat exercise. Furthermore, applying sEMG filters during signal processing of WBV is necessary, because motion artifacts from the vibration frequencies may contribute to the contamination of the sEMG amplitude.

Key words: Electromyography; muscle activity; quadriceps muscle.

Introduction

Whole-body vibration (WBV) has been gaining more prominence in recent years among medical and sports specialists. Considered to be a safe and practical method, training associated with vibration has been shown to be an alternative and efficient exercise modality in treating patients with functional limitations, as well as for high performance training in athletes (Albasini et al., 2010; Ritzmann et al., 2010; Pollock et al., 2010).

Evidence that the vibratory stimulus is capable of increasing neuromuscular activity has been demonstrated by studies involving surface electromyography (Lienhard et al., 2014; Ritzmann et al., 2010; Wirth et al., 2011). Although there is no consensus about the mechanisms by which the vibratory stimulus affects the neuromuscular system, it has been suggested that the cause of the increase in motor unit recruitment is an excitatory response of the muscle spindles, due to the stretch reflex mechanism (Bosco et al., 1999a; Cardinale and Lim 2003; Pollock et al., 2012; Torvinen et al., 2002; Seidel, 1988; Xu et al., 2015).

It has been demonstrated that neurophysiological factors involved in the response to vibratory stimulus have an important contribution of the oscillation frequency at which body structures are exposed (Bazett-Jones et al., 2008; Cardinale and Lim 2003). In a review analyzing the influence of vibration characteristics on neuromuscular performance, Luo et al., (2005) recommended that the most effective frequencies to achieve greater muscle activation are between 30 and 50 Hz.

It is suggested that increased muscle activity during exercises associated with vibration is related to the use of higher frequencies and amplitudes (Hazell et al., 2007; Pollock et al., 2010). Contrary, Cardinale and Lim (2003) reported that the 30 Hz vibration frequency was responsible for providing greater activation of the vastus lateralis (VL) muscle when compared to 40 and 50 Hz.

Despite its wide use in sports training and patient rehabilitation, there is still controversy regarding the factors that initiate neurophysiological responses in skeletal muscle during WBV. In addition, the different types of vibration (synchronous and alternate) and the wide range of frequency and amplitude combinations reported in various studies (Bazett-Jones et al., 2008; Bosco et al., 2009b; Cardinale and Lim, 2003; De Ruiter et al., 2003; Torvinen et al., 2002; Ritzmann et al., 2013), besides the inconsistent results make it difficult to interpret the efficacy of WBV.

Some authors have demonstrated the need for greater caution in carrying out studies involving surface electromyography analysis during vibration (Abercromby et al., 2007; Fratini et al., 2009). Electromyographic signal contamination during the vibratory stimulus occurs due to the presence of motion artifacts caused by the performed oscillation frequency (Lienhard et al., 2014; Sebik et al., 2013; Wirth et al., 2011). Although often neglected in some studies, using additional filters during signal treatment is recommended to remove such vibration-induced artifacts that can lead to misinterpretation of the analyzed data (Lienhard et al., 2015b; Sebik et al., 2013).

Riztmann et al., (2010) conducted an analysis about the factors that may compromise the quality of the sEMG signal. These authors suggested that the contribution of motion artifacts are insignificant and not representative compared to vibration-induced reflex muscle activation, showing that it is possible to use sEMG data collected during vibration without applying additional filters.

Considering the above, this study was designed to analyze the effects of WBV on VL sEMG amplitude in healthy subjects using two different commonly used train-

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ing frequencies (30 Hz and 50 Hz) as well as to verify the existence of vibration-induced artifacts and the influence of additional filters on the analyzed signal's characteristics. To our knowledge, few studies (Abercromby et al., 2007; Fratini et al., 2009; Lienhard et al., 2015a; Ritzmann et al., 2010; Sebik et al., 2013) have analyzed this issue making it difficult to give an exact quantification of sEMG activity during the WBV, which may compromise the quality and reliability of the analyzed data. Moreover, most of them were restricted to aspects related to the frequency spectrogram, without taking into account the effects on the amplitude of the electromyographic signal and its responses to different frequencies of vibratory stimulus after proper sEMG signal processing.

Therefore, we hypothesized that without adequate removal of vibration-induced artifacts from the electromyographic signal, VL muscle activity during a vibration exercise protocol would be higher in comparison in the same exercise without vibration, with no difference between vibration frequencies. In contrast, we believe that a possible increase in sEMG amplitude would no longer be detected after appropriate signal treatment and removal of such vibration-induced artifacts.

Methods

Participants

The study sample consisted of forty physically active women (average age: 22.9 ± 2.8 years; body mass index - BMI: 23 ± 2.5 Kg/m^2) recruited in a non-probabilistic way from a local university. The inclusion criteria were: healthy female, involved in recreational physical activity at least three times a week without training at a competitive level (Pincivero et al., 2003), aged between 18 and 28 years. Exclusion criteria were inability to understand protocol commands, incorrect execution of assessment procedures or presence of pain, discomfort, vertigo or dizziness during the tests and interventions. Following these criteria, there were no reported exclusions for this study (Figure 1).

This study was approved by the local university Research Ethics Committee (protocol number 752.291) and conforms to ethical aspects based on Resolution 466/12 of the National Health Council and Declaration of Helsinki. All volunteers that participated in the study gave their written informed consent after being explained about the research objectives, risks and benefits. This study is registered at www.clinicaltrials.gov under the number NCT02416362.

Design of the study

This is an observational cross-sectional analytical study with a two-group, repeated measures design. The volunteers were randomly divided, using the method of randomly permuted blocks from the website (www.randomization.com). The participants were allocated into two different groups of 20 individuals each: 30 Hz and 50 Hz group.

All participants underwent a preliminary isometric evaluation of the non-dominant lower limb to normalize the electromyographic signal. Participants were seated in a chair of a computerized isokinetic dynamometer (Biodex Multi-Joint System 4, Biodex Biomedical System Inc. ®, New York, USA) where they were secured by straps for chest, pelvic, and thigh regions that prevented possible movement to influence the result. The rotation axis of the dynamometer was aligned with the lateral epicondyle of the femur and the lever arm was adjusted and fixed to the distal region of the leg according to the recommendations of Dvir (2004). The gravity correction factor was performed on the dynamometer using the weight of the lower limb at 30° of knee flexion. The participants performed

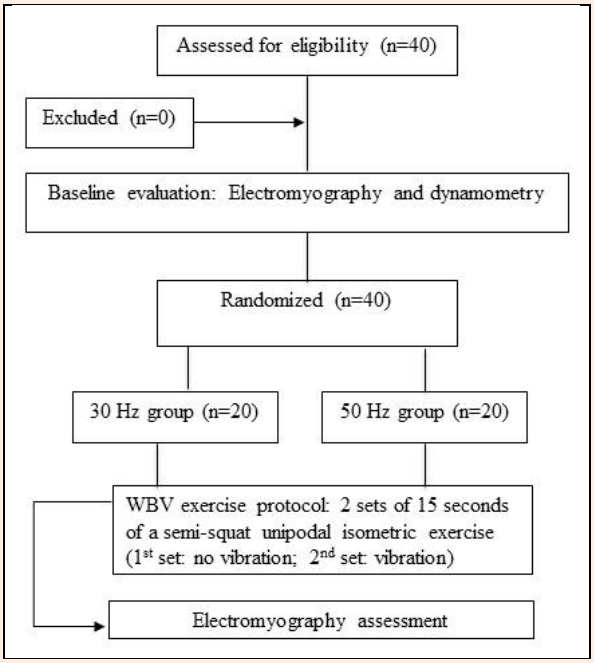

Figure 1. Study flow diagram.

two maximum voluntary isometric contractions (MVIC) for the knee extensors at 60° over five seconds with 60 seconds interval between each repetition (Burden, 2010). The contraction that produced the greatest peak torque was used for the normalization of the electromyographic signal. Familiarization with the equipment was performed 1 minute before the evaluation by conducting two submaximal contractions to allow the subjects to become acquainted to the testing protocol. Throughout the MVIC's standard verbal encouragement was provided, and participants received visual feedback from the isokinetic dynamometer monitor.

sEMG instrumentation and measurement

To record surface electromyography (sEMG) activity, the skin was prepared by cleansing it with 70% alcohol and removing dead skin with a scouring pad prior to electrode placement. The EMG signal was captured by an 8 channels signal module (Telemyo direct transmission system, Noraxon®, USA) with a resolution of 16 bits and common-mode rejection ratio >100 Db. The capture of the signal was accomplished through passive surface self-adhesive bipolar silver-chloride electrodes (Noraxon®, USA), of 4 cm in length and 2.2 cm in width, separated by an inter-electrode distance of 2 cm. EMG amplitude of the VL muscle was captured in accordance with the Surface Electromyography for the Non-Invasive Assessment of Muscles (Hermens et al., 2000). The EMG assessment was conducted in during the MVIC's and the entire WBV exercise protocol, resulting in a sampling period of 5 seconds for the signal collected during the MVIC and 15 seconds for each series of the exercise protocol.

The EMG signal processing was performed using Matlab software (version R2012a Math Works, Inc., Massachusetts, USA). The signals were collected at a sampling frequency of 1500 Hz, filtered at a frequency between 20 and 500 Hz and amplified 1000 times. As previously recommended by some authors (Abercrombry et al., 2007; Fratini et al., 2009; Lienhard et al., 2015b), additional notch-filters were applied for the 30 Hz and 50 Hz vibration frequencies and its multiple harmonics for each group to ensure that all motion artifacts were removed from de EMG signal. The raw sEMG data were full wave rectified, filtered with a 3rd order 60 Hz Butterworth notch filter, and smoothed using a Root Mean Square (RMS) algorithm with a 150-ms moving window with 50-ms overlap. The outcome measure of mean RMS was expressed as a percentage of the MVIC.

WBV exercise protocol

Following baseline evaluation, participants performed the exercise protocol on a vibrating platform (pro5 ™, Power Plate International Ltd., Power Plate North America, Inc.) of synchronous vibration with frequency adjustable in steps of 1 Hz within a range of 25–50 Hz, configurable peak-to-peak displacement between low (2mm) or high (4mm) and minimum peak acceleration of 24.62 $m \cdot s^2$ (2.5 g) and maximum of 197 $m \cdot s^2$ (20 g).

The WBV exercise protocol consisted of remaining barefoot with unilateral standing on the non-dominant leg, which was placed in the center of the vibrating platform at 40° of knee flexion (Caryn et al., 2014; Hannah et al., 2013; Petit et al., 2010), while the upper limbs were extended at shoulder level and the trunk was kept in an upright position. The knee angle was monitored throughout the protocol with a universal goniometer (Figure 2). For the 30 Hz group, the vibration platform was set at a vibration frequency of 30 Hz with a vertical displacement amplitude of 4 mm (Hazell et al., 2007; Marín et al., 2009; Torvinen et al., 2002). The 50 Hz group performed the same WBV protocol, but the vibration frequency was set at 50 Hz. The rationale for the parameter selection was based on several studies that have shown that higher displacement amplitudes and frequencies between 30 Hz and 50 Hz elicit greater EMG responses during static WBV exercises (Hazell et al., 2007; Luo et al., 2005; Marín et al., 2009).

Figure 2. Positioning for the exercise protocol on the vibrating platform.

Every participant performed 2 sets of 15 seconds with a 30 second rest period between sets. In the first set of the protocol, participants performed the WBV protocol with the platform turned off. In the second set the platform was turned on and set to the respective frequency of each group. Familiarization with the procedures was allowed for all groups by performing 1 repetition with duration of 10 seconds of the proposed exercise with a rest period of 2 minutes before the beginning of the intervention.

Statistical analysis

Statistical analysis was performed using SPSS software (version 20, IBM, New York, USA). The normality of data distribution and homogeneity of variances were observed by the Kolmogorov-Smirnov and Levene tests, respectively. A two-way Analysis of Variance (ANOVA) with repeated measures was used to carry out evaluation comparisons. When a significant F value was found, the Bonferroni post hoc test was applied to identify the differences. In all statistical analysis was assigned a significance level of 5% ($p<0.05$) and a confidence interval of 95% (95% CI).

Results

Table 1 illustrates the baseline demographic characteristics of each group, showing that there were no differences between the participants selected for the study.

Table 1. Mean (±standard deviation) values of baseline demographic characteristics and neuromuscular performance values for each group.

Variables	30 Hz (n = 20)	50 Hz (n = 20)
Age (yrs)	22.7 (2.6)	23.2 (3.0)
Height (m)	1.62 (.06)	1.65 (.07)
BMI (kg·m^{-2})	22.7 (2.5)	23.5 (2.7)

BMI: Body Mass Index; Hz: Hertz.

Figure 3 shows the mean and standard deviation values of the RMS of VL of the 30 and 50 Hz frequencies. In relation to sEMG activity during the WBV protocol, there was a significant intra-group interaction (F = 4.6; p = 0.028) between conditions (with and without vibration) in both groups, without differences between them, showing a greater sEMG amplitude of the VL muscle in the condition "with vibration" (Figure 3).

As previously reported by other authors (Abercromby et al., 2007; Fratini et al., 2009), by analyzing the frequency spectrum of the EMG signal without the prior removal of the vibration-induced artifacts, we identified the sharp peaks at the three first harmonics of the active vibration frequency, which were removed by filters (Figure 4). In the 30 Hz group, a significant improvement in the RMS during the WBV protocol was observed in all conditions: WBV with no filter (p=0.018) and WBV with filter (p < 0.001) (Table 2). The same pattern was observed in the 50 Hz group, with a significant improvement in the RMS in the WBV conditions with no filter (p = 0.018) and with filter (p < 0.001) (Table 2).

Discussion

The objective of this study was to analyze the effects of WBV on VL sEMG amplitude during an isometric semi-squat exercise, using two different frequencies, and to verify the influence of additional filters of sEMG signal characteristics. The results demonstrate that when vibration (30 Hz and 50 Hz, 4 mm peak-to-peak displacement) is added to a half squat isometric exercise, it significant increases VL RMS values, after appropriate signal treatment using specific filters for vibration frequencies (30 and 50 Hz), a significant reduction in RMS values was observed when compared to the unfiltered signal. However, VL muscle RMS values with additional vibratory stimulus still remained superior compared to the condition without vibration, thus rejecting our hypothesis that the benefits would no longer be detected after appropriate signal treatment by removing vibration-induced artifacts.

We also found that there were no significant differences in VL RMS values between the implemented frequencies (30 Hz and 50 Hz) during vibration after applying the filters to remove motion artifacts. This data

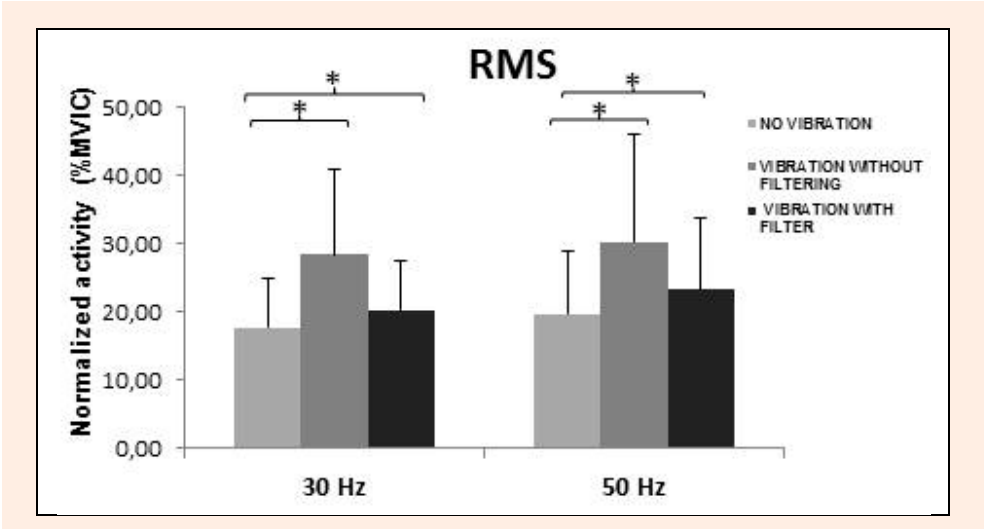

Figure 3. Means and standard deviation values of the Root Mean Square (RMS) and comparison between conditions of 30 and 50 Hz. MVIC = Maximal Voluntary Isometric Contraction; Hz = Hertz. *p < 0.05

Table 2. Mean differences between conditions and confidence intervals for the Root Mean Square (RMS) of VL muscle in the 30 Hz and 50 Hz groups.

	Mean differences between conditions Confidence interval (CI 95%)							
	30 Hz group				50 Hz group			
	No Vibration vs WBV with no Filter	p	No Vibration vs WBV with Filter	p	No Vibration vs WBV with no Filter	p	No Vibration vs WBV with Filter	p
RMS (%MVIC)	10.73 (3.92 to 17.53)	.001	2.57 (0.75 to 4.39)	.002	10.53 (4.68 to 16.39)	.0001	3.55 (1.2 to 5.89)	.001

MVIC: Maximal Voluntary Isometric Contraction; Hz: Hertz; RMS: Root Mean Square; SD: Standard deviation; WBV: Whole-body vibration

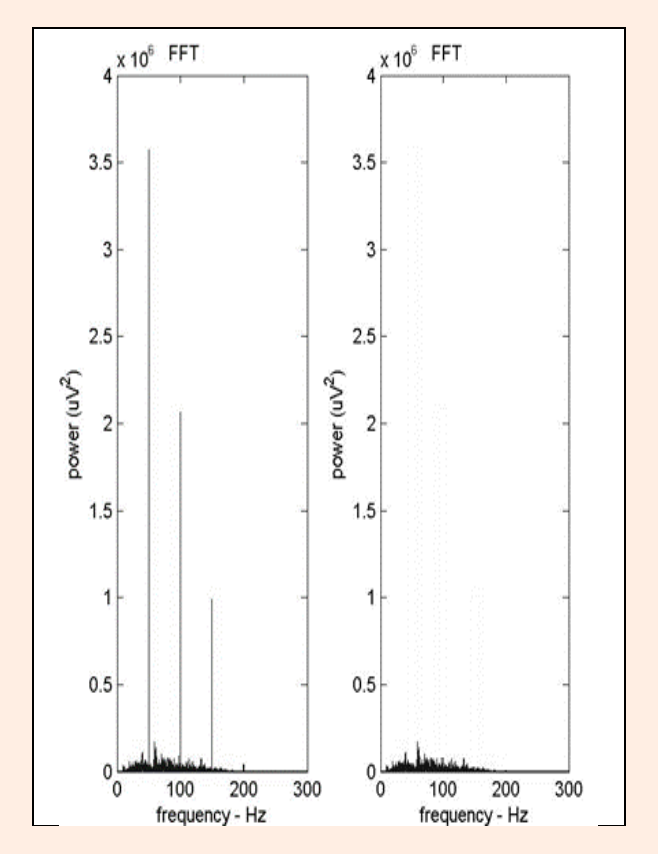

Figure 4. Example of the EMG spectrogram of the vastus lateralis muscle during the WBV exercise protocol in the 50 Hz group. Condition at LEFT represents the signal without removal of the vibration-induced motion artefacts. Condition at RIGHT shows the EMG frequency spectrum after filtering out the sharp peaks of the signal.

suggests that the proposed exercise including the vibratory platform promotes an increase in VL sEMG amplitude, independent of the implemented frequency configurations.

The mechanisms by which vibration causes an increase in sEMG amplitude and the extent to which an exercise protocol with a vibratory platform could elicit such responses of the EMG signal are not clear in the literature (Bosco et al., 1999a; 1999b; De Ruiter et al., 2003; Hazell et al., 2007). Some hypotheses have been raised to explain how the vibratory stimulus added to exercise would increase sEMG amplitude. Reflex muscle contraction in response to type Ia muscle spindle sensitization during vibratory stimulation is suggested to be the main cause of changes in motor unit firing although there is no consistent evidence in the literature for this (Cardinale and Bosco 2003; Cardinale and Lim 2003, Pollock et al., 2012).

Similar results have been previously reported regarding an increase in VL muscle activity during vibratory stimulus (Abercromby et al., 2007; Ritzmann et al., 2013 Wirth et al., 2011). Vibrations are external disturbances which come into contact with body structures and are then perceived by the central nervous system, which in turn modulates the stiffness of the muscle groups stimulated. According to Cardinale and Lim (2003), reflex muscle activity can therefore be considered as a neuromuscular adjustment response that minimizes the effect of soft tissue vibrations. It is important to emphasize that these are individual responses which are probably specific to the population, and may be based on mechanical factors and reflexes (Cardinale and Lim, 2003).

In contrast to our results, some authors have documented a linearly increased sEMG activity as a function of the vibration frequency (Pollock et al., 2010; Ritzmann et al., 2013). The discrepancies in the findings may be related to methodological contrasts, since these authors used different types of vibration and frequencies ranging from 5 to 30 Hz. In addition, the precautions taken in our study regarding the removal of motion artifacts from the sEMG signal may have suppressed the differences reported by these authors.

The spectral analysis of our unfiltered data revealed sharp peaks at the active vibration frequencies and the first three harmonics. The measurement of tonic vibration reflex and neuromuscular activation during WBV is complicated by the common presence of motion artifacts (resulting from electrode/cable movement and near electrical noise) making it difficult to give an exact quantification of electromyographic activity, compromising the quality and reliability of the analyzed data (Abercromby et al., 2007; Fratini et al., 2009; Lienhard et al., 2015a; Ritzmann et al., 2010; Sebik et al., 2013). As previously demonstrated by Fratini et al., (2009), we detected a reduction in RMS values after appropriate signal treatment using specific filters. These findings provide evidence that analysis of muscle activity during vibration, based on the raw sEMG signal, can significantly overestimate the mus-

cle response. Therefore, filtering methods during sEMG signal processing could possibly prevent the misinterpretation of experimental results.

Regarding the sEMG signal processing and its interpretation, Ritzmann et al., (2010) suggested that it is not appropriate to determine the filtering methods based only on a qualitative analysis of the spectrogram, since the addition of filters at the peaks corresponding to the excitation frequencies and their harmonics could significantly alter the electromyographic signal. This could impair the contribution of stretch reflexes in the signal, since part of its shape is encoded in the effective distribution of the vibration frequencies. In our study we found that even after the addition of filters at the studied frequencies, the RMS values still remained higher than those observed in the no vibration condition. This suggests that the representativeness of stretch reflexes possibly triggered by vibration does not necessarily occur at the provided stimulus frequencies.

These characteristics have also been previously demonstrated by other authors (Lienhard et al., 2015a; Fratini et al., 2009; Sebik et al., 2013; Xu et al., 2015), who suggest that reflex activity during vibratory stimulus is spread over a wide sEMG spectrum. This would favor removal of the peaks caused by the motion artifacts, since most information related to reflex activity would still remain upon being removed from the signal after processing (Lienhard et al., 2015b).

It is worth noting that the findings of this study are limited to a single vibratory platform exercise session on healthy and active women. Thus, these results do not apply, for example, to individuals with neuromuscular disorders. Additionally, the exercise was performed in the non-dominant lower limb, which could have required more control and coordination during its execution.

Furthermore, considering the magnitude of the increase verified through our results, as well as being suggested by some authors (Wirth et al., 2011), it is important to emphasize that the relevance of these findings should be further investigated in studies involving vibration application in training.

Finally, we suggest that future studies assess the effects of different frequency and range settings on muscle recruitment during vibration in both healthy and neuromuscular deficient patients in order to further clarify the possible contributions of whole body vibration.

Conclusions

The data from the present study suggest that removing motion artifacts from the EMG signal during WBV exercise is fundamentally important to ensuring that the quality of the signal remains intact. However, when applying additional filters to vibration frequencies of 30 Hz and 50 Hz, the RMS values of the VL remained high when compared to the non-vibration condition, thus rejecting our hypothesis that the benefits would no longer be detected after appropriate signal treatment by removing vibration-induced artifacts. Thus, these data suggest that WBV is capable of increasing the muscle activity level during exercise in healthy female subjects.

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Key points

- WBV increases the sEMG amplitude of the VL muscle during an isometric semi-squat exercise.
- Motion artifacts in the vibration frequencies of 30Hz and 50 Hz during WBV may contribute to the contamination of the RMS values.
- Conditions involving sEMG recordings during WBV require the application of additional filters during the signal processing to ensure the quality and reliability of the analyzed data.

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