J. Phys. Ther. Sci.
27: 2279–2284, 2015

Original Article

Whole-body vibration-induced muscular reflex: Is it a stretch-induced reflex?

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Abstract. [Purpose] Whole-body vibration (WBV) can induce reflex responses in muscles. A number of studies have reported that the physiological mechanisms underlying this type of reflex activity can be explained by reference to a stretch-induced reflex. Thus, the primary objective of this study was to test whether the WBV-induced muscular reflex (WBV-IMR) can be explained as a stretch-induced reflex. [Subjects and Methods] The present study assessed 20 healthy males using surface electrodes placed on their right soleus muscle. The latency of the tendon reflex (T-reflex) as a stretch-induced reflex was compared with the reflex latency of the WBV-IMR. In addition, simulations were performed at 25, 30, 35, 40, 45, and 50 Hz to determine the stretch frequency of the muscle during WBV. [Results] WBV-IMR latency (40.5 ± 0.8 ms; 95% confidence interval [CI]: 39.0–41.9 ms) was significantly longer than T-reflex latency (34.6 ± 0.5 ms; 95% CI: 33.6–35.5 ms) and the mean difference was 6.2 ms (95% CI of the difference: 4.7–7.7 ms). The simulations performed in the present study demonstrated that the frequency of the stretch signal would be twice the frequency of the vibration. [Conclusion] These findings do not support the notion that WBV-IMR can be explained by reference to a stretch-induced reflex.
Key words: Skeletal muscle function, Gravitational physiology, Tonic vibration reflex

(This article was submitted Feb. 25, 2015, and was accepted Apr. 16, 2015)

INTRODUCTION

The use of whole-body vibration (WBV) is becoming an increasingly popular topic in scientific research due to its beneficial effects on neuromuscular performance[1–4)]. WBV elicits muscular contractions, resulting in general improvement in muscular function[5, 6)], enhanced physical strength, increased bone mineral density[7)], better balance, reduced fear of falling[8)], and has positive effects on postural control[9)]. The effects of WBV on neuromuscular performance are supported by neurological processes such as synchronization, changes in motor neuron excitability and motor unit recruitment thresholds, and muscle spindle activity[10–13)]. Moreover, it has recently been shown that WBV induces a reflex response in muscles, but the physiological mechanisms underlying this reflexive activity remain unclear[12, 14)].

The reflex activity observed during an isolated vibration or tap applied to the muscle belly or tendon can be explained by the activation of muscle spindles in a stretch-induced reflex. Although direct evidence is lacking, a number of studies have suggested that the effects of WBV on neuromuscular performance can be explained as a stretch-induced reflex[4, 12–15)]. However, there are several issues with this explanation, for example: vibrations reduce the synaptic input of Ia fibers via presynaptic inhibition[13, 16–20)], WBV decreases or does not increase the amplitude of the stretch reflex[13, 21)], and muscle spindles are not sensitized by WBV[22, 23)].

The tendon reflex (T-reflex) is commonly used to evaluate the stretch-induced reflex[24)]. The present study compared the latency of the T-reflex, a stretch-induced reflex, with the latency of the WBV-induced muscular reflex (WBV-IMR) to determine whether the WBV-IMR can be understood by reference to a stretch-induced reflex. Furthermore, a muscle simulation model was employed to determine the stretch frequency of the muscle during WBV. Hypothesis of the present study was that the WBV-IMR reflex latency would be the same as the T-reflex latency, and that the stretch frequency of the muscle would be the same as the vibration frequency during WBV.

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SUBJECTS AND METHODS

Subjects

The present study initially recruited 23 right-handed male subjects between the ages of 20 and 45 years (mean age: 29.7 ± 5.0 years). Three volunteers were excluded from the study for the following reasons: aortic valve insufficiency (n = 1), a history of a comminuted fracture of the tibial bone (n = 1), and a history of Achilles tendon rupture (n = 1). Thus, 20 participants were included in the final analyses of the present study.

All volunteers provided their written informed consent prior to participation in any experimental procedures. All procedures were performed in accordance with the Declaration of Helsinki and were approved by the local ethics committee (local ethics committee: 2013/102). The research protocol was registered with the Protocol Registration at ClinicalTrials.gov (BEAH FTR-8 and NCT01780376).

Methods

The latencies of the WBV-IMR and T-reflex were measured using surface electromyography (SEMG). Prior to the induction of WBV, T-reflex recordings were elicited and the participants completed a 15-sec trial WBV protocol to familiarize themselves with the procedure. Following the trial protocol and a 15-sec rest, the subjects received the first set of WBV and the WBV-IMR latency was measured. Then, after a 3-min rest, the subjects received a second set of WBV and the T-reflex latency was measured. After an additional 3-min rest, the subjects received a final set of WBV which was designed to simulate the vibration frequency of the muscle. Each WBV set consisted of six vibration periods, each lasting for 16 sec, with 3-sec rest intervals between periods. Within each set, WBV frequencies of 25, 30, 35, 40, 45, and 50 Hz were delivered in random order to negate any order effect.

SEMG, accelerometer, force, and stretch sensor data were obtained while the participants stood upright on the vibration platform with their knees locked. The participants were barefoot, and no sponge or foam was placed between the vibration platform and their feet. The vibrations (2.2-mm vertical displacements) were performed using a PowerPlate® Pro5 WBV (PowerPlate® International, Ltd. London, UK), and the whole plate oscillated in upward and downward linear movements. A very light (<3 g) triaxial MEMS piezo-accelerometer (LIS344ALH, full-scale of ± 6 g, linear accelerometer, ECOPACK) was fixed to the WBV platform to determine the timing of the onset of the mechanical stimulus for the WBV-IMR (platform accelerometer). A similar accelerometer was taped to the participant's right Achilles tendon so that the y-axis coincided with the direction of the tendon (Achilles accelerometer). A force (load) sensor (FC2331-0000-2000L Compression Load Sensor; France) was fixed on the WBV platform to determine the onset point of the increase in upward thrust exerted on the body of the platform during vibration periods. At this onset point, the vibration platform was at its lowest position, and the corresponding point in the acceleration trace of the vibration platform was determined. Subjects stood on the WBV platform with their right heel placed on the load sensor.

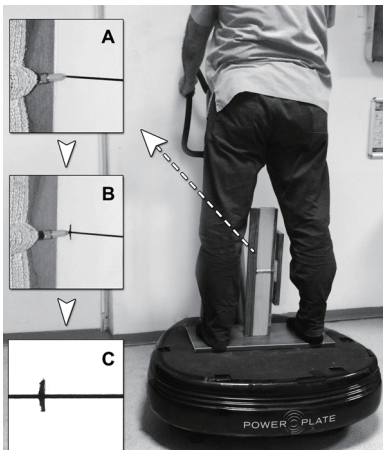


Fig. 1. Experimental setup of simulation 1
(A) Upper figure: the horizontal line represents the position of the tip of the pen prior to WBV. (B) Middle and (C) lower figures: the vertical lines show that the elastic band simulated muscle movement in both the upward and downward directions during WBV. The displayed trace was plotted during 25 Hz WBV.

Two simulations were performed to characterize the dynamics of muscle stretching during WBV. For the first simulation, a custom-made simulator was used (Fig. 1). To simulate the muscle, a piece of elastic band was fixed to two ends of a wooden bar, which was used to simulate the bone. A pen-board system was used to plot the movement of the muscle (elastic band) relative to the bone (wooden bar) during the vibration. This system included a very light pen (<1.8 g) that was fixed to the midpoint of the elastic band and a board that was fixed to the wooden bar to plot the trace during vibration. The bottom end of the wooden bar was fixed to the wooden base, and the simulator was placed on the vibration platform. Then, a researcher (MC) stood upright on the wooden base to load it so that it stayed upright during the vibration. For the second simulation, a piezo-electric stretch sensor (MLT1132 Respiratory Belt Transducer, ADInstruments; Oxford, UK) was used. Two pieces of elastic band were fixed to the two ends of the sensor, which was placed at the midpoint of the participant's left tibia. The elastic band on the upper end of the sensor was fixed to the leg using a Velcro band at the level of the left tuberositas tibia, and the elastic band on the lower end of the sensor was fixed to the leg using a Velcro band at the level of the left medial malleolus.

The SEMG data were obtained using Ag/AgCl electrodes (KENDALL® Arbo). The electrodes had a disc radius of 10 mm and were placed 20 mm apart on the right soleus muscle belly on shaved skin that had been cleaned with alcohol in accordance with the recommendations of the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) project[25]. The ground electrode was placed on the lateral malleolus.

All SEMG, accelerometer, force sensor, and stretch sensor recordings were collected using the Powerlab data acquisition system (ADInstruments) at a sampling frequency of 10

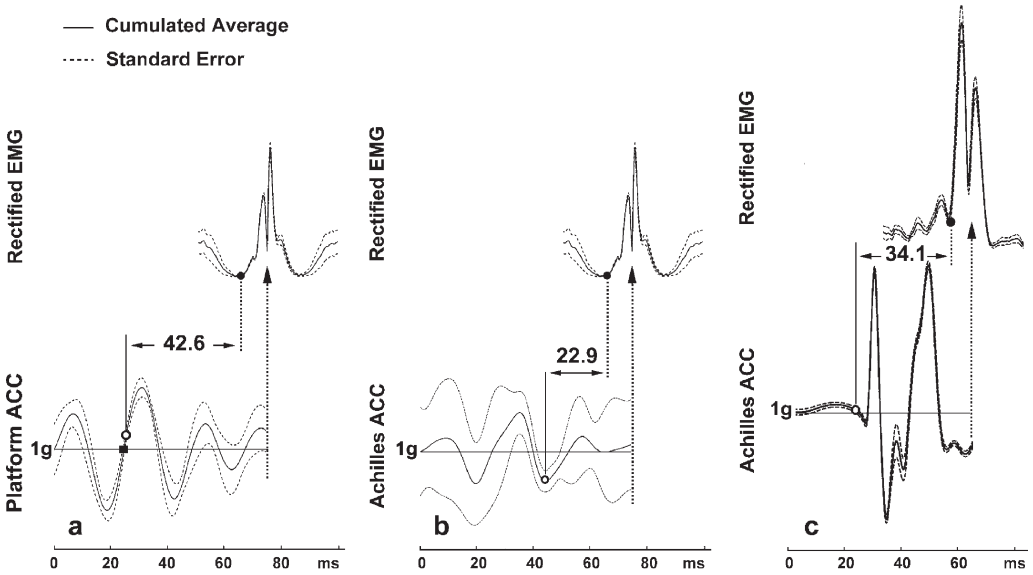


Fig. 2. Measurements of the reflex latencies
Representative latency values of one male participant. The solid circle represents the onset of the EMG spike, and the open circle represents the stimulus onset point. The dotted arrow represents the positive peak of the time derivative of the rectified EMG that was used as the trigger to average the accelerometer data and the rectified EMG data. The solid square shows the lowest position of the vibration platform during the vibration cycle and the onset point of the increase in force of the upward thrust of the platform. The mean time difference between the stimulus onset and the lowest position of the vibration platform was 3.5 ± 1.9 ms (n = 20). ACC: acceleration

kHz. Using MATLAB (R2012a 7.14.0.739), the data were analyzed offline, and all records were processed with infinite impulse response (IIR) filters (Butterworth, 1st order). All SEMG recordings were band-pass filtered at 80–500 Hz, then full-wave rectified to overcome movement artifacts, as previously described[26]; the recordings from the other sensors were high-pass filtered at 5 Hz. Finally, the time derivatives of the rectified EMG records were calculated to determine the time point at which the motor units were most recruited.

Sense of balance may be impaired during WBV, and as a result, additional muscles may be activated to restore balance during the WBV process. Four precautions were taken to address this issue: 1) the participants were asked to use the handles of the WBV device to maintain their balance; 2) the participants stood on the platform with their legs separated at a constant distance of 25 cm between the heels; 3) a trial protocol was performed to familiarize the subjects with the vibration; and 4) the participants were given relaxation training. During relaxation training, the participants were asked to relax while in a standing position and not make any voluntary contractions with the muscles of their lower extremities while the SEMG recordings were obtained. The training also included verbal feedback provided by the same researcher (IK) who monitored the SEMG recordings from the screen. Additionally, the same verbal feedback was given to all subjects to assist the achievement of relaxation during WBV.

In the present study, WBV-IMR latency was defined as the time between the onset of the mechanical stimulus and the onset of the EMG spike on the cumulated average trace, both of which were determined using the cumulative average method, as previously described[27]. The positive peaks of the time derivative of the rectified EMG data were used as a trigger to average the accelerometer data and the rectified EMG data. The point on the cumulative average trace of the platform accelerometer data where the standard error (SE) was the lowest was considered the effective stimulus onset point. The point on the cumulative average trace of the rectified EMG data where the SE was lowest was considered the point of onset for the EMG spike (Fig. 2A).

A mechanical bow T-reflex hammer was aimed so that it tapped the right Achilles tendon just caudal to the accelerometer with a force of 2 kgf. In each WBV session, the Achilles tendon was tapped five times with 3-sec intervals between taps. The precise moment that the hammer hit the tendon was determined using the accelerometer taped to the right Achillestendon. The T-reflex latency was determined using the spike-triggered averaging method in which the first deflection of the acceleration trace was the trigger, and the SEMG of the soleus was the source (Fig 2C).

The Kolmogorov-Smirnov test was used to determine whether the data were normally distributed, and for normally distributed data, the arithmetic means and SEs were used for the descriptive statistics. The mean height of young adult males in Turkey (175 cm) was used to normalize of the T-reflex and WBV-IMR latencies[28], and the 95% CI of the mean was calculated as: arithmetic mean ± 1.96 (SE). When comparing the means of the two datasets in the present study, if the 95% CI of one dataset included the mean of the other dataset, then there was no statistically significant difference between the means.

The paired-sample t-tests was used to analyze differences between the WBV-IMR and T-reflex latencies. Differences

in the mean values and effect sizes with a 95% CI were calculated, and a p value < 0.05 was considered to indicate statistical significance. The PASW for Windows data management software package was used to evaluate the data.

RESULTS

The mean WBV-IMR latency was 40.5 ± 0.8 ms (95% CI: 39.0–41.9 ms), and the mean T-reflex latency was 34.6 ± 0.5 ms (95% CI: 33.6–35.5). The mean difference between the latencies was 6.2 ms (95% CI of the difference: 4.7–7.7 ms; $p < 0.0001$). When the Achilles accelerometer was used to determine the WBV-IMR latency, the mean lag time (latency) between the onset of the stimulus and the onset of the EMG spike was 22.54 ± 1.38 ms (95% CI: 19.83–25.24 ms; Fig. 2B).

The first simulation is shown in Fig. 1. The trace indicates that the pen fixed to the elastic band moved up and down and that the elastic band stretched in both the upward and downward directions during a cycle of vibration. The second simulation is shown in Fig. 3. A frequency spectrum analysis revealed peaks at the vibration frequencies of the accelerometer and the SEMG data. The data obtained from the piezo-electric stretch sensor revealed that the stretch sensor underwent two consecutive stretches in opposing directions during a vibration cycle, and frequency analyses showed that the frequency of the stretch was twice the frequency of the vibration.

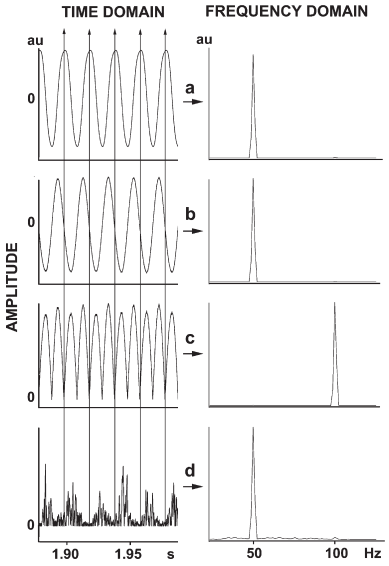


Fig. 3. Simulation 2
(a) *Platform Accelerometer Record*: the peak appears at a vibration frequency of 50 Hz. (b) *Stretch Sensor Record*: the sensor stretches two times during a complete vibration cycle, once during the upward movement and once during the downward movement. (c) *Stretch Sensor Record (Rectified):* the cumulative frequency of the upward and downward stretches was 100 Hz. (d) *SEMG Record:* the rectified SEMG; the vertical arrows separate the vibration cycles in the time domain traces.

DISCUSSION

The present study demonstrated that the mean WBV-IMR latency, which was 40.5 ms, differed significantly from the mean latency of the T-reflex; the mean difference was 6.2 ms (95% CI of the difference: 4.7–7.7 ms; $p < 0.0001$). Additionally, the soleus muscle simulations revealed that the frequency of the stretch was twice the frequency of the vibration during WBV.

To determine the latency of the EMG response to the vibration stimulus, it is important to pinpoint the timing of the stimulus onset. Ritzmann et al. considered the stimulus onset point to be the timepoint where the vibration platform was at its lowest position[13]. In the present study, the effective stimulus onset point was determined using the cumulative average method, as previously described[27]. This method revealed that the stimulus onset point was not the point in time where the vibration platform was in the lowest position. The WBV-induced reflex response occurred 3.5 ms after the time when the platform was in the lowest position; i.e. the onset of the increase in acceleration (gravity) or upward thrust (Fig. 2). The present study also showed that reflexive EMG activity was triggered by the force of the increasing upward thrust, a results which is supported by previous studies. For example, Pollock et al. found that the motor unit typically fired during the upward portion of the vibration cycle[12].

Ritzmann et al.[14] reported that the latency of the vibration-induced reflex of the soleus muscle was 37 ± 1 ms, which differs from the findings of the present study. They defined the reflex latency as the time from the lowest point of the vibration platform to the onset of the first spike in the EMG signal. However, it is incorrect to use the first EMG spike that appears during the vibration for latency measurements, because it is obvious that if this method were used to determine latency, latency would vary depending on the vibration frequency (Fig. 4).

An accelerometer fixed to Achilles tendon was used to determine T-reflex latency, and an accelerometer fixed to the vibration platform was used to determine WBV-IMR latency. WBV-IMR latency was significantly longer than T-reflex latency, and the difference may be due to the placement of the accelerometers. The data from the Achilles accelerometer was used to determine WBV-IMR latency, 22.5 ± 1.4 ms (95% CI: 19.8–25.2 ms) but this does not seem reasonable because this latency was shorter than that of the T-reflex. The Ia fiber is an afferent of the T-reflex and it has the fastest conduction velocity[29]. It is possible that data from an accelerometer on the skin overlying the Achilles tendon does not correctly determine the effective stimulus latency of the WBV-IMR, because the skin and the tendon move independently during WBV and can even move in opposite directions. However, this method may be used for the T-reflex because there is a definite and single stimulus, in response to which the skin and the tendon move in the same direction.

The question remains whether the WBV-IMR can be explained by the stretch-induced reflex. The muscle spindle, which is within the belly of a muscle and detects its stretch, is associated with the stretch-induced reflex. The muscle simulation in this study indicated that two EMG responses should appear during a vibration cycle if the muscle spindle

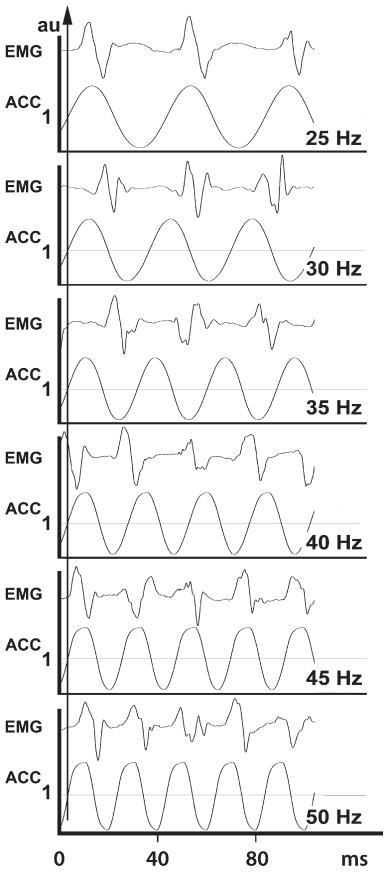


Fig. 4. Measurements of the reflex latencies using the method of Ritzmann et al.[14]

Drawn using data from the present study, this figure illustrates that the time period between the lowest point of the vibration platform and the onset of the first spike in the EMG signal varies depending on the frequency of vibration. The vertical arrow indicates the lowest point of the vibration platform.

is in fact the receptor associated with the WBV-induced reflex. This can be explained by the movements in opposite directions that occurred during the vibration cycle (as in the first simulation) and Newton's laws of motion.

During a vibration cycle, the body moves upward and then downward. During WBV, the soleus muscle also moves upward and then downward along its long axis. However, the WBV plate elicits in a body movement that occurs in the opposite direction of gravity via the application of an upward thrust. The force of the upward thrust is transferred to soft tissues, such as muscles, via the bones, and the relatively more flexible muscle tissue initiates movement later than bone does due to inertia. According to the laws of Newton, the resistance to movement appears as a reaction force when the movement starts[30]. Because the direction of this resistance is opposite to the force of the upward thrust, the muscle tissue may stretch during the upward thrust movement. After the upward movement of the body ends, the body begins to fall due to gravity and at the start of the free-fall movement the muscle and bone tissues do not move downward simultaneously. Like a spring, the muscle mass continues its upward movement during the upward thrust until the stretch decreases during the free-fall. In this case, the muscle tissue goes into the free-fall mode later than the bone tissue, and this delay may cause the muscles to re-stretch. The first simulation performed in the present study indicated that, relative to the bone, the muscle moves up and down during the vibration cycle. The second simulation performed in the present study showed that the muscle tissue might be exposed to this stretch twice during a single vibration cycle.

Reflex latency measurements may be affected by various factors such as gender, the height of a participant, and the temperature of the testing environment[31]. In the present study, all the participants were males, the room temperature was kept constant, and the latency measurements were normalized for height. Additionally, the latency of the WBV-IMR was determined using the cumulative average method, as previously described[27].

In the present study, the mean latency of the WBV-IMR in male subjects was 40.5 ms (range 39.0–41.9 ms), and the WBV-IMR latency was significantly longer than the T-reflex latency. These findings may be explained by the synchronous activation of the spindles following the tendon hammer stimulus relative to the slow rate and asynchronous activation of the spindles following WBV. However, it is also possible that these two methods may have stimulated different portions of the muscle with varying afferent connections to the homonymous motor neuron pool, or that they have completely different afferent pathways. Until this issue is further evaluated, it is impossible to draw a conclusion regarding the receptor origin of the WBV-IMR.

ACKNOWLEDGEMENTS

The authors also gratefully acknowledge the contribution of the volunteers who took part in these experiments. None of the authors has any potential conflicts of interest to be disclosed. The unique protocol IDs were BEAH FTR-8 and NCT01780376 at ClinicalTrials.gov ID.

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