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Original Article

Effects of Vibration Frequency and Knee Flexion on Lower Extremity Muscle Loads

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Occupational exposure to vibration has been identified as a major health risk. However, vibration has been commonly used in physiotherapy and muscle strength training. Despite long-term interest in the effects of vibration on muscles, the literature presents conflicting results regarding muscle activation/performance following vibration stimulation. A commercially available electric vibrating machine was used and 20 subjects were recruited to statically stand with knee flexion at different angles (0°, 60°, 90°) and dynamically stand (stand up/squat down) on vibrating platform, under exposure to different vibration frequencies (0Hz, 20Hz, 35Hz, 50Hz). Surface electromyography (sEMG) was used to assess the effects of posture and vibration frequency on the activation of gastrocnemius, rectus femoris, and vastus lateralis muscles. The results showed that knee flexion angle had a significant effect on muscles of the lower extremity, especially thigh muscles, which support body weight. The most obvious impact was on the calf muscles when vibrations were transmitted from the foot. The frequency of vibration had a certain influence on muscle activation, but was not as significant as the influence of posture. The higher the vibration frequency, the greater the muscle activation. However, when muscles were activated to a certain extent, vibration had little additional effect on muscle activation. Moreover, sEMG signals detected during dynamic posture were generally higher than those detected during static posture. Vibration at higher frequency activated muscles more easily. However, excessive muscle fatigue can cause injuries.

Keywords: Whole-Body Vibration, EMG, Lower Extremity, Muscle Fatigue

1 Introduction

In many industries, such as transportation, construction, and manufacturing, long-term exposure to whole-body vibration (WBV) can result in adverse effects on and occupational injury to workers. It is estimated that approximately one-quarter of European workers are exposed to hand-arm vibration or WBV [1]. Both the Occupational Safety and Health Act and the EU Physical Agents Directives [2] include regulations that require employers to evaluate and limit vibration exposure.

Muscles weaken with age and lack of muscle strength has been identified as one of the key factors in the diagnosis of vulnerability, which can lead to decreased physical activity and increased risk of certain diseases (e.g., cerebrovascular disease, depression, etc.) [3,4]. Muscle weakness has also been found to be associated with balance problems, resulting in harmful consequences (such as fractures, etc.) and decreased quality of life [5].

Many studies have suggested that local direct application of vibrations to stimulate individual muscles or tendons induces a feedback effect in

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the muscles [6, 7]. Musculoskeletal fiber activity is induced by local tendon oscillations, which are transmitted centrally by single synaptic and multi-synaptic pathways. A type of reflex muscle contraction called tonic vibration reflex (TVR) occurs in response to vibration stimulus [8, 9]. Many scholars have studied the influences of muscle activity, neuromuscular control and posture control [10, 11], with much interest focused on the possible applications of WBV therapy to induce TVR [12]. Several studies have demonstrated the impact of WBV therapy on the fields of exercise physiology and exercise and rehabilitation medicine [13-15]. During treatment, vibrations are transmitted through a vibration platform. Many vibration platforms generate vertical sine wave oscillations with frequencies ranging from 10Hz to 80Hz and peak-to-peak displacements from 1mm to 10mm [16]. Vibrations are transmitted from the platform to a specific muscle group via the subject's body. The muscles, which are in different positions on the platform, receive stimulation of differing intensities.

During WBV training, the subject stands on a body vibration training machine such that vibration pulse is transmitted through the foot to the whole body. Such training is said to improve muscle tone, enabling people to jump higher or run faster. However, there are also some studies that have shown that for young and vigorous people, vibration training alone has no significant effect on muscle development. However, WBV may be an effective method of exercise for elderly or sedentary people. For vibration stimulation, vibration frequency and amplitude are important factors in determining the load intensity of the neuromuscular system. Studies have shown that 30 Hz vibration frequency effectively initiates more muscle response under short term vibration training [17], with quadriceps displaying higher electromyography (EMG) signals [18]. However, no systematic inquiry into the effects of vibration training methods on muscles or their mechanisms or optimal vibration intensities has been made [19]. Fratini et al. (2009) [20] pointed out that muscle activity is positively correlated with the acceleration of vibration stimulation and this acceleration is an important indicator of whether vibration is excessive. EMG signals and analysis of acceleration transmission can be used to detect muscle responses to avoid chronic exposure to WBV injury in occupational medicine [21].

When muscles undergo WBV stimulation, EMG activity is significantly higher compared to resting state. Certain frequencies appear to produce higher EMG-RMS signals than other frequencies [22]. However, the findings of previous studies have not been consistent. Some have suggested that some muscle groups improve, while others have shown no significant differences [23, 24]. The response of muscles to vibration is a complex phenomenon that depends on various parameters such as muscle tension, muscle or segment stiffness, and amplitude and frequency of mechanical vibrations [25]. The influence of vibration on muscle activity has been widely discussed for many years, with the literature on muscle activation under WBV stimulation presenting conflicting results [26-29].

All bodies with mass elements and elasticity are capable of vibration. Hence, most machines and structures, including the human body, experience vibration to some degree. When vibrations are attenuated in the body, their energy is absorbed by the tissues and organs. The muscles are important in this respect. Vibration leads to both voluntary and involuntary contractions of muscles and can cause local muscle fatigue, particularly when the vibration is at the resonant-frequency level. Furthermore, it may cause reflex contractions, which can reduce motor performance capabilities. The purpose of this study is to investigate the relationship between muscle motion, generated by vibration, and corresponding EMG activity, as well as EMG and vibration load, in the gastrocnemius, rectus femoris, and vastus lateralis muscles, to further understand how vibration frequency and posture affect the activation of these muscles under WBV.

2 Materials and Methods

2.1 Subjects

Twenty healthy male college students were recruited for this study. They had never suffered from waist or back musculoskeletal diseases. Their mean age, height, and weight were 23.1±1.2

yr, 174.1±4.6 cm, and 71.1±9.8 kg, respectively. Subjects were informed of the experimental purpose and procedures and were required to sign a consent form. They were given the chance to ask questions about the study and the option to withdraw from the study at any time. This study was approved by the Institutional Review Board of Chung Shan Medical University Hospital (CSMUH No: CS2-15066).

2.2 Apparatus and tasks

An electric vibrator (BH-YT18, Taiwan) and a surface EMG (sEMG) measurement system (Zebris Medical GmbH, Germany) were used. The sEMG measurements were obtained from three muscles in subjects' lower extremity (left leg) using disposable skin surface electrodes. The three tested muscle groups were the gastrocnemius, rectus femoris, and vastus lateralis. The raw sEMG signals were filtered at 7Hz-500 Hz lowpass and digitized at a rate of 1000 Hz. The experimental situations were random combinations of four postures: knee flexion of 0° (standing straight), knee flexion of 60° (squatting), knee flexion of 90° (deep squatting) and dynamic (squatting and rising with flexion from 0° to 90° at 1 cycle/s) at four vibration frequencies (0 Hz, 20 Hz, 35 Hz, 50 Hz) along the z-axis for a total of 16 sessions. Meanwhile, physiological EMG signals were collected. Each experimental session lasted for 1.5 minutes and there was a 10-minute interval between experimental sessions. Figure 1 shows the static postures. The displacement of vibration platform was set at about 8 mm (z-axis) during the experiments.

(a) (b) (c)

Fig. 1 Static posture (a) 0° of knee flexion; (b) 60° of knee flexion; (c) 90° of knee flexion

2.3 Experimental process

The electric vibrator and surface EMG measurement system were calibrated before the experiments. Each subject was given a clear explanation of the experimental objectives and procedures. Surface electrodes were attached to the skin over the three tested muscles in the lower extremity after the skin surface was scrubbed with medical alcohol. At the start of the experiments, the maximum voluntary contraction (MVC) of each tested muscle was measured. The positions and tests for MVCs were based on the suggestions of Hislop et al. (1995) [30]. Three MVC measurements were taken and their maximum value was selected as MVC%.

A within-subject design was used with two independent variables: vibration frequency and posture. One dependent variable, EMG, was used to explore muscle loads in this study, with data normalized with root mean square (RMS) method to evaluate muscle load. A brief training period enabled subjects to gain familiarity with the tests before actual data collection. Two effects were observed in this study: (1) the vibration frequency effect on muscle loads in the lower extremity; (2) the posture effect on muscle loads in the lower extremity.

2.4 Data analysis

SPSS Statistics version 20 was applied to determine whether there were any statistically significant differences between the means of independent groups. One-way ANOVA was adopted to analyze the effects of different independent variables (frequency and posture) on the dependent variable (sEMG signals). The RMS values, acquired from the raw sEMG signals, were normalized using the formula: MVC% = (test value – resting value) / (MVC value – resting value). The RMS values of sEMG, calculated for a window of 1s, were then used to examine muscle activation in this study. IBM SPSS Statistics software was applied to determine whether there were any statistically significant differences between the means of independent groups. If there were, the LSD (Least

Table 1. MVC% means and standard deviations of tested muscles in different postures and at different frequencies

Freq	Muscle	0°	60°	90°	Dynamic	P
0Hz	Gastrocnemius	3.1±3.1	3.5±2.2	4.7±3.4	14.6±8.9	0.000*
	Rectus femoris	1.4±1.9	14.8±8.5	33.0±16.2	53.1±14.6	0.000*
	Vastus lateralis	2.5±3.7	3.6±2.4	44.6±18.6	63.1±17.4	0.000*
20Hz	Gastrocnemius	6.1±6.1	3.6±2.4	4.7±2.9	15.9±12.7	0.000*
	Rectus femoris	2.2±2.6	16.2±8.0	35.2±15.6	55.2±16.0	0.000*
	Vastus lateralis	5.6±5.1	29.8±14.7	49.4±18.4	60.9±15.9	0.000*
35Hz	Gastrocnemius	10.9±5.0	8.0±5.1	10.9± 6.6	16.2± 7.6	0.005*
	Rectus femoris	5.5±5.3	18.8±9.9	35.8±15.1	56.5±17.1	0.000*
	Vastus lateralis	7.9±9.3	34.0±14.0	50.4±17.7	65.7±17.7	0.000*
50Hz	Gastrocnemius	14.8±12.7	9.1±7.6	10.5±4.6	18.3±8.2	0.005*
	Rectus femoris	5.8±5.3	19.1±8.2	38.9±17.2	56.6±15.2	0.000*
	Vastus lateralis	11.9±7.7	33.7±13.2	55.8±18.2	66.5±17.5	0.000*

"*" indicates significant difference ($p<0.05$).

Significant Difference) post hoc test (α=.05) was conducted to evaluate the extent and scope of the effects of independent variables.

3 Results

3.1 Effects of different postures on muscle electromyography

As shown in Table 1, in the absence of vibration, there were significant differences in the muscles of the lower extremities, i.e. gastrocnemius, rectus femoris, and vastus lateralis, among the different postures. In the dynamic situation, the highest myoelectric response occurred in the vastus lateralis muscle. At vibration of 20Hz, there were significant differences in the muscles of the lower extremities

Table 2. MVC% means and standard deviations of tested muscles at different frequencies and in different postures

Posture	Muscle	0Hz	20Hz	35Hz	50Hz	P
0°	Gastrocnemius	3.1±3.1	6.1±6.1	10.9±5.0	14.8±12.7	0.000*
	Rectus femoris	1.4±1.9	2.2±2.6	5.5±5.3	5.8±5.3	0.000*
	Vastus lateralis	2.5±3.7	5.6±5.1	7.9±9.3	11.9±7.7	0.000*
60°	Gastrocnemius	3.5±2.2	3.6± 2.4	8.0± 5.1	9.1±7.6	0.000*
	Rectus femoris	14.8±8.5	16.2±8.0	18.8± 9.9	19.1± 8.2	0.23
	Vastus lateralis	28.7±11.5	29.8±14.7	34.0±14.0	33.7±13.2	0.538
90°	Gastrocnemius	28.7±11.5	4.7± 2.9	10.9± 6.6	10.5± 4.6	0.000*
	Rectus femoris	33.0±16.2	35.2±15.6	35.8±15.1	38.9±17.2	0.556
	Vastus lateralis	44.6±18.6	49.4±18.4	50.4±17.7	55.8±18.2	0.335
Dynamic	Gastrocnemius	14.6± 8.9	15.9±12.7	16.2±7.6	18.3± 9.2	0.312
	Rectus femoris	53.1±14.6	55.2±16.0	56.5±17.1	56.6±15.2	0.928
	Vastus lateralis	63.1±17.4	60.9±15.9	65.7±17.7	66.5±17.5	0.643

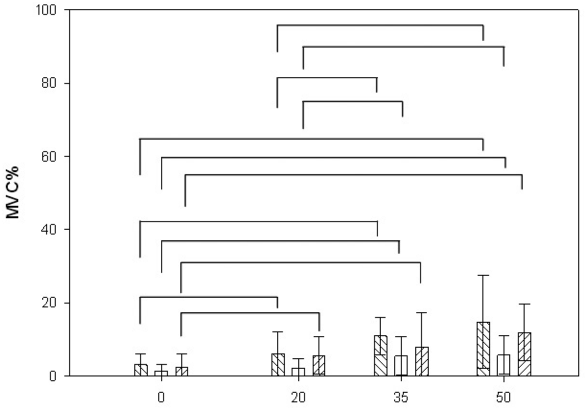
"*" indicates significant difference ($p<0.05$).

among the different postures. Under the dynamic situation, vastus lateralis demonstrated the highest EMG response. At vibration of 35 Hz, there were significant differences in the muscles of the lower extremities among the different postures. When the posture was dynamic, vastus lateralis showed the highest EMG response. At vibration of 50Hz, there were significant differences in the muscles of the lower extremities among the different postures. For the dynamic situation, vastus lateralis demonstrated the highest EMG response.

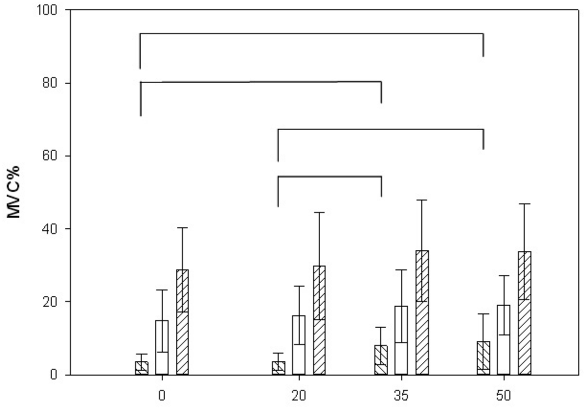
At all vibration frequencies, there were significant differences in the muscles of the lower extremity among the different postures. For the dynamic situation, the gastrocnemius, rectus femoris, and femoral lateralis muscles exhibited higher EMG responses at all tested frequencies. The highest myoelectric response occurred in the vastus lateralis muscle.

3.2 Effects of different frequencies on muscle electromyography

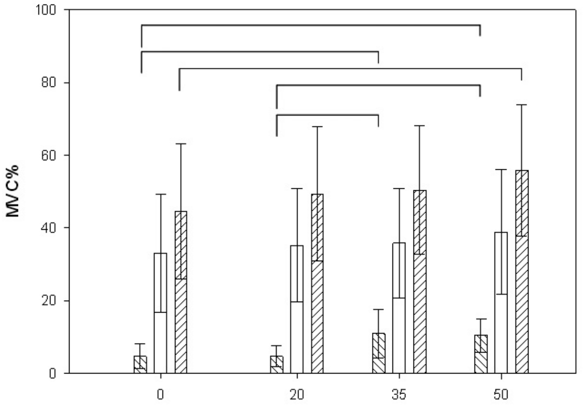
As shown in Table 2, in the case of standing (0° of knee flexion), there were significant differences in the muscles of the lower extremities at different frequencies. Gastrocnemius, rectus femoris, and vastus lateralis muscles exhibited the largest EMG responses at a frequency of 50 Hz, with the gastrocnemius muscle showing the greatest EMG response. In the case of high squat (60° of knee flexion), there was a significant difference for the gastrocnemius muscle. The gastrocnemius and rectus femoris muscles exhibited the largest EMG responses at a frequency of 50Hz. The largest myoelectric response of the vastus lateralis muscle was at a frequency of 35Hz. The vastus lateralis muscle showed the largest EMG response among the tested muscles. In the case of deep squat (90° of knee flexion), there was a significant difference for the gastrocnemius muscle. The largest myoelectric response occurred in the gastrocnemius muscle at a frequency of 35Hz. The greatest myoelectric responses occurred in the rectus femoris and vastus lateralis muscles at a frequency of 50Hz. Among them, the vastus lateralis muscle showed the largest EMG response.



(a) 0 degrees of knee flexion



(b) 60 degrees of knee flexion



(c) 90 degrees of knee flexion

Fig. 2 MVC% of tested muscles at different frequencies and different knee flexion angles;
▧ Gastrocnemius, ☐ Rectus femoris,
▨ Vastus lateralis; "∩"represents $p<0.05$

Figure 2 shows mean MVC% of the tested muscles and their statistically significant differences among vibration frequencies. When standing straight, the vibration frequency had the most significant influence on the activation of the tested muscles. Vibration frequency also had a statistically significant effect on the activation of the gastrocnemius muscle, for both squatting and deep squatting at 0 Hz and 35 Hz. 0 Hz and 50 Hz, 20 Hz and 35 Hz, 20 Hz and 50 Hz.

4 Discussion

Different postures at different frequencies caused significant changes in the myoelectric signal, which represents a significant influence of posture on myoelectric response in the legs. As shown in Table 1, MVC% of thigh muscles (rectus femoris and vastus lateralis), after the normalization of myoelectric signals, significantly increased with increasing knee flexion. This may be due to the role of thigh muscles in supporting body weight. The greater the torque, the greater the load and the stronger the EMG response. This is in line with the biomechanical human musculoskeletal pattern. However, this was not the case for the gastrocnemius muscle, as calf muscles are used less during squatting. The activation of the rectus femoris and vastus lateralis muscles increased with the angle of the knee joint, with the greatest activation during dynamic posture. When the angle of the knee joint changed, the vastus lateralis muscle demonstrated the greatest activation among the tested muscles, followed by the rectus femoris muscle, and gastrocnemius muscle. Muscles can damp externally applied vibrations, with the vibration energy absorbed by activated muscles. Two studies [31,32] have shown that the damping coefficients of whole muscle groups increase with muscle activity. In line with current research results, when the flex angle is large and there is dynamic posture, the influence of vibration is reduced and the frequency has a smaller effect on rectus femoris and vastus lateralis muscles than on gastrocnemius muscle. Avelar et al. [33] obtained similar results. For 60 and 90° angles of knee flexion, WBV produced no significant differences in EMG.

When vibration frequency increased, the load on the gastrocnemius muscle in the standing (0 degrees of knee flexion) posture was higher than that at 60 degrees and 90 degrees of knee flexion. The ankle structure is relatively less-buffered when standing and the contact vibration of the foot is transmitted upwards through the lower leg bones, while the ankle joint is bent during squatting, resulting in a damping effect, such that the vibration cannot be completely transmitted through the bones. Therefore, MVC% of gastrocnemius muscle was high when standing. In addition to knee flexion, some scholars believe that the body's transmission from foot to head may be affected by muscle tension, extremity stiffness [34,35], or vibration (vertical vibration or rotational vibration) [36]. Knee flexion can be likened to performing squats during strength training. Changes in body posture are similar in meaning and purpose to resistance training. Multiple lower extremity muscles can be stimulated over a short period of time to improve functional fitness and avoid direct impact between the body and the ground, thus reducing the risk of sports injuries. The combination of vibration and posture changes can be used in collaborative training. The muscle load is greater than that of resistance training alone and may be more effective in achieving muscle strength.

As shown in Table 2, when there was 0 degrees of knee flexion, there were significant differences among the lower extremity muscles at different vibration frequencies. One reason may be that the ankle joint and the knee joint do not bend when standing upright and do not constitute a damping of the soft tissue, resulting in the vibration passing along the calf skeletal muscle upward. Therefore, the effect of vibration frequency was obvious. In addition, no matter the posture (i.e. 0 and 60 degree of knee flexion), the gastrocnemius muscle showed significant differences due to the influence of frequency. The influence of frequency change on the gastrocnemius muscle was more obvious than the influence of posture change, as it was closer to the vibration source (vibration platform) and was directly subjected to vibration impact. On the contrary, the effect of posture change was greater than the effect of frequency change in the thigh muscle groups.

As shown in Table 2, there were significant differences in MVC% at 0, 60, and 90 degrees of knee flexion in static posture for the gastrocnemius muscle. However, there were no statistically significant differences in the gastrocnemius muscle in dynamic posture. Furthermore, there were no significant differences in MVC% among rectus femoris and vastus lateralis muscles at 60 or 90 degrees of knee flexion in static posture or in dynamic posture. It may be that muscle activation generated by the dynamic situation is already large, indicating that the motor units of the muscle have been recruited to a certain level and that vibration stimulation does not lead to further recruitment of motor units or muscle activation. Alternatively, when the dynamic situation continues, the effect of vibration transmission is blocked or reduced by flexion of the knee, such that the effect of vibration decreases and becomes non-significant.

Based on the above results, the frequency of vibration has a certain influence on muscle activation, but is not as significant as the influence of posture. When muscles are activated to a certain level, the effect of vibration on muscle activation becomes negligible. As far as the authors are aware, very few studies have discussed the activation of lower limb muscles in terms of standing posture and vibration frequency. The vibration frequency affects muscle activation, but when posture or muscle activation differs, the effect of vibration frequency on muscle activation may also differ. While both posture and frequency can activate muscles, combining them may enhance the degree of activation. At present, many studies have pointed out that if WBV is used for muscle activation, the recommended vibration frequency is in the range of 20Hz to 50Hz. Scholars believe that if the frequency is too low, there is no training effect. However, vibration at high frequency can easily cause muscle fatigue.

Although there were no female subjects, we believe that the results of this study apply equally to women. Regular WBV training, i.e. standing on a platform that vibrates at a high frequency over a small amplitude, has been reported to produce neuromuscular adaptation and increase bone mineral density in some frailer populations. As such, it has attracted interest for its potential benefits regarding physical function and fall and fracture risks in older people. These potential benefits could be counteracted by detrimental effects associated with vibration exposure.

The results of this study could potentially differ if different parameters of WBV exposure are used: amplitude, direction of dominant frequency, duration of exposure, shape of vibration. Therefore, there is a potential for future studies to investigate these parameters either alone or in combination. Moreover, the subjects' characteristics were relatively homogeneous relative to age and sex, which may have affected the response to WBV.

5 Conclusions

The experimental results showed that in different postures, statistically significant differences are common in thigh muscle groups. At different frequencies, calf muscle group generally had statistically significant differences. Vibrations can induce significant differences in myoelectric responses, demonstrating that vibration can directly or indirectly stimulate target muscles, causing neuromuscular response to achieve muscle activation and increase muscle strength. Excessive vibrations can harm the human body. In addition to the scope specified in regulations, the exposure time to vibration should be reduced as much as possible.

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