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Original Article

# Does the motor unit synchronization induced by vibration enhance maximal voluntary isometric contraction force? A randomized controlled double-blind trial

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**Abstract**

**Objectives:** Motor unit synchronization has been proposed as a potential mechanism underlying muscle strength gains for vibration training, but it has yet to be definitely demonstrated. Aim of this study was to determine whether motor unit synchronization induced by vibration has an effect on isometric muscle strength. **Methods:** Thirty-six healthy volunteers were randomized into two groups: the vibration and the control (sham vibration) groups. Two sets of test measurements and vibration resistance training between the two sets were applied to the right wrist flexors. The maximal voluntary isometric contraction force, and flexor carpi radialis EMG activity were recorded in the first (without vibratory stimulation) and the second (with vibratory stimulation) set. **Results:** There was no difference in the normalized peak force between the first and the second set in the vibration group ($p$=0.554). Motor units fired with maximal voluntary isometric contraction synchronized at the vibration frequency (25 Hz) during vibration in all participants of the vibration group. **Conclusion:** The present study indicates that vibration-induced motor unit synchronization does not have a significant effect on the maximal voluntary isometric contraction force.

**Keywords:** Muscle Strength, Muscle Spindle, Motor Unit, Tonic Vibration Reflex

## Introduction

In recent years, the use of vibration stimulation during resistance training has gained in popularity due to its acute and chronic beneficial effects on the neuromusculoskeletal system. These benefits include improved muscle strength and power[1-5]. However, little is known about the physiological mechanisms underlying the effects of vibration on muscular performance. The performance related changes due to vibration are attributed to neural factors such as recruitment and synchronization of motor units, and reflex responses such as tonic vibration reflex, bone myoregulation reflex[2,6-9].

The authors have no conflict of interest.

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The neural factors play also an important role in muscle strength gains through resistance training. The role of neural factors is particularly strong during the early phase of strength training. An increase in muscular strength without noticeable hypertrophy is the first line of evidence for neural involvement in muscular strength gain during the early phase of strength training[8,10]. The cross-education phenomenon is another strong evidence for neural involvement in muscular strength gain. This phenomenon is known as that strength training of one limb causes an increase in voluntary strength not only in the trained limb but also in the contralateral untrained limb and explained with neural factors[11,12].

The general neural mechanisms for muscle force generation are well known. The recruitment of motor units and modulation of firing rates of active motor units are the two mechanisms for regulation of muscle force. Motor unit synchronization is another possible mechanism for increases in muscle strength, but it has yet to be definitely demonstrated[10,13-15].

A synchronization of motor units has been proposed as a potential mechanism underlying muscle strength gains for both resistance training and vibration training. Moreover, it has been reported that vibration has been combined with conventional resistance training in an attempt to attain greater gains in muscle strength than conventional resistance training alone[3,4,16,17]. The additive effect of vibration and resistance training on muscle strength may be explained by motor unit synchronization as a common mechanism of vibration and resistance training.

Short-term studies have shown that it is unclear whether the maximal voluntary isometric contraction (MVIC) force and motor unit activity can be enhanced by vibration[3]. Motor units synchronize at the vibration frequency during single-session vibration exercise[7,18,19]. Consequently, we hypothesized that:

1. Single-session vibration exercise does not affect MVIC force.
2. Motor units fired with MVIC synchronize at the vibration frequency during vibration.
3. Vibration-induced motor unit synchronization does not have an effect on MVIC force.

Aim of this study was to test these hypotheses.

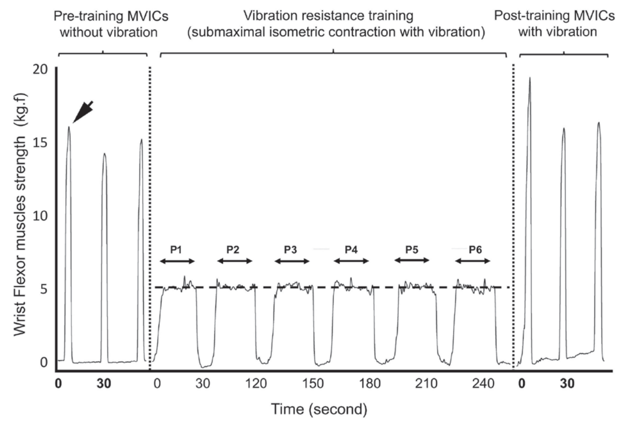


**Figure 1.** Study flow diagram: Pre-training MVICs without vibration (1.set), vibration resistance training and post-training MIVCs with vibration (2.set). After the first set, 30% of the MVIC trial with the highest peak force value was determined as a threshold for the submaximal isometric exercise. The horizontal dashed line shows the threshold. P1-P6: training periods.

## Materials and methods

The current study was a randomized, controlled, double-blind clinical trial.

### *Participants*

Thirty six right-handed, healthy volunteer students and staffs of our institute (aged between 18-40, 19 females, and 17 males) participated in the study. Pregnant or non-cooperable subjects were excluded. The participants were naive to the vibration exercise. All participants gave written informed consent to the experimental procedures, which were in accordance with the Declaration of Helsinki and were approved by the local ethics committee (2016/430).

Participants were randomized into two groups, the vibration and the control groups. Only one investigator (MC) was involved in the all randomization process. Coin-flipping was used for the randomization procedure.

### *Experimental procedure*

Two sets of test measurements and a vibration resistance training between the two sets were applied (Figure 1). To facilitate motor unit synchronization, a vibration resistance training (submaximal isometric voluntary contraction + real or sham vibration) was performed. To evaluate the acute training effect (which was during application of vibration) of vibration on MVIC, the muscle strength and EMG activity were recorded in the first (without vibratory stimulation) and the second (with vibratory stimulation) sets.

### *Experimental setup*

The superimposed vibration during the isometric exercise was transmitted to the wrist flexor muscles by a specially designed vibratory resistance training device (Figure 2). The anti-vibration pads were put under the feet of the exercise table to dampen the vibrations. POWERPLATE PRO5® (London UK) as a vibrating source was used in this study. This vibration device elicited peak-to-peak oscillations of 2 mm with a frequency of 25 Hz. The acceleration of the handle bar during vibration was measured with an accelerometer (LIS344ALH; ECOPACK®, Mansfield, TX, USA) fixed to the handle bar. Acceleration of the handlebar was 5g during real vibration, 0.2 g during sham vibration.

### *Test measurements*

The acute effect of vibratory stimulation on the muscle strength was assessed as the difference between the muscle strength amplitudes in the second set (maximal voluntary isometric contraction (MVIC) with vibratory stimulation) and in the first set (MVIC without vibratory stimulation) (Figure 1).

Participants were asked to sit on a chair and put their arms on the exercise table and were asked to hold a handlebar of the exercise apparatus with their right hand (Figure 2). Participants were also first instructed to perform selective contraction of the wrist flexor muscles by pulling the handlebar with the palm of their hand. They quickly learned to keep finger, arm and shoulder muscles relaxed during this task. Five minutes after this instruction, the isometric muscle strength of the right wrist flexor muscles was measured during MVIC at the first set. Simultaneously, EMG activity of the flexor carpi radialis was recorded. These test measurements were repeated at the second set. During the second set, a real vibration of 25 Hz applied was applied in the Vibration group or a sham vibration of 25 Hz was applied in the Control group.

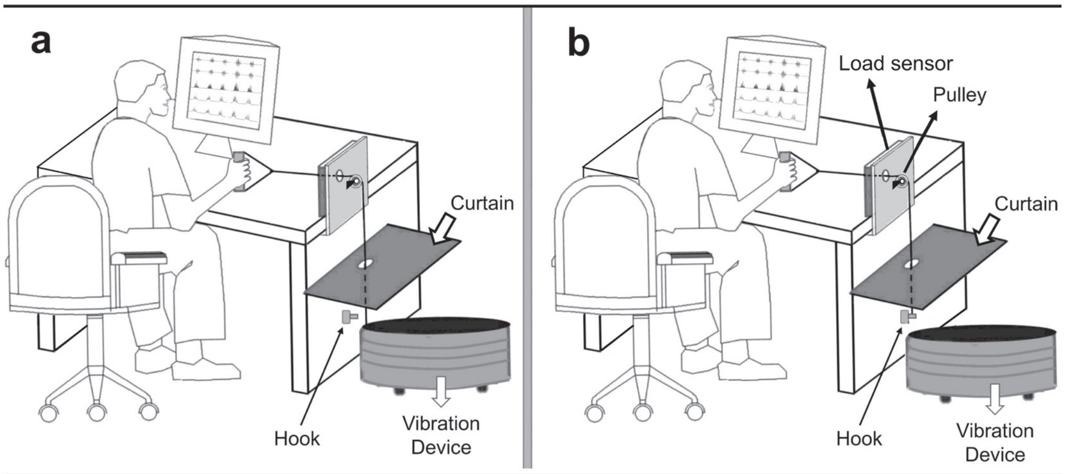


**Figure 2.** Experimental setup: a) To apply real vibration, the steel rope was connected to the vibration platform b) To apply the sham vibration, the steel rope was fixed a hook on the side wall of the exercise table.

The participants were asked to do three times MVIC at the the first and second set. Each MVIC lasted for 5 seconds. The rest interval between MVICs was 20 seconds. Participants were provided with verbal encouragement during MVIC.

The MVIC force was measured with a force transducer (FC2331-0000-2000L Compression Load Sensor, MEASUREMENTS® Specialties France) fixed to exercise apparatus and calculated as the peak force. Precision of the force transducer is 1%.

Vibration signals were recorded by using an accelerometer (LIS344ALH, full-scale of ± 6 g, linear accelerometer, ECOPACK®, Mansfield, TX, USA) fixed to the handlebar. The gravitational constant (g) was used as acceleration unit. All force transducers and accelerometer were calibrated before starting this study.

*Vibration resistance training*

The purpose of the vibration exercise was to train the neuromuscular system so that the motor unit firing rate could be synchronized with the vibration frequency during voluntary contraction.

The peak force values of the MVIC for each three trials were calculated after the first set. The highest peak force value among three MVIC trial was defined as “maximum peak force”. 30% the maximum peak force was determined as “the threshold force level” for submaximal isometric muscle contraction. Subjects were asked to contraction at the threshold force level. Visual feedback was used to achieve this. The subjects were asked to follow the force trace recorded from their wrist flexors on the screen and perform a contraction at the threshold line level during the vibration exercise (Figure 1, Figure 2).

After familiarization training for submaximal contraction, subject completed the vibration resistance training which consisted of six training periods (Figure 1). Each period lasted for 30 seconds. The rest interval between periods was 10 seconds. A real vibration of 25 Hz applied was performed in the Vibration group; a sham vibration of 25 Hz applied was performed in the Control group.

To prevent muscle fatigue, two precautions were taken. First, a low intensity training program (submaximal contraction) was employed. As a second precaution, the second set of trial was started after a rest interval 5 minute.

*Data recording and processing*

Surface EMG (SEMG) recordings were obtained from the right flexor carpi radialis (FCR) muscle. The Ag/AgCl electrodes (KENDALL® Coviden, Massachusetts, USA) with a disc radius of 10 mm were placed 20 mm apart on the right FCR muscle belly on shaved skin that had been cleaned with alcohol. The reference electrode was placed at the processus stylo radialis.

SEMG, acceleration and force data were recorded using a POWERLAB® data acquisition system (ADInstruments, Oxford, UK) at a sampling frequency of 1 kHz. Data were processed and analyzed offline using LABCHART 7® software (ver.7.3.8, ADInstruments).

We used a 60-499 Hz band pass filter to eliminate the motion artefact and 50 Hz power line interference in the SEMG signal without losing information on the discharge rates of the underlying motor units. After band pass filtering, the SEMG signal was rectified to bring forth information regarding the discharge rates of motor units[18].

Fast Fourier transform (FFT) analysis was used to determine the frequency components of the recorded SEMG and vibration signals.

To normalize the MVIC peak force amplitude, the MVIC with the highest peak force value was determined among

**Table 1.** The characteristics of participants in both groups.

| | Vibration Group (n=18) | Control Group (n=18) | *P*-value |
|---|---|---|---|
| Age (yrs) | 23.8 ± 4.3 | 26.3 ± 5.1 | 0.12 |
| Body height (cm) | 172.2 ± 9.1 | 171.5 ± 9.5 | 0.816 |
| Body weight (kg) | 70.1 ± 13.7 | 66.4 ± 11.1 | 0.383 |
| Body mass index (kg/m$^2$) | 23.7 ± 4.5 | 22.5 ± 3.0 | 0.386 |
| Female/Male | 8/10 | 9/9 | 0.99 |
| *Values are arithmetic mean (SD).* | | | |

six MVIC trials for each subject. This value was then used as the 100% MVIC (MVICmax) value for normalizing the force values of remainder of MVIC trials for that subject. The force output was calculated for each MVIC trial as a percentage of the MVICmax value and expressed as %MVICmax. These normalization procedures were carried out for each of the subject individually. This approach allowed us to pool the results of all subjects.

*Fatigue analysis*

Fatigue analysis was performed to determine whether there was a fatigue due to MVICs during the test protocol or not. Considering DeLuca's recommendations[20], to determine the muscle fatigue, the median frequency of the SEMG signals (EMGmdf) recorded from the FCR and normalized muscle strength values (%MVICmax) of the wrist flexors were calculated for the Control group.

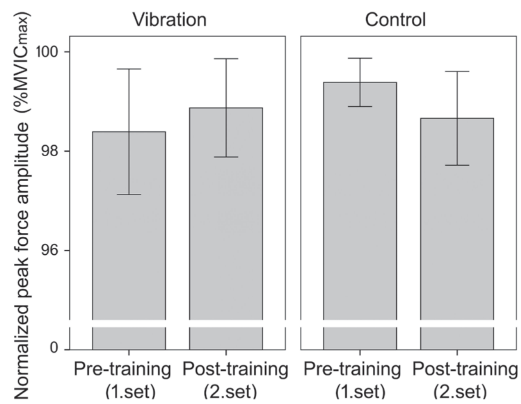


**Figure 3.** Error bars with 95% confidence interval of the normalized muscle strength.

*Blinding*

Researcher (IK) analyzing data and participants unaware of which real vibration or sham vibration was being administered (double blind).

*Statistical analysis*

The Kolmogorov-Smirnov test was used to test if the data were normally distributed. Continuous variables are presented as the arithmetic mean and standard deviation (SD). Continuity Correction Chi-square test was used to compare gender distribution of two groups. Unpaired t-test was used to compare the mean age, body height, body weight and body mass index of two groups. The Wilcoxon test was was used to compare mean of the %MVICmax between the pre-training (1.set) and the post-training (2.set). Comparisons of two groups were made using the Mann Whitney U test. Friedman test was used to compare the mean of the %MVICmax among six MVIC trials in Control group. The median power frequency was analyzed using an ANOVA appropriate for multiple dependent variables with repeated measures. Results with a "*P*" value of <.05 were considered statistically significant. Data were analyzed using PASW Statistics software (SPSS Inc., Chicago, IL, USA).

The main parameters of the present study were the %MVICmax . Curry and Clelland found that vibration induced a significant increase in MVIC force of the wrist extensors[16]. Using their data, the effect size was calculated with G*Power software (version 3.1.9.2, Franz Paul, Universität Kiel, Germany). For the given effect size (Cohen's d, 0.85), power (0.80), and alpha (0.05, two-tailed), required minimum sample size was calculated as 13 for vibration group.

## Results

The groups were similar in demographic and anthropometric characteristics of the subjects (Table 1).

There was no significant difference in the mean normalized amplitude of peak force between the first and second set in the Vibration group (n=18) (*P*=0.55) and in the Control group (n=18) (*P*=0.33). There was no significant difference in the mean normalized amplitude of peak force of the first and second set between the Vibration group and Control group (*P*=0.21 and *P*=0.39, respectively) (Figure 3) Table 2.

A prominent peak in the vibration frequency was found in the SEMG spectrograms of all six periods of the vibration exercise training and the second set MVIC trials. This peak was found in all participants of the vibration group but not Control group (Figure 4, Figure 5). A maximum power frequency was

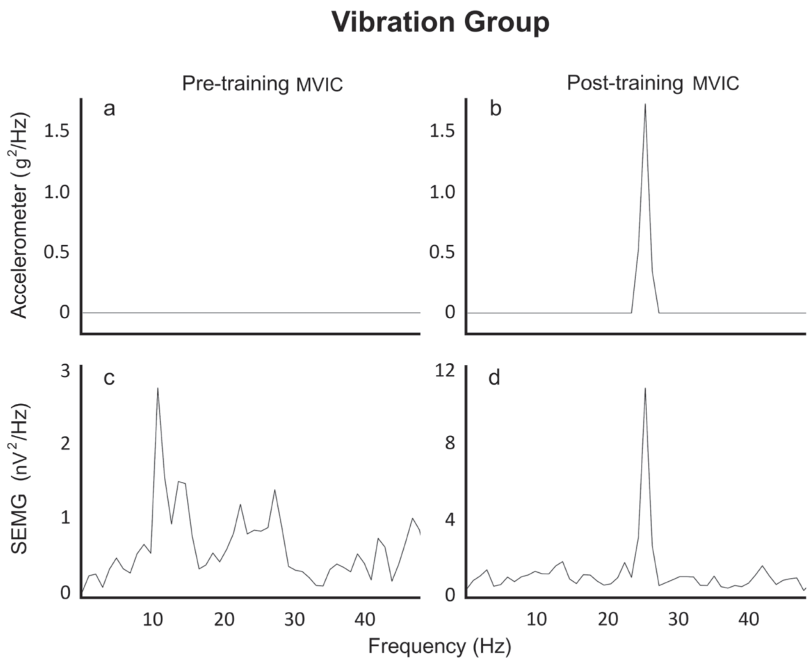


**Figure 4.** Representative frequency spectrograms of vibration (4a, 4b) and SEMG signals (4c, 4d) for a participant of the vibration group. Fig 4c: A prominent peak frequency of a pre-training MVIC at 10.7 Hz. Fig 4d: The prominent peak during real vibration at the vibration frequency (25 Hz) due to synchronization.

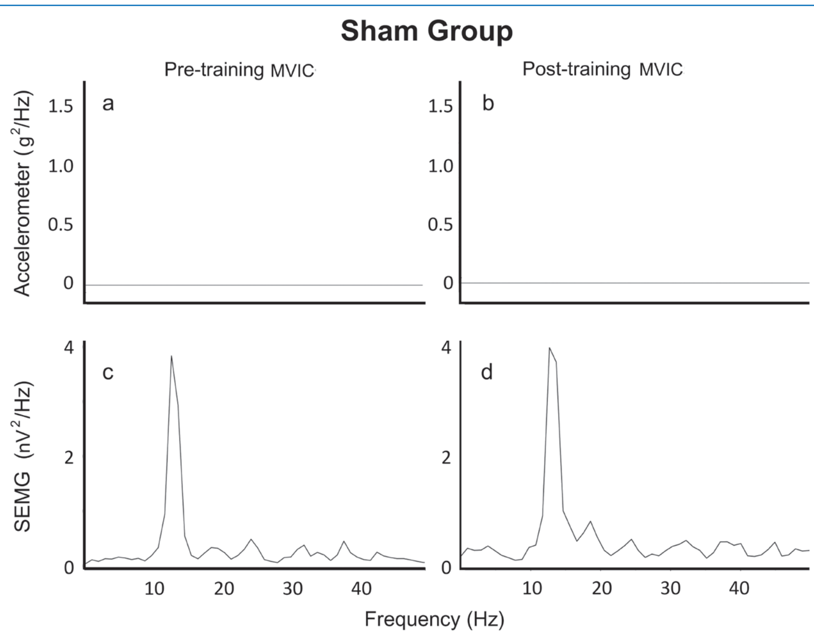


**Figure 5.** Representative frequency spectrograms of vibration (5a, 5b) and SEMG signals (5c, 5d) for a participant of the Control group. Fig 5c: A prominent peak frequency of a pre-training MVIC at 12.7 Hz. Fig 5d: The prominent peak during sham vibration at 12.7 Hz.

**Table 2.** Effects of the real or sham vibration resistance training on the maximal volutary isometric contraction (MVIC) force.

| | | Vibration Group (real vibration) (n=18) | Control Group (sham vibration) (n=18) | *P*-value |
|---|---|---|---|---|
| %MVICmax | 1.set (Pre-training) | 98.4±2.5 | 99.4±1.0 | 0.21 |
| | 2.set (Post-training) | 98.9±2.0 | 98.7±1.9 | 0.39 |
| | *P*- value | 0.55 | 0.33 | |
| Maximum power frequency (Hz) | 1.set (Pre-training) | 15.0 ± 4.5 | 13.9 ± 4.1 | |
| | 2.set (Post-training) | 25.0 ± 0.0 | 13.3 ± 3.2 | |

*%MVICmax: normalized muscle strength values. Values are arithmetic mean (SD).*

**Table 3.** Muscle fatigue analysis in the Control group.

| | The first set | | | The second set | | | *P*-value |
|---|---|---|---|---|---|---|---|
| | MVIC1 | MVIC2 | MVIC3 | MVIC4 | MVIC5 | MVIC6 | |
| Normalized peak force (%MVICmax) | 98.6 (1.6) | 97.7 (2.4) | 98.4 (2.3) | 98.7 (2.9) | 97.3 (3.1) | 97.8 (2.9) | .14 |
| Median power frequency (Hz) | 137.2 (23.8) | 138.5 (25.8) | 135.1 (27.3) | 134.7 (23.9) | 131.4 (21.8) | 130.7 (25.2) | .57 |

*Values are arithmetic mean (SD).*

15.0 ± 4.5 Hz for the first set MVIC trials in vibration group. A maximum power frequency was 13.9 ± 4.1 Hz for the first set MVIC trials and 13.3 ± 3.2 Hz for the second set MVIC trials in Control group (Table 2).

Although motor units fired with MVIC synchronize at the vibration frequency during real vibration, wrist flexor muscle strength was not increased after the real vibration resistance training in the vibration group (Table 2).

All participants reported that they did not feel the right upper extremity pain, cramping, or fatigue during the MVIC trials or vibration resistance training. There was no significant difference in the mean normalized peak MVIC force amplitude among six MVIC trials in the Control group ($P$=0.14). In the frequency domain the change for the median power frequency was not significant in Control group ($F_{(5, 85)}$= 0.77, $P$=0.57) (Table 3).

## Discussion

This study was conducted to determine whether the acute effect of vibration on neuromuscular performance is explained by motor unit synchronization that induces vibration. The acute effect was evaluated as the difference between the muscle strength in the second (with vibratory stimulation) and first (without vibratory stimulation) sets. Between the first and second set, the submaximal vibration resistance training was performed to ensure that the neuromuscular system could adapt to vibration and thus achieve motor unit synchronization effectively. In all participants, it was determined that the motor units were synchronized at the vibration frequency during submaximal vibration resistance training. There are a number of original findings in this study. Firstly, the present study showed that the amplitude of the MVIC force did not change during vibration confirming our first hypothesis. Secondly, using SEMG recordings we have confirmed the motor units fired by MVIC synchronized at the vibration frequency during vibration confirming our second hypothesis. Thirdly, we have shown that vibration-induced motor unit synchronization did not have an effect on MVIC force confirming our third hypothesis

### *Acute effect of vibration on isometric muscle performance*

Short-term studies have shown that it is unclear whether the MVIC force and motor unit activity can be enhanced by vibration[3]. In their controlled study, Curry and Clelland found that vibration induced a significant increase in MVIC force of the wrist extensors[16]. Humphries et al. found non-significant changes in maximal knee extensor force with vibration[21]. Bongiovanni et al. found that vibration induced a non-significant change of maximal ankle dorsiflexion force[22]. Neither the exerted force nor EMG signals from the knee extensor during the MVIC were significantly changed by prolonged vibration to the knee extensor[23]. In the present study, we found that vibration did not have a significant effect on MVIC force during maximal wrist isometric flexion.

The effect of vibration on muscle strength enhancement appears dependent upon the vibration characteristics (amplitude, frequency and method of application, i.e. vibration applied directly or indirectly to a targeted muscle) and exercise protocols (training type, e.g., isometric or isotonic and training intensity, e.g., maximal or submaximal) employed. To activate the muscle, low frequency (30-50 Hz) may be more effective than high frequency (>50 Hz). It is less clear to what the optimal amplitude should be to elicit an enhancement. The method of vibration application may have an influence on the magnitude of amplitude and frequency that are delivered to the muscle[3,24]. We found that vibration has no acute effect on maximal isometric force enhancement. This may be due to a low frequency, indirect vibration employed in that study.

Another reason of ineffectiveness of the vibration on the force enhancement may be the muscle fatigue due to maximal voluntary contraction. Short-term studies have shown that it is unclear whether the MVIC force can be enhanced by vibration, but submaximal isometric contraction force enhance the during vibration[3]. It was evaluated whether the MVIC protocol used in the present study produced fatigue. The participants reported that they did not feel fatigued in the right forearm muscles during or after the MVIC trials. The muscle strength and median power frequency analysis showed that the MVIC protocol used in this study did not cause fatigue.

During the initial part of the contraction, the median frequency of the spectrum might reside slightly above 100 Hz. During muscle fatigue, there might be a downward shift in the shape of the power density such that the median frequency would then reside at about 55 Hz 25. The median frequencies were about 135 Hz and a downward shift in the median frequency did not occur in our study.

*Motor unit synchronization at vibration frequency*

One of the main results of the present study is that firing of motor units synchronized at the vibration frequency. This result is consistent with that of previous studies[2,7,8,18]. Typical repetition rate of muscle motor unit firing is about 15-25 Hz, depending on the size of the muscle during maximal voluntary contraction[20]. In the present study, pre-training (1.set) peak firing rate of motor units was about 14 Hz in the Vibration and Control groups. While the post-training (2.set) peak firing rate of motor units remained about 14 Hz during sham vibration but synchronized at vibration frequency (25 Hz) during real vibration.

Motor unit synchronization is a pattern of motor unit activation that might result in augmented force involves the simultaneous activation of numerous motor units[10]. Although motor units fired by MVIC were synchronized at the vibration frequency, vibration did not have a significant effect on MVIC force during maximal wrist isometric flexion in the present study. This implies that motor unit synchronization have no effect on maximal isometric contraction force.

*Why was there no increase in MVIC force despite the motor unit synchronization?*

The temporal or spatial summation of motor units may help to explain this question. It is generally accepted that recruitment of motor units (spatial summation) and modulation of firing rates of active motor units (temporal summation) are the two mechanisms available to the nervous system for regulation of muscle force[13,26]. The same mechanisms proposed to explain the effect of vibration on enhancement of muscle strength[2,7,8,18]. In the present study, the firing rates of active motor units during MVIC with vibration increased from 15 Hz to 25 Hz and the motor units were synchronized at a frequency of 25 Hz. There was no increase in MVIC force, despite the synchronization and the increase in firing rate of active motor units. This may be explained by an ineffective temporal summation at low motor unit firing rates.

The temporal summation of motor units may also help to explain why there was no increase in MVIC force despite the motor unit synchronization. During MVIC without vibration, the peak frequency was 15 Hz in vibration group. During post-training (2.set) MVIC trials, motor units were synchronized to the vibration frequency (25 Hz) in all participants. Raikova et al, using a simulation of the muscle force modelling, studied the effects motor unit synchronization on the maximal tetanic contraction force at firing rates of motor units varied between 10-100 Hz. Their simulation model showed that an increase in maximal tetanic force contraction force with the firing rate was no significant in the firing rate between 10-25 Hz for fast fatigable motor units[27]. It seems that the temporal summation provided by synchronization is ineffective on the enhancement of MVIC force at low motor unit firing rates.

Even when carefully performed, SEMG recordings can contain movement artifacts, especially when a mechanical stimulation is applied on the limb or on the muscles that move under the surface electrodes[28]. These artifacts often contaminate the SEMG so much that it makes SEMG almost useless. Using various filtering regimens that effectively remove the frequency band that contains the vibration frequency and its harmonics is the most common approach in the efforts of eliminating motion artifacts[29,30]. Sebik et al. showed that filtering and rectification was efficient in discriminating motion artifacts from motor unit synchronization[18]. We used proposed signal processing technique by them to eliminate the effects of vibration treatments on SEMG signals.

*Study limitations*

This study had some limitations. The first was that motor unit recruitment has not been evaluated in the present study. The surface EMG global variables (e.g., mean or median spectral frequency and conduction velocity, EMG RMS) give poor indications about motor unit recruitment strategies[3,13,20,31]. Therefore, it would be valuable to study an intramuscular EMG (e.g., single unit or multiunit EMG).

A second limitation was that EMG recordings were only obtained from flexor carpi radialis muscle. Voluntary wrist flexion primarily involved the flexor carpi radialis, the flexor carpi ulnaris, and the palmaris longus[32]. Due to the reasons explained below, EMG recordings were not taken from the palmaris longus and flexor carpi ulnaris. Firstly, the palmaris longus is a small muscle and is often absent[33]. On the other hand, the anatomical localization of the flexor carpi ulnaris muscle was problematic in terms of the experimental setup of this study. The surface electrodes are placed on the flexor carpi ulnaris muscle belly to obtain flexor carpi ulnaris EMG recordings[34]. The ulnar aspect of forearm, which the electrodes are placed on, was in contact with the exercise table during MVIC trials in the present study. In this condition, EMG recordings may be deteriorated as the electrodes may be exposed to varying pressures between the forearm and the exercise table during MVIC trials.

## Conclusion

Short-term studies have shown that it is unclear whether the MVIC force can be enhanced by vibration[3]. The present study showed that single session vibration has no an effect on MVIC force. The main inference of this study is that vibration-induced motor unit synchronization does not have an effect on MVIC force.

It is important to determine the main physiological mechanisms underlying the vibration-induced muscle activity, for the most effective use of vibration as a method of exercise training in clinical rehabilitation and athletic training. The present study is the first trial to examine whether vibration-induced motor unit synchronization can affect on MVIC force. However, future studies are needed for a full delineation of the the physiological mechanisms underlying the effects of vibration on muscular performance.

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