The Effects of a 28-Hz Vibration on Arm Muscle Activity during Isometric Exercise

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ABSTRACT

MISCHI, M., and M. CARDINALE. The Effects of a 28-Hz Vibration on Arm Muscle Activity during Isometric Exercise. *Med. Sci. Sports Exerc.*, Vol. 41, No. 3, pp. 645–652, 2009. **Purpose**: The aim of this study was to evaluate activation and coactivation of biceps and triceps muscles during isometric exercise performed with and without superimposing a vibration stimulation. **Methods**: Twelve healthy volunteers (age = 22.7 ± 2.6 yr) participated in this study. The subjects performed five trials of isometric elbow flexion and five trials of elbow extension with increasing levels of force in two conditions: vibration (V) and normal loading (C). V stimulation was characterized by a frequency of 28 Hz. Surface EMG activity of biceps and triceps muscles was simultaneously measured by bipolar surface electromyography and assessed by the estimation of the root mean square (RMS) of the electrical recordings over a fixed 5-s interval. Frequency analysis was adopted to estimate the RMS related to muscle activation and to exclude the harmonics generated by movement artifacts due to V. **Results**: The analysis of the recordings revealed a significant EMG_{RMS} increase when V was applied. On average, the EMG_{RMS} of biceps and triceps during elbow flexion was, respectively, 26.1% ($P < 0.05$) and 18.2% ($P = 0.15$) higher than C. During elbow extension, the EMG_{RMS} of biceps and triceps was 77.2% and 45.2% ($P < 0.05$) higher than C, respectively. The coactivation was assessed as the ratio between the activation of antagonist and agonist muscles during arm flexion and extension tasks. The results revealed an increase of coactivation during V exercise, especially for lighter loads. **Conclusion**: This study shows that V exercise at 28 Hz produces an increase of the activation and the coactivation of biceps and triceps. This exercise modality seems therefore suitable for various applications. **Key Words:** VIBRATION EXERCISE, ELECTROMYOGRAPHY, SINUSOIDAL FORCE MODULATION, MUSCLE ACTIVATION, ANTAGONIST MUSCLES

Skeletal muscle is a plastic tissue able to adapt to specific demands. Numerous studies have shown that disuse leads to atrophy whereas resistance exercise and physical training result in hypertrophy in young individuals and maintenance of muscle mass in the elderly (26).

Various forms of exercise such as weight training and plyometrics have been suggested to produce improvements in neuromuscular performance as measured by increases in force and mechanical power production in isometric and/or dynamic tasks. The observed improvements have been ascribed to neural aspects in the first few weeks of a training program, with changes in the morphology, architecture, and size of muscle tissue occurring at a later stage (35).

The effectiveness of resistance exercise resides in the high neuromuscular demands of such training modality as measured by EMG activity of the targeted muscles. Previous authors have identified a linear relationship between EMG amplitude and force production in various muscle groups (15). The EMG amplitude in fact increases in parallel with the levels of force used for training and is maximal with loads near maximal voluntary contraction. To improve the ability to generate force, it is therefore necessary to identify training modalities able to impose a moderate to high neuromuscular demand. For this reason, it is well accepted that to gain strength, strength training prescriptions should incorporate exercises characterized by lifting heavy loads (>60–70% of 1 repetition maximum) (26).

In the last decade, an alternative form of exercise characterized by the superimposition of vibration has been suggested as an effective methodology to improve strength and power performance in various populations ranging from disabled children to elite athletes to aged individuals (1,4,7,8,10,13,22–24,43). Vibration training has been proposed in various forms. Whole-body vibration platforms have been suggested to be an effective modality to exercise the lower limbs (10); however, a recent review indicated that the purported benefits of this modality are debatable (31). Vibrating dumbbells (7), vibrating pulley-like devices (23,24), vibrating barbells (32), and other devices producing a sinusoidal force-modulated (V) stimulation (25,30,36) have been shown to acutely enhance strength,

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power, and flexibility mainly due to the neuromuscular demands placed by such force modulation on skeletal muscles. Although some positive applications of vibration have been suggested in the last 10 yr, it is important to remember that vibration has been extensively studied for its harmful effects on humans (19). For this reason, specific health and safety guidelines have been developed to regulate exposure to such stimuli (19).

The effectiveness of vibration in improving force and power production has been associated with the increased EMG activity observed while exercising on a vibrating platform (11,34) or by lifting a vibrating dumbbell (7). In these studies, vibration was shown to EMG activities 34–360.6% higher than the control condition in all muscle groups measured. All the studies mentioned did not control for muscle activation and did not apply specific EMG-filtering algorithms to exclude noise artifacts. This would probably explain the large variability in EMG responses to vibration stimulation. Vibration directly applied to the muscle tendon or to the muscle belly has been shown to elicit a reflex muscle contraction named tonic vibration reflex (TVR) (14,21). Using vibrating tools during exercise has been suggested to elicit similar responses (6), hence suggesting such modality of exercise to be potentially capable of increasing force and power production.

We have previously suggested that to identify the optimal way of using vibration to maximize strength gains, it is necessary to understand how muscles behave when said stimulation is applied at different levels of muscle tension (13). Muscle tuning in response to sinusoidal force-modulated signals has previously shown to be affected by the characteristics of the input signal, that is, frequency and amplitude (10,11) and muscle stiffness (40,41). In particular, the elevated muscle activity observed when superimposing vibration stimulation has been ascribed to muscle tuning to damp vibration power (42) with preferential recruitment of faster motor units (39).

Therefore, if vibration training has to determine an increase in force and power production, an increased EMG activity should be sought when compared with conventional training methods, and with this in mind, an optimal vibration training protocol should be defined to identify the level at which muscle exertion vibration could be beneficial.

Cocontraction is a neural strategy used to control joint stability in various tasks. Mechanical instability of a joint has been in fact shown to determine an increase in agonist–antagonist cocontraction (29). The ability to modulate the coactivation of antagonist muscles around a joint to minimize the perturbing effects of external loads is important not only in athletes trying to improve the effectiveness of specific movement tasks but also in aged individuals to reduce the risk of falls. Vibration represents a destabilizing stimulus and as such has been shown to affect cocontraction around the knee joint in whole-body vibration studies (2).

Although most studies have focused on muscle activation and acute effects on simple and complex motor tasks, to our knowledge no study has analyzed the effects of vibration on various levels of muscle tension and cocontraction in joints targeted by vibration training. Considering some of the effects previously observed, ascribed to alterations in cocontraction of muscles acting on the joints targeted by vibration (10), it is appropriate to ascertain how such training modalities influence neuromuscular activity also in antagonist muscles.

Recent developments in equipment design allows the possibility of using a sinusoidal force-modulated stimulation superimposed to typical strength training devices used in gyms and leisure centers (30). Such device has been shown to provide a reliable sinusoidal stimulation at 28 Hz able to produce increases in EMG activity of target muscles similar to the ones observed with whole-body vibration exercise devices and vibrating dumbbells.

Considering the potential of such modality of exercise, we aimed at studying the effects of superimposing sinusoidal vibration at 28 Hz at various levels of muscle tension during arm flexion and arm extension tasks.

We hypothesized that vibration was able to determine a higher EMG activity in biceps and triceps brachii than the same exercise performed without V. We also hypothesized that V superimposed to lower levels of muscle tension would stimulate a higher degree of cocontraction around the elbow joint.

METHODS

Experimental setup. EMG was measured by the setup presented in (30). Briefly, an electromagnetic actuator produces a mechanical torque that is fully controlled by a personal computer (PC). The generated torque consists of a base (steady) torque that is modulated in time by a sinusoidal function, as shown in Figure 1. A mechanical transmission is then used to transmit the generated force to the muscles (Fig. 2).

The adopted electromagnetic actuator was an industrial permanent magnet motor (MSK060C IndraDyn®, Bosch-Rexroth, Boxtel, The Netherlands) controlled by a dedicated drive (Rexroth IndraDrive®). The drive received its

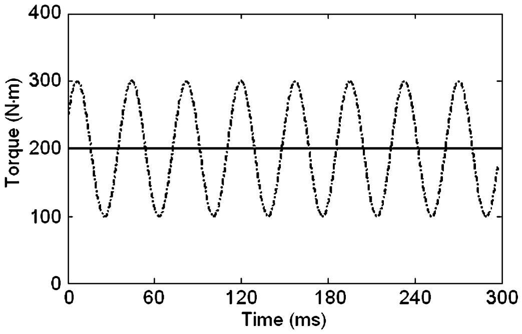

FIGURE 1—Example of force modulation (FM) loading function. The torque generated by the motor is the sum of a base load of 200 N·m modulated at 28 Hz with an amplitude of 100 N·m.

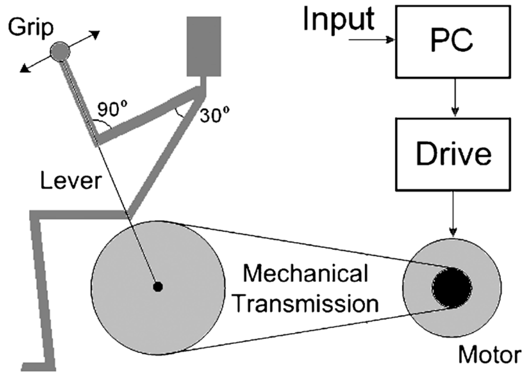

FIGURE 2—Measurement setup.

voltage input from a PC. The control software that generates the input waveform was developed with LabView® (National Instruments, Austin, TX). Torque transmitted to the user was hence determined in real time by the software controlling a PCI-5402 wave generator (National Instruments), inputting the motor drive the sum of a DC (constant) and a sinusoidal voltage.

As shown in Figure 2, the mechanical transmission transfers the torque generated by the motor to a rotating lever, which applies the force to the muscles. In static conditions, this force is linearly related to the input voltage to the motor drive.

To characterize the system in dynamic conditions, it was necessary to fully identify the transmission, measuring the moment of inertia of the transmission wheels as well as the elastic and damping coefficients of the transmission belts. This was done by measuring the dynamic response of the system for varying frequencies of the input voltage. Using this procedure, the transfer function of the system could be characterized between 20 and 40 Hz, showing a peak at 29 Hz and a deep at 30 Hz (30). In this study, the loading force was therefore modulated at 28 Hz to be able to superimpose a reliable vibration stimulation. Frequencies around 30 Hz are typically adopted in vibration training, and they are reported to provide the highest increase of electrical activation of the vastus lateralis (11). In the adopted setup, the amplitude of the input sinusoidal waveform was set to 1.2 V. Combining the linear and dynamic characterization of the mechanical system, the amplitude of the force oscillations was estimated to be equal to 400 N.

Subjects. The test subjects were 12 healthy volunteering students of the Eindhoven University of Technology, five males and seven females with ages varying between 19 and 27 yr (mean = 22.7; SD = 2.6). The level of training varied significantly, from sedentary to physically active. None of the subjects had history of muscular injuries or diseases. Written informed consent was obtained from each subject, and the test procedures were approved by the board of the Student Sport Centre of the Eindhoven University of Technology.

Measurement protocol. The subjects were asked to perform an isometric arm flexion or extension task with the setup shown in Figure 2 to establish their maximum force. The subjects were sitting in the testing device with their elbow at a forward elevation of 30° and an angle of 90°. An increasing force was applied by the electromagnetic actuator until the subject could not sustain it. The maximum sustained force (MSF) was measured three times, and the average value was considered as the reference for the MSF.

After establishing the MSF, the subjects performed 15-s isometric contractions (five different loads) with a resistance between 20% and 100% of the MSF. Each measurement was performed with (experimental condition [V]) and without (control condition [C]) vibration. The arm flexion task was performed first, with a 3-min rest between the measurements. After 15-min rest, the arm extension measurements were performed following the same procedure.

EMG measurement. During the isometric contractions, surface EMG was recorded simultaneously from the biceps and triceps by two pairs of electrodes in bipolar configuration. The electrode pairs were aligned with the muscle fiber direction and placed between the tendon (at the elbow side) and the muscle belly. Circular Ag–AgCl electrodes of 1-cm diameter were used. The interelectrode distance was 2 cm. The skin was prepared by abrasion before the application of the electrodes to reduce the contact impedance.

The measured signals were amplified and digitized by a Mobi8 amplifier (TMS International, Enschede, The Netherlands). The sampling frequency was 2048 Hz. Active grounding and shielding of the cables were used to minimize the electromagnetic interference coming from the electrical motor and the powerline (50 Hz) (38). The active ground electrode was placed on the wrist. The digitized signals were transmitted to a personal computer by Bluetooth® wireless technology.

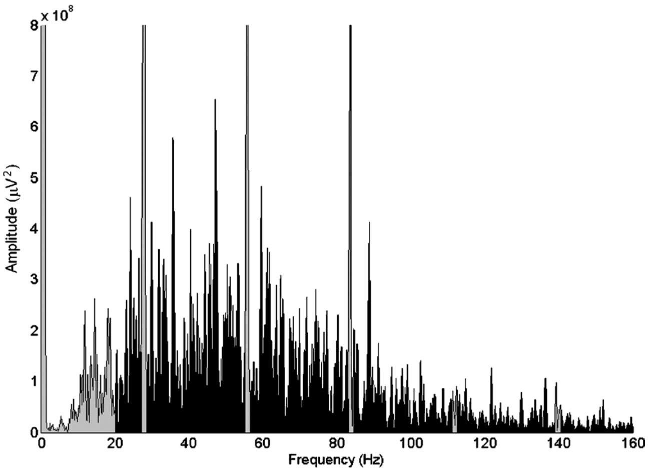

FIGURE 3—Power spectrum of a signal recorded from the biceps during V with a load of 40% of MSF over the complete 5-s interval. In gray, the frequency components that are excluded from the RMS calculation, that is, the low-frequency range up to 20 Hz and the frequencies corresponding to the motion artifact harmonics. To improve the visualization, the spectrum is presented up to 160 Hz, and the motion artifact harmonics are not shown up to the peak.

The root mean square (RMS) of the recorded EMG signals was used to establish muscle activation patterns as also suggested by previous authors (28). During isometric exercise, the recorded EMG signals are expected to be stationary. As a result, the signal characteristics, such as the power spectrum, do not vary over time, and the RMS can be calculated over longer time segments.

Vibration measurements can be affected by motion artifacts resulting in spectral components at the modulating frequency and its harmonics (2). Therefore, we developed a simple approach to make the RMS measurement insensitive to motion artifacts. This approach was based on the Parseval's equality, which permits the estimation of the RMS in the frequency domain based on the power spectrum (28). Given the signal stationarity, the spectrum was analyzed in the time interval between 2 and 7 s, providing a frequency resolution of 0.2 Hz. The RMS of the signal $s(nT_s)$, being T_s the sampling period (1/2048 s), was then derived from the sum of the power at each frequency $S(2\pi/nT_s)$ for $n \in [1,\ 5/T_s]$. Therefore, the frequencies corresponding to the modulation frequency and its harmonics could be excluded very precisely from the estimation, without the transition band limits of standard filtering techniques.

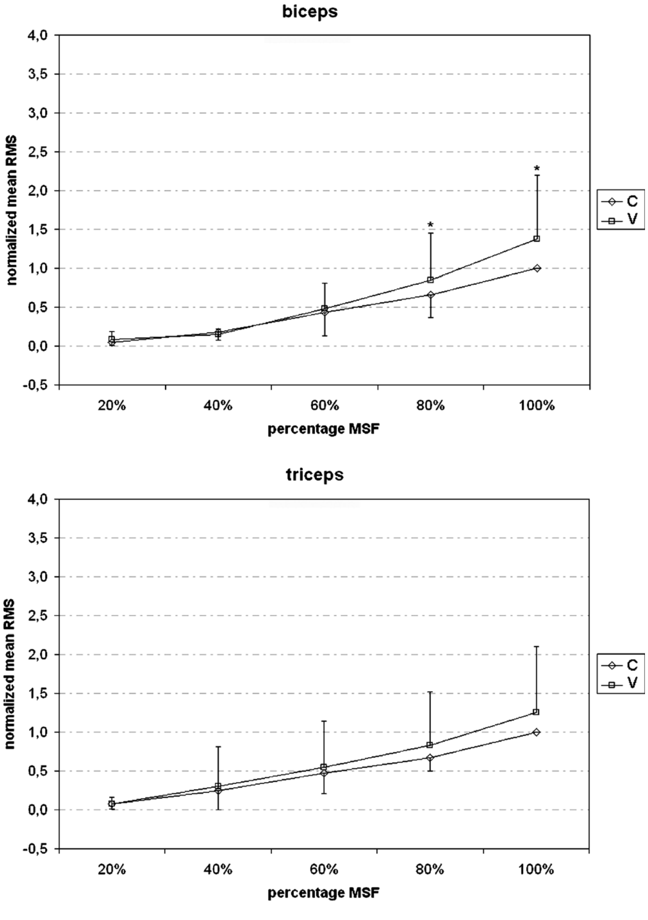

FIGURE 4—During elbow-flexion task, RMS estimates normalized with respect to the values estimated at 100% of MSF without V. The mean values and SD over the test subjects are reported. The asterisk indicates a significant difference ($P < 0.05$) between C and V exercise.

The recorded data were analyzed using a custom written routine in Matlab® (The MathWorks, Natick, MA), and the frequency spectrum was estimated using a fast Fourier transform (28). On the basis of the frequency analysis, a bandwidth of ±0.8 Hz around each harmonic was excluded from the RMS calculation, and only frequencies between 20 and 450 Hz were considered. Previous studies have suggested that this is the EMG bandwidth, containing the most relevant information to estimate the level of muscular (electrical) activity (2,28). Figure 3 shows a power spectrum example together with the frequency intervals that were excluded from the RMS calculation.

Due to the active grounding and shielding of the cables, the measurements were not influenced by the 50-Hz powerline interference. This was verified by assessment of the ratio between the 50- and the 45-Hz frequency components over the complete set of measurements. The average ratio was close to one (1.07 ± 0.29), which proves the assumption of a negligible interference. The absence of the powerline interference can also be noticed in Figure 3.

The RMS of the data recorded from each subject with and without V was normalized with respect to the value measured at 100% of the MSF without 28-Hz V. This procedure was used for both biceps and triceps.

To evaluate the effect of V on the level of coactivation of the muscles acting on the elbow joint, the ratio between the normalized RMS values measured from the antagonist and the agonist muscle was also calculated with and without V.

Statistical analysis. All data are presented as mean and SD. EMG data were normalized to EMG recorded during MSF without V. A two-way ANOVA (treatment [2] × intensity [5]) was used to analyze the differences in average EMG_{RMS} between treatments and intensities for each muscle. Alpha was set at 0.05. In addition, paired Student's *t*-tests (one tail, different variance) were applied at each load intensity (percentage of MSF) to compare EMG activity during V with C and to establish the significance level (*P* value) of the deviations of the mean values.

RESULTS

Effects of V on EMG activity. The statistical analysis revealed significant differences in both triceps and biceps muscle activity not only for different load intensities ($P < 0.001$) but also for different treatments (V and C, $P < 0.05$), with the exception of the triceps during the arm flexion task. In general, a larger EMG_{RMS} activity of the biceps and the triceps brachii muscles was observed when V was applied. The analysis of the mean EMG_{RMS} values at each intensity level revealed an average increase of the EMG_{RMS} in V ranging from 18.2% to 77.2% when compared with C.

The triceps brachii EMG activity was more influenced by the V when used as agonist (arm extension task), with an

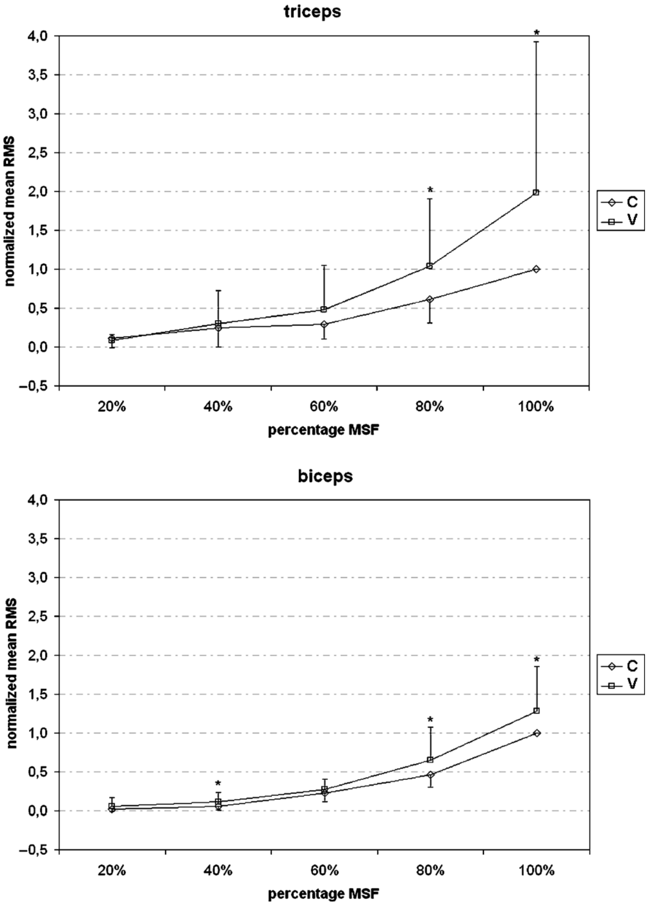

FIGURE 5—During elbow-extension task, RMS estimates normalized with respect to the values estimated at 100% of MSF without V. The mean values and SD over the test subjects are reported. The asterisk indicates a significant difference ($P < 0.05$) between C and V exercise.

average increase of 45.2% ($P < 0.05$) against the 18.2% ($P = 0.15$) when used as antagonist (arm flexion task). The opposite was shown to occur to the biceps brachii, which showed an average increase of 77.2% ($P < 0.05$) when used as antagonist (arm extension task) and of 26.1% ($P < 0.05$) when used as agonist (arm flexion task).

Effects of V on different levels of contractile activity. During the arm flexion task (see Fig. 4), the benefit of V on biceps brachii was significant when superimposed to load intensities equal to 80% (+28.3%, $P < 0.05$) and 100% of MSF (+37.7%, $P < 0.05$). The measured EMG_{RMS} increase of the triceps was not statistically significant.

During the arm extension task (see Fig. 5), the effects of V on triceps brachii EMG_{RMS} activity were significant when superimposed to loads equal to 80% (+68.7%, $P < 0.05$) and 100% (+97.9%, $P < 0.05$) of MSF, whereas a significant increase in biceps brachii EMG_{RMS} activity was observed at 40% of MSF (+112.6%, $P < 0.05$).

A large variability was observed in the coactivation values. However, despite this variability, ANOVA revealed a significant difference between intensities and between treatments (V and C) during arm extension task ($P < 0.01$). In particular, for intensities equal to 20% and 40% of MSF, the level of coactivation increased by more than 125% ($P < 0.05$). During arm flexion, no significant difference could be observed (P values ranged from 0.2 to 0.3 for different intensities and treatments). Figure 6 shows the complete set of results for both tasks. The coactivation increase can be especially noticed at lower intensities in the arm extension task.

DISCUSSION AND CONCLUSION

The results confirm our hypothesis that superimposing a sinusoidal V signal to strengthening exercises increases neuromuscular activity. In fact, a higher EMG activity was found when V was applied as compared with the control condition in both the triceps and the biceps brachii muscles when acting as agonists in the extension and the flexion task, respectively. The effect of superimposing V was more evident when higher levels of muscular tension were exerted, reaching the maximum at 100% of the MSF.

Soft tissues have been suggested to act as wobbling masses that vibrate in a damped manner in response to mechanical stimulation (41). Muscle activity is able to alter the vibration characteristics of the soft tissues. In fact, changes in muscle

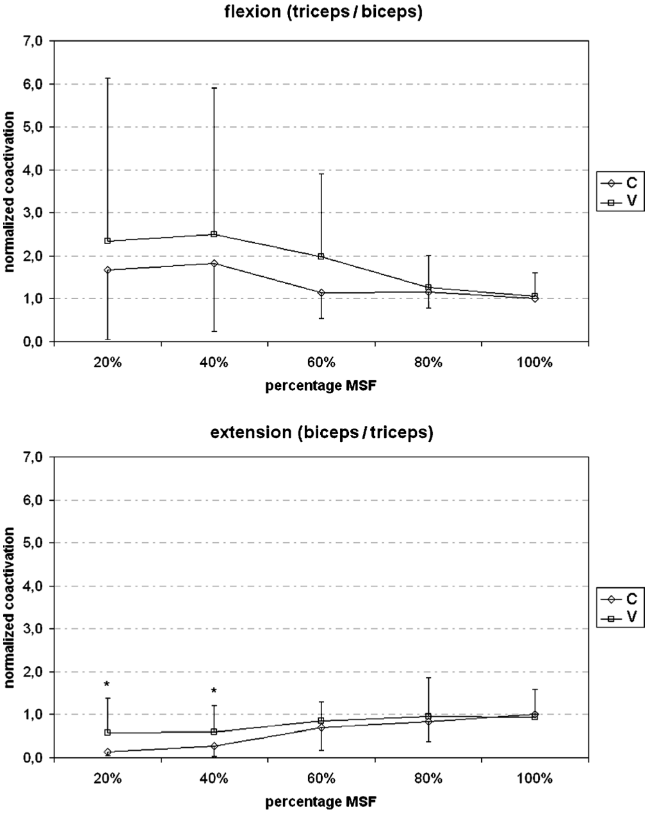

FIGURE 6—Muscle coactivation estimated during arm flexion (top) and extension (bottom) task as the ratio between the normalized RMS values measured from the antagonist and the agonist muscle. The mean values and SD over the test subjects are reported. The asterisk indicates a significant difference ($P < 0.05$) between C and V exercise.

tension alter frequency and damping coefficient of soft tissues. The muscle activation response observed when V was superimposed to various levels of force suggests that sinusoidal V signals of a relatively low frequency are effective when added to high levels of muscle tension (>70%).

This observed increase in EMG activity suggests that to dissipate the power of the sinusoidal stimulation, alterations in motor units recruitment patterns are necessary. Previous authors have suggested that faster motor units would be more suited to the damping of 15- to 50-Hz vibrations (42) when studying lower limbs muscles. The increase in EMG activity observed when muscles are exposed to sinusoidal stimulations, such as vibrations, has been previously attributed to the tonic vibration reflex (TVR) (20). The EMG response observed in the current experiment does not confirm the occurrence of TVR when V is applied. However, the large increase in EMG activity observed at force levels higher than 70% of MSF cannot be accounted for only by the TVR because only at this and at higher levels of muscle tension there was a large EMG increase.

Considering that rate coding and synchronization of motor units have been indicated as the main mechanisms able to increase force beyond 80% of maximal voluntary contraction in biceps brachii (18), it seems feasible to suggest that V may alter normal motor unit recruitment patterns, determining an increase in rate coding and synchronization and possibly facilitating the recruitment of faster motor units. In support of this hypothesis, Bongiovanni et al. (5) indicated a larger decline in the firing rates of high threshold motor units as a mechanism of prolonged vibration-induced maximal voluntary contraction depression.

Furthermore, Martin and Park (27) previously found an increase in motor units synchronization with increasing levels of force up until 20% of the maximum voluntary contraction in finger and wrist flexors muscles exposed to vibrations of frequencies ranging from 40 to 200 Hz. They concluded that the vibration-induced increases in EMG activity and the degree of motor unit synchronization were dependent on both vibration frequency and muscle contraction level. In our experiment, we aimed at understanding how a V affects muscle activation when superimposed to various levels of muscle contraction. Our results suggest that the effectiveness of such modulation is clearly muscle-tension dependent.

The large increase in EMG_{RMS} of the target muscles observed in both arm flexion and extension tasks when acting as agonists supports our idea that muscle activation is larger, possibly due to recruitment of large motor units and improvements in voluntary drive when trying to perform such tasks with the superimposition of V. However, a central component should not be discarded. Previous studies have in fact suggested that vibration has an effect on motor cortical excitability modulation (16,37). Therefore, the increased neural drive cannot be ascribed only to local mechanisms, but some central involvement has to be taken in consideration and should be the focus of future studies.

Further consideration should be given to other mechanisms likely to be involved. It is well documented that applying a sinusoidal stimulation directly to a muscle or a tendon stimulates Ia afferents inducing the TVR (5,17). Ia afferent sensitivity has been previously shown to be affected by muscle length and muscle tension with TVR magnitudes affected also by muscle groups not directly stimulated with V (44). Furthermore, alterations in spindle sensitivity and γ-drive have been observed during reinforcement maneuver such as the Jendrassik maneuver (33). It follows that the increase in neuromuscular response observed with V may be the result not only of motor unit activation strategies but also of alterations in spindle sensitivity.

Although the activation of agonist muscles seems to benefit from V when the levels of muscle activity are high, cocontraction around the elbow joint follows the opposite pattern. The coactivation levels measured by the EMG ratio of antagonist to agonist were in fact higher at lower levels of force production. We hypothesized this was the case because when the agonist muscles produce low levels of force, joint rotation is mainly controlled by the antagonist, in particular when sinusoidal signals are superimposed. It is reasonable to suggest that the observed level of cocontraction served only to stabilize the joint and not to modulate agonist force output as both muscles were exposed to the V.

Interesting observations concern also the different increase of EMG activity in the triceps and the biceps brachii. Both triceps and biceps seem to be more sensitive to the use of V loading during elbow extension tasks, showing an average increase of EMG activity equal to 45.2% and 77.2%, respectively ($P < 0.05$). In general, arm flexion tasks are more commonly used in daily activities, and it is likely that our subjects were more capable of performing and controlling the arm flexion tasks. The large EMG_{RMS} responses observed by both muscles during the arm extension task can be because the subjects were less accustomed to such movement and had more difficulty in controlling joint rotation, hence adopting a neural strategy favoring increased EMG activity.

In the present study, the frequency of V was fixed at 28 Hz. Previous studies on WBV exercise have suggested 30 Hz as the optimal training frequency for the vastus lateralis muscle (11). A variety of studies has been conducted with vibration exercise devices for the elbow (7) or vibrating plates (2,3,6,9,10). As reported in previous reviews, the adopted vibration frequencies have been in the range of 15–60 Hz (12). Although our study suggests the possibility of using such V frequency to determine a large EMG activity, the effect of different modulating frequencies could differ for different muscles, and the optimal frequency to determine the best training stimulus in the biceps and the triceps might be different. Our future research will therefore focus on these aspects and investigate the effects of different frequencies on the EMG activity of biceps and triceps.

Another interesting aspect that should be investigated concerns the EMG frequency components at the harmonics of the modulating frequency. Due to the presence of motion artifacts, these frequencies were excluded from the calculation of the EMG_{RMS}. However, these components could contain interesting information that is worth investigating. Therefore, the use of electrodes that are less sensitive to motion artifacts and the implementation of adaptive filters based on motion estimation are being considered for future measurements.

This study is the first attempt to understand if superimposing V signals during resistance exercise can be effective. The observed effects of V on muscle activation and cocontraction as measured by EMG suggest this modality as a potential effective intervention not only for training athletes but also for developing rehabilitation programs. The observed cocontraction at low levels of muscle force suggests that such approach could be effective in subjects in the early stage of a rehabilitation program where low levels of muscle force are required paired with limited joint mobility.

Further studies are needed to elucidate the neurophysiological mechanisms involved with V and the most effective safe and effective protocols for various populations.

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The results of this study do not constitute endorsement by the American College of Sports Medicine.

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