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Contribution of the tonic vibration reflex to muscle stress and muscle fatigue

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PARK H-S, MARTIN BJ. Contribution of the tonic vibration reflex to muscle stress and muscle fatigue. *Scand J Work Environ Health* 1993;19:35–42. The aim of the investigation was to determine the influence of vibration displacement amplitude (200, 300 μm peak-to-peak), as opposed to acceleration effects at selected frequencies (40, 80, 100, 120, 150, 200 Hz), on a commonly observed but often undesired motor response elicited by local vibratory stimulation, that is, the tonic vibration reflex (TVR). Vibration was applied to the distal tendons of the hand flexor muscles. Changes in the activity of hand flexor and extensor muscles were analyzed as a function of both their initial contraction level (0, 10, 20% of maximal voluntary contraction) and the vibration parameters. The main results indicate that TVR increases with the initial muscle contraction and increases with vibration frequency up to 100–150 Hz but decreases beyond. High-frequency vibration seems to induce less muscle and tendon stress. This result is particularly important for the design of handheld vibrating tools.

Key terms: force control, hand-arm vibration, proprioception.

Exposure of whole or part of the body to mechanical vibration has been shown to be detrimental to human sensorimotor performance (1–4). The most pervasive effects of vibration, other than its direct mechanical effects on the biomechanical structure of the human body, result from its ability to influence the neurological network by stimulating sensory receptors within the cutaneous, muscular, and articular structures (5–8) and its ability to affect spinal reflexes (9–12). The vibration-induced activity of these receptors is considered a leading cause of specific perceptive and sensorimotor impairments in persons exposed to a vibratory environment (2, 4, 11, 12). In addition, exposure to repetitive long-duration vibration leads to specific pathologies (13, 14).

A commonly observed motor effect of vibration is a phenomenon called the tonic vibration reflex (TVR) (15). It is well known that vibration applied to a muscle or its tendon elicits a tonic reflex contraction in that muscle (16–19), or its antagonist (7), depending upon the experimental context. This motor response results primarily from the vibration-induced activity of the primary endings (Ia) in the muscle spindle (20–23) (activity mediated by monosynaptic and polysynaptic spinal pathways), and it is highly dependent on central influences. Thus, the amplitude of the TVR is dependent on motor neuron accessibility by proprioceptive afferents. In addition,

a cutaneous component mediated by cutaneous afferents is likely to contribute to the TVR (23, 24). The tonic contraction increases progressively with exposure time and can persist a few seconds after vibration ends. It appears in both contracting and relaxed muscles.

On one hand, this tonic activity superimposed on ongoing voluntary contractions is partly responsible for the alteration of force control, which results in an increase in force exertion, force variability, and tendon stress (3, 25). Another component of this alteration is related to the vibration-induced modification of the structure of the proprioceptive afferent messages (26, 27). On the other hand, the TVR can contribute to muscle fatigue and increase the risk of cumulative trauma disorders resulting from exposure to repetitive long-duration vibration (25, 28). Furthermore, in a worker population that has used vibrating tools, the prevalence of the hand-arm vibration syndrome ranges from 6 to 100% (29).

Thus it appears that the TVR can be one origin of motor control perturbation and that it can contribute to specific soft-tissue disorders. Further understanding of the mechanisms by which vibration interacts with motor activities should lead to better prevention of the short- and long-term risks associated with vibration exposure.

In addition, vibration transmitted by the hand varies with the impedance or stiffness of the hand-arm system and vibration frequency (30). A tight grip is often associated with an increase in impedance (14). Thus the grip force can influence the harmfulness of vibration.

Most investigations thus far have studied the frequency dependency of the measured performance at a constant acceleration amplitude. According to a

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previous study (9), the use of a constant displacement amplitude would be more appropriate than acceleration to describe the neurophysiological effects underlying impairment in sensorimotor performance and vibration-induced motor responses such as TVR.

The objectives of the present study were, first, to quantify the changes in TVR as a function of the level of voluntary muscular activity and the frequency of the vibration applied with a constant displacement amplitude to muscle tendons and, second, to refine the understanding of the underlying neurophysiological mechanisms.

Subjects and methods

Subjects

Ten healthy subjects who gave their informed consent were paid for their participation in the experiments. All of the subjects were college students, and their average age was 22.6 years. They were free from any known neurological or musculoskeletal disorders.

Experimental apparatus

The subject was seated in a comfortable armchair with the right arm supported by a padded armrest. The right hand, in slight extension, gripped a vertical handle fixed to the armrest. An adjustable support helped to maintain the wrist in this position and thus imposed an isometric condition. The handle was equipped with a strain-gage dynamometer (figure 1). The height of the armrest and the horizontal position of the handle were adjusted so as to obtain approximately a 120-degree angle of the elbow.

Mechanical vibration was applied perpendicularly to the distal tendons of the hand flexor muscles by means of an electromagnetic vibrator (Ling Dynamic System, type 203) equipped with a specially designed probe (figure 1). An accelerometer placed

inside the vibrating probe provided feedback to a vibration compressor (Trig-tek 801B) driven by a sine-wave generator. The compressor, coupled to a vibration monitor (Trig-tek 610B) which computed the vibration displacement amplitude, was used to maintain this latter constant in the tested frequency range. The servo-controlled vibration signal was transmitted to the vibrator through a power amplifier.

The electrical activity (electromyography) of a finger flexor muscle (flexor digitorum profundus) and a wrist flexor muscle (flexor carpi radialis) was recorded by pairs of small cupular surface electrodes embodied in preamplifier devices to minimize noise and wire artifacts. The respective signals were then amplified, rectified, and integrated to obtain the root-mean-square (rms) values. A ground electrode was attached on the radial styloid of the wrist, and it provided an electrical reference.

Procedure

The maximal voluntary contraction (MVC) of the grip was determined before each experiment. Then the subjects were trained to maintain a grip force of 10 and 20% of their MVC for 1-min periods, using only the proprioceptive feedback. At first, a visual feedback from a voltmeter connected to the dynamometer was provided. After the subject felt familiar with the required submaximal level of contraction, the visual feedback was gradually suppressed and replaced by oral information. The test session started only after the grip performance had reached a steady state level and varied less than 4%.

For each trial, the subject started to exert one of three different grip forces, namely, 0, 10, or 20% of the MVC, while viewing the voltmeter. (The 0% MVC corresponded to a resting situation in which the fingers are wrapped around the handle without exerting a significant grip.) Once the proper level was reached, the visual feedback was suppressed, and oral feedback was given by the experimenter until the percentage of the MVC stabilized and the subject felt ready for the trial to begin. Force stabilization was reached within 5 to 10 s. No external feedback was provided during the trial.

Data were collected after force stabilization while the subject maintained the submaximal level of contraction for 60 s, consisting of a 15-s control period followed by a 45-s period during which vibration was applied continuously. The vibration frequency (40, 80, 100, 120, 150, or 200 Hz) was varied randomly across the contraction levels for constant peak-to-peak vibration displacement amplitudes of 200 and 300 μm .

For each subject, the experiment was carried out in 2 d to reduce any possible effect of boredom and fatigue. Data were collected for a total of 36 trials for each subject (three levels of contraction $\times$ six vibration frequencies $\times$ two vibration displacement

Figure 1. Experimental setup, vibration being applied perpendicularly to the muscle tendons of the hand flexor muscles.

amplitudes). The subjects served as their own controls. Because of the practical limitations imposed by the setting of the vibration displacement amplitude, the trials were randomized only across the vibration frequencies and muscle contraction levels. A 2-min rest period separated each consecutive trial.

Data recording and analysis

The raw electromyographic (EMG) data, the rms EMG data, and the grip force signal were continuously monitored on two oscilloscopes and simultaneously digitized (1000 Hz) and stored by a computer.

The rms EMG data and the grip force were time-averaged before (15 s) and during (40 s) the vibration periods. Changes in these values were analyzed as a function of the vibration parameters. The first 5 s of data of the vibration periods were not included in the analysis to eliminate the transient effects.

For each experimental condition, the grip force and the rms value of the vibration-induced increase in muscle contraction (rms VIC), defined as

$$\text{rms VIC} = \text{ave}(\text{rms EMG}_{\text{vib}}) - \text{ave}(\text{rms EMG}_{\text{ref}}),$$

the time averages (ave) having been obtained during and before vibration respectively, were computed and averaged over the subjects. A repeated-measures analysis of variance (ANOVA) treating the subjects as a random blocking factor was performed on the average rms VIC value and the grip force to test whether they were affected by the initial muscle contraction level, vibration displacement amplitude, or vibration frequency. The Tukey method of multiple comparisons with the 95% family comparison coef-

ficient was applied to evaluate the effect of the factor levels.

Results

Muscle activity

As an example, the time recordings reproduced in figure 2 illustrate the effects of the application of the vibration (120 Hz, 300 μm) on the EMG activity of the finger flexor muscle and the grip force exertion. Vibration induced an increase in muscle contraction, as clearly shown by the rms EMG trace. This effect primarily resulted from the expression of the TVR.

For all of the subjects, there was a significant increase in the time-averaged rms EMG data during vibration ($P = 0.01$) for both the finger flexor and wrist flexor muscles. However, the rms VIC varied with the initial muscle contraction level, vibration displacement amplitude, and vibration frequency.

Initial level of muscle contraction. For both muscles, the initial contraction level had significant effects on the rms VIC ($P = 0.0001$), as illustrated in figure 3. For the finger flexor muscle, the rms VIC was maximum at 10% MVC and was less pronounced at 20% MVC. For the wrist flexor muscle, however, the increase in the rms VIC was similar at 10 and 20% MVC.

Vibration displacement amplitude. For the finger flexor muscle, there was no significant difference in

Figure 2. Grip force exertion. Time recording sample of a raw and root-mean-square electromyogram (rms EMG) of a finger flexor (flexor digitorum profundus) muscle, grip force (10% maximal voluntary contraction) and vibration (120 Hz, 300 μm). The 5-s transitory period following vibration onset (between bars) was excluded from the time-average analysis. [Vibration frequency not scaled]

Figure 3. Effect of the initial muscle contraction level. Changes in the root-mean-square vibration-induced increase in muscle contraction (rms VIC), summed over the vibration displacement amplitudes and frequencies, versus initial muscle contraction level for finger flexor (flexor digitorum profundus, FDP) and wrist flexor (flexor carpi radialis, FCR) muscles. (MVC = maximal voluntary contraction)

Figure 4. Effect of vibration displacement amplitude. The average root-mean-square vibration-induced increase in muscle contraction (rms VIC) in a wrist flexor muscle (flexor carpi radialis), summed over the vibration frequencies and initial muscle contraction levels, versus vibration displacement amplitude.

Figure 5. Effects of vibration frequency on the activity of a finger flexor muscle (flexor digitorum profundus). Changes in the average root-mean-square vibration-induced increase in muscle contraction (rms VIC) as a function of vibration frequency represent the average results for all of the subjects at rest, exerting 10% maximal voluntary contraction (10% MVC), and exerting 20% maximal voluntary contraction (20% MVC).

Figure 6. Effects of vibration frequency on the activity of a wrist flexor muscle (flexor carpi radialis). Changes in the average root-mean-square vibration-induced increase in muscle contraction (rms VIC) as a function of vibration frequency represent the average results for all of the subjects at rest, exerting 10% maximal voluntary contraction (10% MVC), and exerting 20% maximal voluntary contraction (20% MVC).

the rms VIC resulting from the vibration displacement amplitude of 200 μm and 300 μm ($P = 0.43$). However, the increase in the rms VIC with the vibration displacement amplitude was significant ($P = 0.015$) for the wrist flexor muscle. This change is illustrated in figure 4. The rms VIC was summed over the vibration frequencies and initial muscle contraction levels.

Vibration frequency. For both the finger flexor and wrist flexor muscles, the vibration frequency had significant effects on the rms VIC ($P = 0.0001$). Figures 5 and 6 show changes in the rms VIC for the finger flexor muscle and wrist flexor muscle, respectively, represented as a function of vibration frequency at constant vibration displacement amplitudes for three different initial muscle contraction levels (top to bottom). For the finger flexor muscle, the rms VIC increased with the vibration frequency up to 100 Hz; it then increased at a slower rate up to 150 Hz, whereafter it decreased. This trend was consistent for all of the experimental conditions with the exception of those for 20% MVC. For the wrist flexor muscle, the trend was slightly different. The rms VIC increased with the vibration frequency up to 100 Hz and then decreased.

Least-square regressions were performed to determine whether second-order concave curvilinear associations between the rms VIC and vibration frequency existed. Table 1 summarizes the results of the curve fitting. For the wrist flexor muscle, a clear trend was observed under the following three experimental conditions: 10% MVC, 200 μm ; 0% MVC, 300 μm ; and 20% MVC, 300 μm . The trend was

more obvious for the finger flexor muscle than for the wrist flexor muscle, except at 20% MVC. An example is presented in figure 7.

Grip force

Although the EMG activity of the flexor muscles increased as the vibration increased, a decrease in the time-averaged grip force was observed during the vibration exposure ($P = 0.05$). This apparent paradox was observed for nine out of the ten subjects. A re-

Table 1. Second-order curve fitting for the finger flexor and wrist flexor muscles. (MVC = maximal voluntary contraction, NS = not significant)

Muscle	Coefficient of determination (R^2)
Finger flexor (flexor digitorum profundus)	
200 μm displacement amplitude	
0% MVC	0.924
10% MVC	0.727
20% MVC	NS
300 μm displacement amplitude	
0% MVC	0.816
10% MVC	0.742
20% MVC	NS
Wrist flexor (flexor carpi radialis)	
200 μm displacement amplitude	
0% MVC	NS
10% MVC	0.837
20% MVC	0.585
300 μm displacement amplitude	
0% MVC	0.846
10% MVC	0.541
20% MVC	0.787

Figure 7. Examples of curvilinear regressions for a wrist flexor muscle (flexor carpi radialis) and a finger flexor muscle (flexor digitorum profundus). The initial contraction level is 10% maximum voluntary contraction (10% MVC) and the vibration displacement amplitude is 200 μm . The curves indicate a difference in vibration sensitivity of the muscles in the high vibration frequency range.

peated-measures ANOVA was performed on the differential grip force ($DGF = GF_{vib} - GF_{ref}$) to test whether the changes in grip force correlated with the vibration displacement amplitude, frequency, and initial muscle contraction level. Neither significant main effects nor interaction effects were found ($P = 0.05$).

Discussion

Differences in the response of the muscles to the various vibratory situations were observed. They appeared to be dependent on the specific muscle, its initial level of activity, and the parameters of the vibratory stimulus. Nevertheless, the increase in muscle contraction resulting from the application of the vibration was primarily related to the development of the TVR. This conclusion is supported by the observation of the classical attributes of the TVR, such as latency of onset, progressive build-up, and variability. Furthermore, the EMG activity increased concomitantly with a grip force decrease. The versatility of the TVR (12, 17, 22) certainly contributed to the large inter- and intraindividual variability.

Sensitivity of the tonic vibration reflex to initial muscle contraction level

The contribution of the TVR increased with initial voluntary muscle contractions of moderate level (10% MVC). This effect may have resulted from a combination of the following factors affecting the muscle spindles: (i) an increase in the responsiveness of the primary spindle endings to the vibratory stimulus as a result of the increased fusimotor drive (5, 31); (ii) a facilitation of the accessibility of alpha motoneurons by Ia-afferents as induced by the descending voluntary command; (iii) an increase in vibration transmissibility produced by the stiffening of the tissues accompanying muscle contraction (Martin, unpublished results). However, a higher level of voluntary contraction (20% MVC) failed to increase the TVR. A saturation or even a smaller increase was observed for the wrist flexor muscle and finger flexor muscle, respectively. Such a result suggests that the driving of alpha motoneurons by the vibration-induced activity of the Ia-afferents is close to its maximum at moderate levels of voluntary contraction.

Sensitivity of the tonic vibration reflex to vibration amplitude

The increase in vibration amplitude resulted in either an increase or a nonsignificant change in the TVR evoked in the wrist flexor and finger flexor muscles, respectively. These differential effects may have been due to the spatial arrangement of the muscle tendons, which are not in the same plane, and the biomechanical properties of the tissues. It seems that an increase in vibration displacement amplitude fails to produce a larger stretch of the tendon of the flex-

or digitorum profundus (the measured finger flexor muscle). However, the apparent higher sensitivity of the primary spindle endings of the flexor digitorum profundus, as described later, may lead to an early saturation of the number of Ia-afferents recruited in the muscle by the vibratory stimulus in the 200–300 μm displacement amplitude range. As indicated by a microneurographic study (27), almost all of the Ia-afferents of the pretibial muscles are activated in synchrony by low-amplitude tendon vibration below 100 Hz. Therefore, we suggest that this sensitivity contributes to the maximal strength of the TVR at a moderate vibration intensity for some muscles.

Sensitivity of the tonic vibration reflex to vibration frequency

Several studies have investigated the frequency dependency of the TVR at constant acceleration (32, 33). These studies have shown a monotonous decrease in muscular activity as the frequency increases. As suggested previously (9, 10), the decrease in displacement amplitude as the frequency increases at constant acceleration yields a spatial derecruitment of the firing of Ia-fibers. Therefore this process results in a decrease in the TVR component. In the present study, since the displacement amplitude was constant regardless of the frequency, we assume that a quasi identical recruitment took place at all of the frequencies. The positive slope of the TVR up to 100–150 Hz probably resulted from an increase in the depolarization of motor neurons with the firing frequency of the Ia-afferent fibers, which increases the number of responding motoneurons. The negative slope exhibited beyond correlated highly with the “frequency response” of the primary spindle endings. Indeed, these receptors can respond in 1:1 synchrony up to about 100–150 Hz (5, 26, 27); beyond this “cutoff” frequency, driving is less secure and most of the receptors start to misbehave and respond at subharmonic frequencies or at random. Thus a derecruitment process affecting the motoneurons is likely to occur. Since it has been shown that the firing frequency of the motor units is not significantly modified by the vibration frequency in the 30–95 Hz range (23), the contribution of a temporal summation to TVR changes can be ruled out.

The slight difference in the “cutoff” frequency of the TVR elicited from the finger flexor and wrist flexor muscles seems to indicate a higher stretch sensitivity of the spindle endings in the measured finger flexor muscle. It may result from the functional difference of the two muscles. Indeed, precise regulation of muscle activity, and thus accuracy of proprioceptive feedback, is conceivably more critical for the fingers than the wrist.

Some of our results that were related to vibration displacement amplitude and frequency effects differed from those obtained earlier by Eklund & Hagbarth (17). However it is important to note that Ek-

lund & Hagbarth applied vibration using an "eccentric vibrator" strapped to the limb over the muscle tendons. The vibration amplitude was two to ten times higher than the levels used in our experiment. Thus we assume that under their experimental conditions the spread of vibration to the limb and the activation of the skin area covering the vibrated muscles, which is known to have a facilitatory effect (34), contributed to the overwhelming strength of the TVR.

Grip force

The mean results over the 10 subjects indicate a decrease of grip force while the activity of the flexor muscles increases. However a detailed analysis of the individual results in each situation showed either an increase or a decrease in the time-averaged grip force, the latter being predominant. In addition, an initial increase in the force at vibration onset was often observed, followed by a decrease, as illustrated in figure 2. These results are not inconsistent. They rather confirm the plasticity of the organization of a motor response as a function of the context, as suggested by many authors (7, 11, 35, 36). It is worth mentioning that, in the present case, the subjects were required to maintain a selected force level while relying only on proprioceptive feedback.

During vibration, the subjects generally reported the sensation of an increase in grip force. Such a perception probably led to a reorganization of the central command in an attempt to match the previbration sensation. This reorganization seems indicated by force changes over time. It may be that vibration-induced activity of Golgi tendon organs is interpreted by the central nervous system as an increase in muscle contraction. This latter phenomenon leads to a decrease in the grip force through a complex interaction of the flexor and extensor components, since flexor muscle activity does not decrease. This hypothesis parallels the classical interpretation of movement amplitude undershoot resulting from vibration-induced activation of agonist muscle spindles (37—39).

The increase in grip force observed for some of the subjects probably resulted more simply from a lack of voluntary control of the grip force, and this lack of control allowed an opportunity for the full expression of the common effects of the TVR. This result contrasts with the general observation of force increase provoked by "whole-limb" vibration (3, 25). However, it is not a paradox if we assume that force control, similarly to position or velocity control, of slow movements is based on the differential imbalance between agonist and antagonist proprioceptive feedback (4, 39—41). Thus, in that case, vibration-superimposed activity of "antagonistic" proprioceptive afferents decreases the relative differences of the respective signals and leads to an increase in movement amplitude and velocity (4, 39, 41). Further-

more, in the experiment carried out by Radwin et al (25), the task consisted of holding various loads attached to a vibrating handle. Thus maintaining a constant grip force while holding the load was not specifically required.

To conclude, our results indicate, first, that the contribution of the TVR to muscle activity may already reach a maximum at low vibration intensities or at moderate levels of voluntary muscle contraction comparable with the average exertion usually required to hold pneumatic screwdrivers (42). Second, the general increase in muscle activity resulting from vibration exposure contributes to muscle stress and fatigue. Finally, high-frequency vibration (>150 Hz) tends to induce a relatively weaker TVR and thus superimposes less muscle and tendon stress. Such remarks are of particular importance for the design of handheld vibrating tools. From a neurological point of view, they may provide justification for increasing tool speeds when possible. Obviously, maintaining a constant vibration displacement amplitude while increasing the frequency increases the acceleration considerably. Such an effect may increase tissue insults and is not recommended.

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References

1. Lewis CH, Griffin MJ. A review of the effects of vibration on visual acuity and continuous manual control: part II. continuous manual control. *J Sound Vib* 1978;56:415—57.
2. Martin BJ, Gauthier GM, Roll JP, Hugon M, Harlay F. Effects of whole-body vibrations on standing posture in man. *Aviat Space Environ Med* 1980;51:778—87.
3. Gauthier GM, Roll JP, Martin BJ, Harley F. Effects of whole-body vibration on sensory motor system performance in man. *Aviat Space Environ Med* 1981;52:473—9.
4. Martin BJ, Roll JP, Di Renzo N. The interaction of hand vibration with oculo-manual coordination in pursuit tracking. *Aviat Space Environ Med* 1991;62:145—52.
5. Burke D, Hagbarth KE, Lofstedt L, Wallin BG. The responses of human muscle spindle endings to vibration of non-contracting muscles. *J Physiol* 1976;261: 673—93.
6. Johansson RS. Tactile sensibility in the human hand: receptive field characteristics of mechanoreceptor units in the glabrous skin. *J Physiol* 1978;281:101—23.
7. Roll JP, Gilhodes JC, Tardy-Gervet MF. Effets perceptifs et moteurs des vibrations musculaires chez l'homme normal: mise en évidence d'une réponse des muscles antagonistes. *Arch Ital Biol* 1980;118:51—71.
8. Roll JP, Vedel JP, Gilhodes JC, Ribot E. Propriocep-

- tive sensory coding of motor activities in man. In: Jeannerod M, Ron S, Schmidt R, ed. *Sensorimotor plasticity: theoretical, experimental and clinical aspects*. Paris: National Institute for Health and Medical Research (INSERM), 1986:283—304.
9. Martin BJ, Roll JP, Gauthier GM. Spinal reflex alterations as a function of intensity and frequency of vibration applied to the feet of seated subjects. *Aviat Space Environ Med* 1984;55:8—12.
10. Martin BJ, Roll JP, Gauthier GM. Inhibitory effects of combined agonist and antagonist muscle vibration on H-reflex in man. *Aviat Space Environ Med* 1986;57:681—7.
11. Martin BJ, Roll JP, Hugon M. Modulation of cutaneous flexor responses induced in man by vibration-elicited proprioceptive or exteroceptive inputs. *Aviat Space Environ Med* 1990;61:921—8.
12. Roll JP, Martin BJ, Gauthier GM, Mussa-Ivaldi F. Effects of whole-body vibration on spinal reflex in man. *Aviat Space Environ Med* 1980;51:1127—233.
13. Dupuis H, Zelett G. *The effects of whole-body vibration*. Berlin: Springer-Verlag, 1986.
14. Griffin MJ. *Handbook of human vibration*. London: Academic Press, 1990.
15. Hagbarth KE, Eklund G. Tonic vibration reflexes (TVR) in spasticity. *Brain Res* 1966;2:201—3.
16. Eklund G, Hagbarth KE. Motor effects of vibratory muscle stimuli in man. *Electroenceph Clin Neurophysiol* 1965;19:619.
17. Eklund G, Hagbarth KE. Normal variability of tonic vibration reflexes in man. *Exp Neurol* 1966;16:80—92.
18. De Gail P, Lance JW, Neilson PD. Differential effects on tonic and phasic reflexes mechanisms produced by vibration of muscles in man. *J Neurol Neurosurg Psychiatry* 1966;29:1—11.
19. Lance JW, Burke D, Andrews CJ. The reflex effects of muscle vibration: studies of tendon jerk irradiation, phasic reflex inhibition and the tonic vibration reflex. In: Desmedt JE, ed. *New developments in EMG and clinical neurophysiology*. Basel: Karger, 1973:444—62.
20. Homma S, Kanda K, Watanabe S. Tonic vibration reflex in human and monkey subjects. *Jpn J Physiol* 1971;21:419—30.
21. Roll JP, Bonnet M, Hugon M. Comparative study of proprioceptive reflexes in man and baboon. In: Goldsmith EI, Moor-Jankowski J, ed. *Medical primatology 1972: proceedings of the 3rd conference on experimental medicine, surgery of primates; part II*. Lyon: Karger, 1972:305—14.
22. Desmedt JE, Godaux E. Mechanism of the vibration paradox: excitatory and inhibitory effects of tendon vibration on single muscle motor units in man. *J Physiol* 1978;285:197—207.
23. Romaiguere P, Vedel JP, Azulay JP, Pagni S. Differential activation of motor units in the wrist extensor muscles during the tonic vibration reflex in man. *J Physiol* 1991;444:645—67.
24. Abbruzzese G, Hagbarth KE, Homma I, Wallin U. Excitation from skin receptors contributing to the tonic vibration reflex in man. *Brain Res* 1978;150:194—7.
25. Radwin RG, Armstrong TJ, Chaffin DB. Power hand tool vibration effects on grip exertions. *Ergonomics* 1987;30:833—55.
26. Vedel JP, Roll JP, Ribot E. Sensitivity of muscular and cutaneous receptors to vibratory stimuli in man. In: Frolov KV, ed. *Man under vibration, second intl CISM-IFTOMM symp*. Moscow: Academy of Sciences, 1985:130—8.
27. Roll JP, Vedel JP, Ribot E. Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. *Exp Brain Res* 1989;76:213—22.
28. Armstrong TJ, Fine LJ, Radwin RG, Silverstein BS. Ergonomics and the effects of vibration in hand-intensive work. *Scand J Work Environ Health* 1987;13:286—9.
29. National Institute for Occupational Safety and Health (NIOSH). *Criteria for a recommended standard: occupational exposure to hand-arm vibration*. Washington, DC: US Government Printing Office, 1989. (DHHS publication; no 89—106.)
30. Reynolds DD, Soedel W. Dynamic response of the hand-arm system to sinusoidal input. *J Sound Vib* 1972;21:339—53.
31. Ribot E, Roll JP, Vedel JP. Efferent discharges recorded from single skeletomotor and fusimotor fibers in man. *J Physiol* 1986;375:251—68.
32. Iwata H, Dupuis H, Hartung E. Übertragung von horizontalen sinusschwingungen auf die oberen extremitäten bei halbpronationsstellung und rektion des m biceps. *Int Arch Occup Med* 1972;30:313—28.
33. Dupuis H, Hartung E, Hammer W. Biomechanics verhalten, muskelreaktion und subjektive wahrnehmung bei schwingunserregung der oberen extremitäten zwischen 8 und 80 Hz. *Int Arch Occup Environ Health* 1976;37:9—34.
34. Hagbarth KE. Post-tetanic potentiation of myotatic reflexes in man. *J Neurol Neurosurg Psychiatry* 1962;25:1—10.
35. Lackner JR, Levine MS. Changes in apparent body orientation and sensory localization induced by vibration of postural muscles: vibratory myesthetic illusions. *Aviat Space Environ Med* 1979;50:346—54.
36. Roll JP, Roll R. Kinaesthetic and motor effects of extraocular vibration in man. In: O'Regan JK, Levy-Schoen A, ed. *Eye movements: from physiology to cognition*. Amsterdam: Elsevier, North Holland, 1987; 57—68.
37. Goodwin GM, McCloskey DI, Matthews PBC. The contribution of muscle afferents in kinesthesia shown by vibration induced illusions of movement and by the effects of paralysing joint afferents. *Brain* 1972; 95:705—48.
38. McCloskey DI. Differences between the sense of movement and position shown by the effects of loading and vibration of muscles in man. *Brain Res* 1973;61:119—31.
39. Gilhodes JC, Roll JP, Tardy-Gervet MF. Perceptual and motor effects of agonist-antagonist muscle vibration in man. *Exp Brain Res* 1986;11:395—402.
40. Sittig AC, Denier van der Gon J, Gonn JJ, Gielen CCAM. Separate control of arm position and velocity demonstrated by vibration of muscle tendon in man. *Exp Brain Res* 1985;60:445—53.
41. Martin BJ. Contribution à l'étude de la dégradation du fonctionnement des systèmes sensori-moteurs life à l'exposition aux vibrations mécaniques chez l'homme (these de docteur es sciences). Marseille: Université D'Aix-marseille I, 1989.
42. Radwin RG, Armstrong TJ. A study of physical stresses associated with pneumatic screwdrivers (technical report]. Ann Arbor, MI: Center for Ergonomics, The University of Michigan, 1982.

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