Center for Ergonomics
Department of Industrial and Operations Engineering
The university of Michigan
Ann Arbor, MI 48109-2117

VIBRATION, OCULOMANUAL COORDINATION & TRAUMATIC INJURIES

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Principal Investigator: Bernard J. Martin

Co-Investigator: Thomas J. Armstrong

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SIGNIFICANT FINDINGS

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Withdrawal reflex

Both components of the reflex response of cutaneous origin are facilitated by hand vibration. This facilitation increases with initial muscle contraction; however, each component is affected differently by vibration frequency. For the early component, the facilitation is significantly less pronounced for a 200 Hz vibration, while for the late component vibration frequency had no significant effect.

Tonic vibration reflex (TVR)

- The strength of this reflex response of muscular proprioceptive origin
  - a) increases with muscle contraction for initial contractions up to 10% of the maximum voluntary contraction,
  - b) increases with vibration amplitude at low level of initial muscle contraction,
  - c) increases with vibration frequency up to 100- 150 Hz and then decreases beyond.
- Vibration induces a synchronization of motor units, which decreases as frequency increases
- Muscle fatigue tends to increase when the TVR is present

2. Vibration induces alterations of sensorimotor performances which persist after exposure

Manual dexterity

- Vibration induced a significant increase in errors and a significant decrease in tracking time of visually guided hand movements, which indicate an impairment of movement velocity control.
- These impairments decay with time after vibration exposure. The recovery period is greater than 5 minutes but less than 10 minutes.

Oculo-manual coordination

- Hand pointing error, eye fixation error and error variability increase during short term (2 minutes) vibration exposure. These effects persist lest than 5 minutes after long term (10 minutes) vibration exposure when the hand is visible. However, the constant error in hand pointing induced by vibration remains at the same level for a long period after vibration exposure when the hand is not visible.

3. Motor effects are frequency dependent

The involuntary (proprioceptive and cutaneous reflexes) motor responses show an inverted u-shaped like relationship between the alteration and the vibration frequency. The highest levels of increase in muscle response and "performance impairment" tend to occur for vibration frequencies about 100 Hz.

4. Sensory perception is significantly affected by vibration

In general, all studies indicate that vibration-induced alterations of involuntary or voluntary motor activities are not consciously perceived.

Withdrawal reflex

- When the muscles were initially at rest, a decrease in perceived discomfort elicited by the electrical stimulus was indicated by 7/10 subjects during vibration exposure.
- When a moderate level of voluntary contraction was exerted the sensation evoked by the electrical stimulus was not clearly differentiated between pre and per-vibration situations.

Manual dexterity

- The subjective rating of the performance indicates that the subjects tend to perceive the visuo-manual tracking task as being easier after vibration exposure despite an overall alteration of the tracking performance.

5. Vibration-induced perturbations of the sensorimotor systems can be compensated to some extent by the visual feedback

Manual dexterity

- Despite a constant visual control of the hand, velocity control of hand movements is affected by vibration exposure.

Oculomanual Coordination

- Hand pointing errors increase in the absence of visual feedback during and immediately after vibration exposure. These errors persist over 10 minutes after vibration exposure when the hand is not seen.
- Eye fixation errors increase with vibration; however, foveal vision is not lost since the target is always visible.

USEFULNESS OF FINDINGS

Recommendations

- Tool selection and tool design

  The magnitude of the effects of hand vibration on hand movements and the mechanisms underlying the control of hand movements is higher for vibration frequencies near 100 Hz.

  In order to 1) avoid the resonance of the hand arm system occurring mainly in the low frequency range, 2) minimize the influence of vibration on force exertion, which is a factor contributing to musculoskeletal injuries, and 3) minimize the degradation of movement precision, which is a factor in manufacturing quality and a potential risk factor of traumatic injuries, vibration frequencies above 200 - 300 Hz should be "preferred" (provided that these high frequencies are not accompanied by high displacement amplitude). Thus, every other parameter being equal, powered hand tools or vibrating machines exhibiting high frequencies (> 300 Hz) are preferable. Furthermore, high vibration frequencies are easier to attenuate than low frequencies using damping apparels. Finally, our data suggest that vibration displacement amplitude should be less than 0.2 mm.

- Workplace design

  Precision of hand movements decreases significantly when the hand is not directly visible.

  Visual control of hand movements should be permanent in vibratory. environments to partially or fully compensate the degradation of manual tasks. This implies that 1) machine or vehicle controls should be within the field of view of the operator, 2) vision of the hand and/or the tool should not be obstructed by obstacles when the task require tool positioning or tool motion around the work piece and 3) safety shield, when used, should allow a clear vision of the hands, the tool and the work object.

- Work attributes

  The alteration of movement precision is not perceived and may persist for several minutes after vibration exposure.

  Vibrating tools or vibrating machines should not be operated continuously for long periods.

Future research

- Muscle fatigue

  Muscle fatigue is a harbinger to performance decrement and musculoskeletal disorders. Muscle fatigue tends to increase and develop faster under vibration exposure. Changes in the TVR as a function of vibration frequency suggest that fatigue increment induced by vibration is frequency dependent. Two types of studies should be undertaken:

1. A systematic analysis of muscle fatigue as a function of vibration frequency for various levels of initial muscle contractions to determine the "least effective" frequencies,
2. Further the understanding of motor unit synchronization generated by vibration and the contribution of this process to fatigue mechanisms during and after vibration exposure.

- Performance and perception

  Low levels of vibration (0.2 mm) can alter sensorimotor performances. In addition, these alterations are not properly perceived. Future research should attempt to:

  1. Determine acceptable levels of vibration as a function of task requirements
  2. Further the understanding of the dissociation between perception and motor performances (this phenomenon is an acute potential risk factor).
  3. Investigate eventual performance adaptation to long term vibration exposure

ABSTRACT

Importance to Occupational Safety and Health

The focus on manual control perturbation resulting from vibration exposure as a potential risk factor is of particular importance. Indeed, performance of visually guided motor activities is an important factor in accidents involving falls, dropping objects and improper use of controls. Furthermore, an estimated 1.45 million workers use vibrating tools and disabling injuries numbered 570,000 for mining, construction and manufacturing industries where vibrating hand tools and vibrating machines are intensively used. Although one cannot blame vibration as a common denominator to those injuries, a significant number are likely to be related to manual control impairment resulting from vibration exposure.

The aim of this project was to contribute to the reduction of risk of acute occupational traumatic injuries associated with vibration-induced alterations of oculo-manual coordination. The proposed work modeled eye-hand performance and the withdrawal reflex responses as a function of vibration frequency, displacement amplitude and exposure time of vibration applied to the hand.

The results are aimed at estimating a vibration limit relevant to manual performance effects. The importance of visual control of the limbs can be used to formulate safety and design recommendations concerning the work place, the placement of controls and handles.

Objectives

The overall objective was to emphasize the often ignored or neglected role of movement errors in accidents occurring in vibratory environments. The general hypothesis is that vibration-induced modification of sensory messages, used by the central nervous system to control and regulate sensorimotor activities, contribute to the alteration of both movement accuracy and oculo-manual coordination. The following hypotheses were tested:

1. Involuntary motor activities, such as reflexes, are significantly affected during vibration;
2. Vibration-induced alterations of reflex responses varies with vibration frequency
3. Involuntary muscle contraction induced by vibration exposure contribute to muscle fatigue
4. Sensory perception is significantly affected by vibration,
5. Oculo-manual coordination is significantly affected during vibration,
6. Vibration-induced alterations persist after exposure and vary with intensity,
7. Permanent visual control of the upper limbs should compensate to some extent vibration-induced affection of other sensory modalities and contribute to performance improvement,
8. Vibration displacement amplitude should exhibit a high correlation with performance decrement over the 80-200 Hz frequency range, and
9. Sensorimotor performance should be less affected by high frequency vibration (> 200 Hz)

Methodology

Withdrawal reflex

This protective muscular response, elicited in the forearm flexor muscles by electrical stimulation of the radial nerve at the wrist was studied during low level grip exertion (at rest or 10% of the maximal voluntary contraction). Electrical activity of the fingers and wrist flexor and extensor muscles were monitored using pairs of small cupular electrodes. Hand vibration (90, 150, 200 Hz, 0.2 mm) was applied perpendicularly to a vertical handle held by the subject. Changes in the amplitude of both components of the reflex responses were quantified as a function of vibration parameters.

Tonic vibration reflex

The tonic vibration reflex (TVR) was elicited in flexor forearm muscles by a vibration applied perpendicularly to the distal tendons using an electromagnetic vibrator. The mioelectric activity (EMG) of the flexor carpi radialis and flexor digitorum profundus was recorded by pairs of small cupular surface electrodes. The influence of vibration frequency (40, 80, 100, 120, 150, or 200 Hz) at selected displacement amplitudes (0.2, 0.3 mm) on motor unit synchronization was determined by the analysis of the EMG spectra.

Manual dexterity

Manual movement precision and performance time were evaluated through a visuo-manual tracking task performed before and after long term hand vibration exposure (90, 150, 300 Hz, 0.2 mm and 0.3 mm, 10 min. duration). Task consisted of moving a ring attached to a thin rod held between the index finger and thumb along a zig-zagged wire. The alterations of tracking errors and tracking time were analyzed as a function of the vibration parameters. The subjective evaluation of task difficulty was quantified on a visual analog scale. Pre and post-vibration perceptions were compared.

Oculo-manual coordination

A pointing task consisting of aiming simultaneously with the hand and the eye at visual targets placed in front of the subject were performed before and during short term hand vibration exposure (200 sec) and, after long term hand vibration exposure (10 min.). The vibration frequencies were 100, 200 Hz, with a displacement amplitude of 0.2 mm. Eye and hand horizontal positions were measured to quantify ocular and manual performance and evaluate oculo-manual coordination. The influence of vibration parameters was analyzed statistically.

Overall Findings

Withdrawal reflex

Motor effects - Both components of the reflex response are facilitated by hand vibration and this facilitation increases with initial muscle contraction; however, each component is affected differentially by vibration frequency. For the early component, the facilitation is significantly less pronounced for a 200 Hz vibration, while for the late component vibration frequency had no significant effect.

Effects on perception - When the muscles were initially at rest, a decrease in perceived discomfort elicited by the electrical stimulus was indicated by 7/10 subjects during vibration exposure. When a moderate level of voluntary contraction was exerted the differentiation between pre and per-vibration sensation evoked by the electrical stimulus was not statistically significant.

Tonic vibration reflex

The TVR increases with the vibration level for low initial muscle contraction, increases with muscle contraction for initial contractions up to 10% of the maximum voluntary contraction and increases with vibration frequency up to 100 - 150 Hz and then decreases beyond. The spectral analysis of the EMGs indicates that motor unit harmonic synchronization with the vibratory stimulation decreases as vibration frequency increases, while subharmonic synchronization increases as frequency increases. The corresponding curves exhibit a sigmoid shape in the tested frequency range. The synchronization mechanisms contribute to modulation of the amplitude of the TVR as the vibration frequency increases. Furthermore, muscle fatigue tested during long duration isometric voluntary contraction tends to be higher with than without vibration. It is suggested that the synchronization process influences muscle fatigue, since it impels motor unit activity and thus the development of metabolism. High frequency vibration (>150 Hz) tends to induce less motor unit synchronization in a frequency range beyond known mechanical resonance of biological tissues.

Manual dexterity

Vibration induced a significant increase in errors and a significant decrease in tracking time. The number of tracking errors tended to increase with vibration frequency. These impairments decay with time after vibration exposure. The recovery period is greater than 5 min. but less than 10 min for frequencies above 90 Hz. The recovery tends to be slower for the 0.3 mm than 0.2 mm vibration displacement amplitude. The subjective rating of the performance indicates that the subjects tend to perceive the task as being easier after vibration exposure. Thus, the results show that vibration affects precision and velocity control of visually guided hand movements and that performance decrements are not perceived. Vibration amplitude do not seem to have a strong influence.

Oculo-manual coordination

Vibration induced an increase in hand pointing constant error and error variability. These alterations were more particularly pronounced for the 100 Hz vibration and when the hand was masked. In this latter visual condition, the persistence of the constant error 10 minutes after vibration exposure suggests the loss of the initial pointing reference. The eye gaze constant error and error variability increased during and immediately after vibration exposure. The influence of vibration frequency on eye movements was slightly different during and after vibration exposure. Recovery of pre-vibration performance was less than 5 minutes for the eye fixation.

These results indicate that vibration similar to hand-tool vibration affects hand movement precision and the coordination of hand and eye movements. The visual control of the hand counteracts, to some extent, the alterations of hand movements resulting from vibration exposure.

Conclusion

Overall, vibration displacement amplitude as low as 0.2 mm can induce strong alterations of sensorimotor performances; frequencies about 100 Hz produce the largest effects. Furthermore, visual control of the hand appears to be a necessary condition to limit the vibration-induced degradation of manual tasks but this condition is not sufficient. Finally, dissociations between perception and motor responses suggest that subjective evaluation of vibration-induced discomfort, risk or self assessment of performance during and immediately after vibration exposure should be carefully scrutinized.

BODY OF REPORT

Background

This study analyzes the function of the neural mechanisms underlying sensorimotor control to further the understanding of the effects of mechanical vibration on manual performance and its relation with traumatic injuries. The focus on manual control perturbation resulting from vibration exposure as a potential risk factor is of particular importance. Indeed, an estimated 1.45 million workers use vibrating tools (NIOSH, 1989) and disabling injuries numbered 570,000 (NSC, 1985) for mining, construction and manufacturing industries where vibrating hand-tools and vibrating machines are intensively used. Although one cannot blame vibration as a common denominator to those injuries, a significant number is likely to be related to manual control impairment resulting from vibration exposure.

Human factors and environmental factors play a significant role in injury causation and some population group are at increased risk of injury because of greater exposure to hazard or decreased ability to avoid hazard (Baker, 1975), which seems to be the case in industrial vibratory environments. For example, alteration of motor control when using a shaper may put the operator at risk as the blade of the spinning cutter cannot be seen clearly and the operator cannot control/estimate precisely the position of the hands without permanent visual control of the upper limbs (Martin et al. 1990). In addition, sensorimotor reflexes are greatly altered by vibration exposure too (Martin et al. 1986; 1990). It is well known that woodworkers using shapers have a high probability of having their left hand fingers cut. Besides some known mechanical reasons, sensorimotor performance impairment is often cited as one of the causes of the accident.

Epidemiology

Specific and non specific pathologies resulting from whole body or hand vibration exposure are extensively described in the literature (See for review: Pope et al. 1980; Wasserman, 1987; Dupuis and Zerlett, 1986-87; Griffin, 1990; Bovenzi, 1990). However, little or no attention has been paid to the causality of traumatic injuries occurring in vibratory environment. This probably results from the fact that vibration-induced alteration of sensorimotor activities are neither perceived nor evidenced like pathologies, and are reversible (see below). In a similar manner, while the literature about occupational traumatic injuries is extensive, it pertains more to statistics, the treatment and care of injuries than to the mechanism of injury (Armstrong, 1978).

Nevertheless, the number of traumatic injuries to the arms, hands and fingers total 430,000 (NSC, 1985), which represents 28% of injuries at work There are 200,000 to 300,000 disabling injuries in work-related falls each year according to NSC estimates (1985). About 65% of those workers were employed in construction and manufacturing, and loss of balance or losing one's grip was reported by one fourth of the workers. Remember that postural stability and grip exertion are integrated sensorimotor activities. Such data (or absence of data) suggest the need to define the risk factors associated with traumatic injuries, including motor performances, as the first step to designing programs of prevention related to vibration exposure.

Oculo-manual coordination

The hand is the primary physical interface of human interaction with the surrounding space. Reaching, grasping, manipulating objects, handles, tools or controls with or without direct visual control of the limbs are essential daily activities which rely on complex sensory-motor relationships. The cues provided by the multiple sensory modalities involved in these tasks (vision, proprioception, exteroception, exproprioception) and more particularly in visuo-manual tracking combine at a central level to control coordination of ocular and manual movements. This coordination is of prime importance for the success of precise manipulation and control under visual guidance (Bernstein, 1967; Jannerod and Prablanc, 1983; Gauthier et al. 1988). Hazardous situations may arise when inadequate coordination or impaired manual control result from the influence of environmental stressors. It is a common observation that vibration can interfere with these human activities.

Vibration effects on sensorimotor performances

A voluminous but somewhat diffuse literature describes the effects of vibration on the performance of manual control. Recent reviews have compiled the quasi totality of the data (Lewis and Griffin, 1978; Martin 1989; Griffin, 1991). With the exception of very few, most of the studies have used whole-body vibration of low frequency (< 20 Hz), where body resonances occur. This correspond to the fact that low frequency components constitute the frequency bandwidth of the vibration spectrum of vehicles where the major part of the energy is concentrated, but also underlines the traditional mechanistic approach to the problem (Griffin and Lewis, 1978; Martin, 1989). However, high frequency vibration is also present in vehicles, and the spectral energy of powered hand-tools or vibrating machines is almost entirely contained in the high frequency range. Little work related to manual control has been done in this domain.

Recently, it has been demonstrated that the exposure of whole or part of the body to high frequency vibration has detrimental effects on human sensorimotor performances, such as postural stability (Eklund, 1972; Martin et al. 1980; Roll, 1981) and continuous manual control (Lewis & Griffin 1976, -79; Gauthier et al. 1981; Roll, 1981; Ribot et al. 1986; Martin et al. 1991). In addition, performance decrement may persist after vibration exposure. Furthermore, Martin et al. (1991) have disclosed that hand vibration (150 Hz, 70 m/s^2 rms) alters significantly oculo-manual coordination when the hand is out of sight.

Besides its direct mechanical effects on the biomechanical structure of the human body, the most pervasive effects of vibration result from its ability to affect neurological function through stimulation of sensory receptors within the cutaneous, muscular, and articular structures (Burke et al. 1976; Johansson, 1978; Roll et al. 1980, 1986). The somesthetic receptors can respond in 1:1 synchrony to the vibratory stimulus in their respective frequency ranges (Johansson and Vallbo, 1983; Vedel et al. 1985; Ribot et al. 1986), and their "natural" messages can be completely masked/erased by their response to the vibratory stimulus (Ribot et al, 1986; Roll et al. 1986; Ribot, 1988). The vibration-induced activity of these receptors is considered a leading cause of specific perceptive and sensorimotor impairments observed in those exposed to the vibratory environment (Gauthier et al. 1981; Martin et al. 1980; 1984; 1986; 1990; 1991).

In addition, monosynaptic spinal reflexes, known to play a role in sensorimotor regulation, are largely inhibited by whole-body (Roll et al. 1980), segmental (Martin et al. 1984) and local musculo-tendinous vibration (De Gail et al. 1966; Lance et al. 1973; Desmedt and Godaux, 1978; Van Boxtel, 1979; Martin et al. 1984, 1986). The displacement amplitude of the vibration appears to be the parameter best correlated with the inhibition (Martin et al. 1984). Paradoxically, an involuntary tonic contraction, the so called TVR (tonic vibration response), coexists with the inhibition of the monosynaptic reflexes elicited in the same muscle (De Gail et al. 1966; Lance et al. 1973; Desmedt and Godaux, 1978). These two phenomena are likely to contribute to motor control alteration (Matthews and Watson, 1981; Martin et al. 1981, -84, -86; Radwin et al. 1987).

Furthermore, the withdrawal reflex, a protective flexor reflex, is also affected by local musculo-tendinous or tactile vibration (Martin et al. 1990). This recent study has disclosed a possible dissociation between pain perception and the corresponding motor response elicited by the offending stimulus. The data suggest that the inadequacy of the withdrawal response may put a worker at risk under vibratory environmental conditions.

It is important to note that in all cases sensorimotor performance impairments resulting from vibration exposure are not consciously perceived. On the contrary, a sensation of improvement is often reported (Martin et al. 1980, Gauthier et al. 1981, Martin et al. 1991).

Work needed

From the literature, it was clear that vibratory environments contribute to the alteration of 1) manual control, 2) visuo-oculo-manual coordination, 3) perception 4) the function of the neurophysiological mechanisms underlying these activities, and finally 5) the effects persist over vibration exposure. These findings strongly suggest that a risk of an injury can be associated with hand vibration, during and immediately after exposure. Therefore, knowledge of manual abilities and human performance limitations, and knowledge of the integrity of our built-in protective mechanisms in vibratory environments created by powered hand-tools or machines, are necessary in order to design machines, jobs and workplaces that have a minimum risk of injury. These data will contribute as a first step in the establishment of a relationship between vibration-induced alteration of manual dexterity and their potential incidence on traumatic injuries. Implementation of manual work practice guidelines and reduction of vibration transmission to the hand should combine to improve worker safety.

Specific Aims

This work studies the effects of mechanical vibration transmitted by the hands on eye-hand (oculo-manual) coordination of human operators. Following prior findings showing that whole-body or hand vibration exposure result in 1) manual performance decrements, 2) alteration of protective reflexes, and 3) unawareness of these impairments, this work evaluates the extent of the alterations in the withdrawal reflex, the tonic vibration reflex, finger dexterity, manual control and oculo-manual coordination resulting from hand vibration similar to that generated by powered hand tools, such as drills, grinders, sanders, or vibrating machines such as shapers.

The immediate aim of the investigation was to evaluate vibration-induced impairment of oculo-manual coordination. It is believed that these impairments are a potential factor of accidents involving falls, dropping objects, and improper movements in general. Thus, the long term goal is to reduce risk of acute occupational traumatic injuries associated with vibration-induced alterations of oculo-manual control.

Neurophysiological (reflexes) and behavioral (sensorimotor control) techniques were used as complementary approaches to achieve the proposed aims.

Reflex responses and performance were tested before, during and after vibration exposure. The recovery period was also investigated. University students unfamiliar with occupational vibration exposure and a limited number of workers from industry, using powered hand tools, participated in the study as paid volunteer subjects.

The general hypothesis is that vibration-induced modification of sensory messages, used by the central nervous system to control and regulate sensorimotor activities, contribute to the alteration of both movement accuracy and oculo-manual coordination. Therefore, these perturbations, not consciously perceived, constitute a risk factor in the etiology of occupational traumatic injuries. The following hypotheses were tested:

1. Involuntary motor activities, such as reflexes, are significantly affected during vibration;
2. Vibration-induced alterations of reflex responses varies with vibration frequency
3. Involuntary muscle contraction induced by vibration exposure contribute to muscle fatigue
4. Sensory perception is significantly affected by vibration,
5. Oculo-manual coordination is significantly affected during vibration,
6. Vibration-induced alterations persist after exposure and vary with intensity,
7. Permanent visual control of the upper limbs should compensate to some extent vibration-induced affection of other sensory modalities and contribute to performance improvement,
8. Vibration displacement amplitude should exhibit a high correlation with performance decrement over the 80-200 Hz frequency range,
9. Sensorimotor performance should be less affected by high frequency vibration (> 200 Hz)

The overall objective was to emphasize the often ignored or neglected role of movement errors in accidents occurring in vibratory environments.

Added aim

Analysis of the tonic vibration reflex and the synchronization of motor units was added. This work was initiated to investigate the suspected influence of the TVR on muscle fatigue. A pilot study had shown changes in the magnitude of the TVR as a function of vibration frequency. We attempted to determine the mechanisms of these changes and their contribution to the increase in muscle load under vibration exposure that may lead to muscle fatigue and musculoskeletal disorders (see TVR section).

Unaccomplished aim

The comparison of workers using hand tools and "naive" students was not performed. Despite aggressive recruitment procedures (newspaper advertisements, contact with unions, contact with plants, increase in the salary initially planned), only 3 workers participated in the manual dexterity experiment. As we had a limited budget for subject salaries we assume that the amount of money proposed to the workers ($45 for 3 hours) was not sufficient to attract them from distant residence and work location. The salary limitation was imposed by the reduction of the overall budget.

The data obtained with the worker population (3 subjects) did not indicate significant changes in visuo-manual tracking after vibration exposure. However, because of the small sample size statistical significance is not reached.

WITHDRAWAL REFLEX

Aims

The aim of this study is to test the integrity of this behavioral protective response under hand vibration exposure according to the following hypotheses :

1) involuntary motor activities, such as reflex responses are significantly altered by vibration;
2) perception of the stimulation generating the reflex response is affected by vibration;
3) motor effects and effects on perception are highly correlated with vibration displacement amplitude.

Effects of hand vibration exposure on cutaneous reflex responses and stimulus perception

ABSTRACT

This research investigates the effects of vibration frequency and voluntary muscle contraction on the cutaneous reflex responses of the hand flexor muscles, and perception of the intensity of transcutaneous stimuli. Vibration was applied to the hand and electromyographic activities of the hand flexor muscles were recorded using surface electrodes. The cutaneous reflex responses, composed of an early and a late component, were elicited by series of electrical pulses applied to the radial nerve at wrist level. Changes of reflex response magnitudes were analyzed as a function of vibration frequency (90, 150, 200 Hz, at 0.2 mm) and initial muscle contraction level (rest or 10 % MVC). A psychophysical experiment was performed to assess the effects of vibration on perception of the electrical stimulus. The cutaneous reflex responses were facilitated during vibration, which may contribute to the exaggeration of the behavioral withdrawal response and simultaneously decrease sensorimotor control performance. For the early component, the facilitation was significantly less pronounced for a 200 Hz vibration, while for the late component vibration frequency had no significant effect. During vibration, a poor correlation was found between the reflex responses and stimulus perception. This dissociation might be a source of inadequate responses to sensory stimulation triggering protective behaviors.

Background

Various technical developments in our society have introduced mechanical vibration into our daily life. One of the immediate concerns about vibration is its effects on health. Many studies on occupational vibration have been concerned with the long-term effects such as hand-arm vibration syndrome. However, short term responses of the neuromuscular system to vibration are of particular interest from an occupational safety standpoint. It has been demonstrated that exposure to mechanical vibration has immediate detrimental effects on human sensorimotor performance (1, 2). This impairment originates mainly from the vibration-induced activity of sensory receptors (3, 4, 5) and thus, its repercussion on sensorimotor systems (1, 3, 4).

Among the various neurophysiological mechanisms involved in sensorimotor activities, the withdrawal reflex is a protective mechanism. This reflex is a response to a noxious stimulus applied to the skin, which elicits a movement causing a withdrawal from the offending stimulus. This withdrawal reflex is triggered by the activation of cutaneous receptors. This input mostly results in limb flexion via polysynaptic pathways (6, 7). Hagbarth and Finer (7) observed two components in the withdrawal reflex responses elicited in the lower limbs: an early component appearing on average 60 to 80 milliseconds (ms) after the stimulus onset, and a late component with a latency between 120 and 200 ms. A recent study showing the maintenance of the functionality of withdrawal responses in spinalized rats (8) indicated that the reflex responses are mediated by a spinal neural network whose excitability is under descending control. The pattern of the withdrawal reflex responses found in the upper limbs is similar but the range of latency of the responses is slightly shorter than in the lower limbs.

Many studies have been carried out on the withdrawal reflex itself but little is known about the ways in which this reflex is integrated into the total adaptive defense behavior of human operators under vibratory environments similar to those encountered in real industrial situations. One of the hypotheses of this study is that vibration-induced perturbation of sensory messages, which uses the spinal and supraspinal systems to control sensorimotor activities, contributes to an alteration of the protective mechanism. Therefore, such perturbation, if not consciously perceived, could constitute a hazard factor in the etiology of occupational traumatic injuries. The objectives of this study were, first, to quantify the changes in cutaneous reflexes elicited in the finger and wrist flexor muscles as a function of vibration frequency and initial voluntary contraction level of the flexor muscles, and second, to identify some of the underlying mechanisms responsible for the impairment of the behavioral protective response during exposure to hand vibration.

Materials and methods

Subjects

Ten subjects participated in the study and their average age was 29. The subjects gave informed consent and were paid for their participation. They were in good health and reported neither neurological nor musculoskeletal disorders.

Experimental Apparatus

The subject was seated comfortably in a armchair, the right hand held a vertical handle equipped with a strain gage dynamometer. The hand was in a semi-supinated position and the forearm was supported by a padded horizontal arm rest (figure 1), and the handle was attached to an electromagnetic vibrator (Vibration Test Systems 100). The height and position of the handle were adjusted so as to obtain approximately a 120° elbow angle. The posture was maintained identically for all trials.

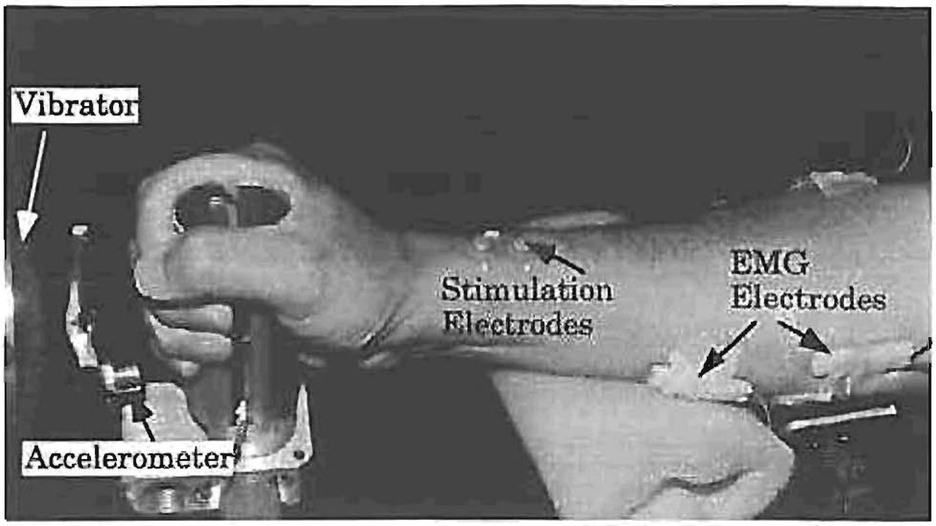

Figure 1. Experimental setup. Vibration is applied to the hand while the subject is holding a vertical handle equipped with a strain gauge dynamometer.

The vibrator was driven by a sine wave generator and servo-controlled by a vibration compressor (Trig-teak 801B) that maintained constant vibration displacement amplitudes in the tested frequency range. Feedback to the vibration compressor was provided by an accelerometer placed on the handle, while the vibration displacement amplitude was computed by, and monitored through a vibration monitor (Trig-tek 610B). The controlled vibration signal was amplified and transmitted to the electromagnetic vibrator.

Cutaneous electrical stimuli were generated by a stimulator (Grass S8800) and fed into an isolation unit (Grass SIU5) and a constant current unit (Grass CCU1A). The constant current unit was connected to two small cupular surface electrodes.

Two experiments were performed. First, a reflex experiment investigated the alteration of the withdrawal reflex induced by hand vibration. Second, a psychophysical experiment quantified the perception of the electrical stimulus with and without hand vibration exposure.

Experiment I: reflex responses

Stimulation and recording

Exteroceptive responses from the finger flexor (flexor digitorum superficialis) and wrist flexor (flexor carpi radialis) muscles were elicited by transcutaneous electrical stimulation of the anterior branch of the radial nerve. Stimulation electrodes were placed 2 cm apart longitudinally over the radial nerve at the wrist. The site of stimulation was identified using a pair of brass test electrodes. Adequate positioning of the electrodes was ascertained when the subject reported a sensation projecting from the electrodes to the dorsal area of the three first fingers and reflex responses were obtained for that position. Once the site was located, the test electrodes were replaced by small cupular surface electrodes. Each stimulus consisted of a series of five pulses each with a duration of 0.5 ms separated by a period of 1 ms. The stimuli were delivered randomly at intervals of 10 to 30 seconds (s). Data acquisition was synchronized by the stimulus.

Electromyographic activity (EMG) of the flexor digitorum superficialis and the flexor carpi radialis muscles was recorded by small cupular electrodes embedded in a preamplifier. The respective EMGs were then amplified, band pass filtered (10-500 Hz) and displayed in real time on the computer screen after digitization.

Procedure

Before the experiment, the level of the maximum voluntary contraction (MVC) of the grip force was determined using the dynamometer connected to a digital display. The subject then was trained to maintain 10% of her/his MVC by looking at the force monitor display. This visual feedback was provided throughout the experiment.

Vibration was applied to the hand along the forearm axis (Z axis). The vibration displacement amplitude was set at 0.2 mm peak-to-peak. Three vibration frequencies (90, 150, and 200 Hz) and two levels of muscle contraction (0% and 10% MVC) were used in the experiment and were randomly presented.

The reflex responses were evaluated before and during vibration exposure. Each "sequence" consisted of 10 stimuli before vibration and another 10 stimuli during vibration, and was reproduced twice. A 1 minute recovery period was given between control and treatment and a 3-minute resting period was provided between consecutive sequences. Comparisons between controls and treatments were made for each subject.

Data recording and analysis

Recordings of the raw EMG signals and grip force were triggered by the electrical stimulation for a sweep length of 0.5 s, digitized at a sample rate of 1000 Hz and stored by a computer.

The amplitude, latency, and number of occurrence of the early and late components of the cutaneous reflex responses were analyzed. Amplitude was taken as the area under the rectified EMG curve for each component. Latency and duration of the integration window were adjusted for each subject as a function of the corresponding parameters of the two components. The latency of each component was measured from stimulus onset to the start of each EMG response; the threshold was determined visually. Statistical tests were performed to determine whether vibration has a significant influence on the three parameters (amplitude, latency, and number of occurrences of both components of the cutaneous reflex responses). Repeated measures analysis of variance (ANOVA) treating each subject as a block was performed to determine the effects of vibration frequency and muscle contraction level on the three parameters. The effect of the factor levels was evaluated using the Tukey method of multiple comparisons.

Experiment II: Subjective perception

To evaluate the influence of vibration on perception of the intensity of the electrical stimulus, a separate psychophysical experiment using a rating method was carried out immediately after Experiment I. The lowest and highest intensities of the electrical stimulus, corresponding to the tactile threshold and pain tolerance, respectively, were presented to the subject as the "anchor" points. They were assigned values corresponding to the lower and the upper limit, respectively, on a 10 cm visual analog scale. The intensity used to obtain the reflex response in Experiment I was presented to the subject as a reference and remained constant throughout the experiment, which the subjects were not aware of.

Each subject was asked to rate the intensity perceived before and during hand vibration by placing a mark on the scale. The same vibration (90, 150, and 200 Hz, 0.2 mm peak-to-peak) and the two levels of muscle contraction (0% and 10% MVC) were again used in this experiment. For each muscle contraction level, a control trial was carried out without vibration, and the subject rated the reference intensity on the scale. Then vibration was applied and the stimulus intensity was again rated. The vibration frequencies were randomly presented at each muscle contraction level. Comparisons between the control and treatment were made for each subject. Electrical stimuli were separated by a 10-s recovery period. Two consecutive comparisons were separated by a 30-s period

Data analysis

To determine whether perception of the stimulus intensity (PI) is influenced by vibration and muscle contraction levels, distances from the tactile threshold to the rated intensities on the visual analog scale were measured. A repeated measures ANOVA treating each subject as a block was performed on the distances.

Results

Experiment I: Reflex responses

Examples of cutaneous reflex responses are reproduced in figure 2. These responses usually consisted of two components. An early component, with a short latency, was of short duration and often showed a biphasic or triphasic shape. A late component, with a longer latency, was of longer duration and polyphasic shape; however, biphasic and triphasic shape were not rare. The late component had usually a higher amplitude than the early component. A reflex response could consist of either component alone (figure 2a) or both components (figure 2b). In fact, neither component was consistently present, but for nine of the ten subjects, the late component was present more frequently and consistently than the early component. When a voluntary muscle contraction was present in the background, the emergence of these two components was more "diffused" but the overall pattern remained the same. However, the presence of the silent period separating the two components, as in the case without muscle contraction, enabled the identification of the presence of the components.

Application of vibration to the hand induced a facilitation of the reflex responses (figure 2b) . More specifically, i) the amplitude of both components increased during vibration; ii) this increase was often accompanied by latency reduction; iii) the occurrence of responses increased. When both the early and late components were present, both were facilitated during vibration. When either component was present without vibration, the missing one often appeared during vibration.

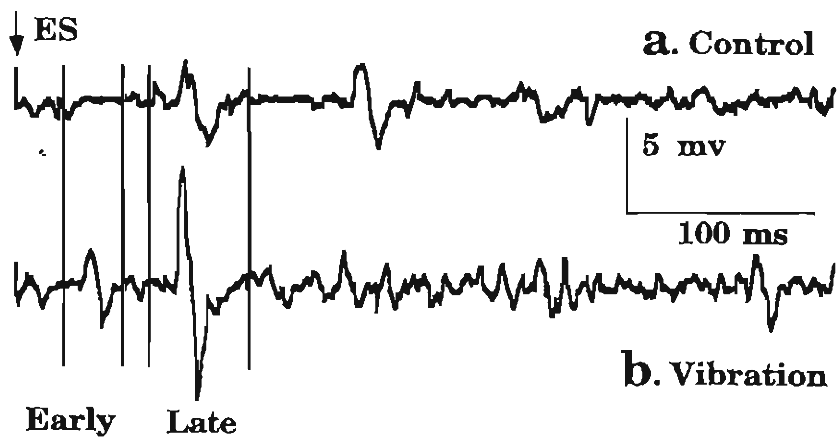

Figure 2. Withdrawal reflex responses. Raw EMG signals from the finger flexor muscle (0% MVC). The upper (a) and lower (b) traces represent the EMG signals without and with vibration, respectively. A reflex response could consist of either component alone (a) or both components (b). Vibration caused a facilitation of the reflex responses (b): the amplitude increased, and the early component which was missing in the control condition was present during vibration in this case.

Amplitude of the Reflex Responses
The amplitude of the reflex responses represented by the corresponding EMG integrals significantly increased with vibration ($p < 0.05$) for the muscles tested. For each muscle, ANOVA was performed on the vibration-induced incremental EMG integral ($\Delta\int EMG = \int EMG_{vib} - \int EMG_{ref}$) for each component, to determine the significance of the influence of vibration frequency and initial muscle contraction level (Table 1). The analysis was performed on differences as the responses were not systematically present.

Table 1. ANOVA results for the amplitude (INC $\int$EMG) of the early and late components of the flexor muscles.

Effect	df	P-value			
		Early component		Late component	
		Finger	Wrist	Finger	Wrist
Frequency (F)	2	0.024*	0.169	0.319	0.409
Contraction (C)	1	0.003*	0.043*	0+*	0.014*
F x C	2	0.256	0.334	0.824	0.465

Note: df=degree of freedom
* = significant

Early Component. The average data are represented in Figure 3. For the finger flexor muscle, vibration frequency had a significant influence on the increase in amplitude of the early component (p=0.024); Tukey comparisons revealed that the $\Delta\int$EMG at 90 Hz was significantly higher than at 200 Hz (p=0.018), but there was no significant difference either between 90 Hz and 150 Hz (p=0.425) or between 150 Hz and 200 Hz (p=0.283). For the initial muscle contraction of 0% MVC (resting) a large facilitation of the response was observed for a 90 Hz vibration, while no significant inhibitions of the responses were observed at 150 or 200 Hz. When the initial muscle contraction was 10% MVC facilitation of the response decreased as vibration frequency increased (Fig. 3, upper panel). When averaged across muscle contraction, the $\Delta\int$EMGs represent 218%, 91% and 20% of the reference values for vibration of 90, 150 and 200 Hz, respectively . For the wrist flexor muscle vibration frequency was not significant (p=0.169). For the initial muscle contraction of 0% MVC (resting) the facilitation tended to decrease as vibration frequency increased, while at 10% MVC, the 150 Hz vibration tended to induce a larger facilitation (Fig. 3, lower panel).

The early component significantly increased ($p<0.05$) with initial muscle contraction for both flexor muscles during vibration exposure, as shown in figure 4.

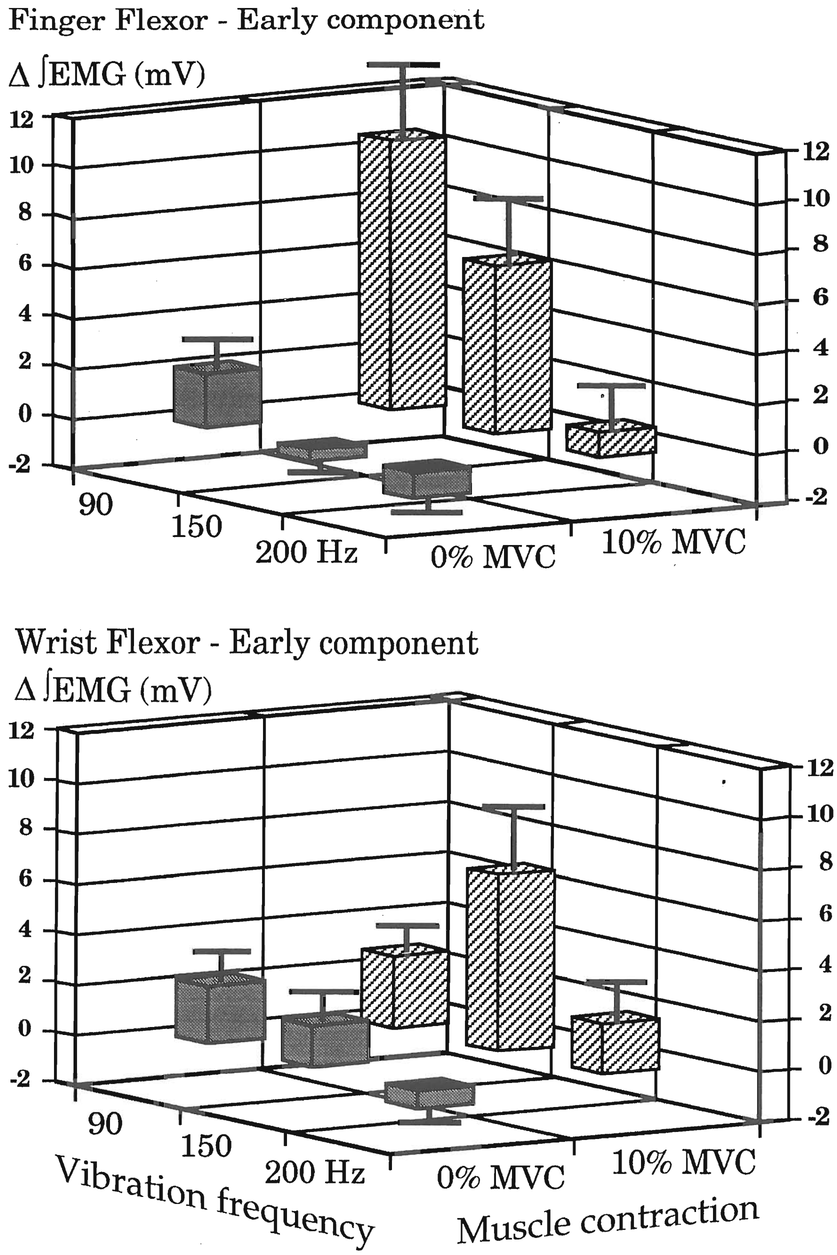

Figure 3. Effect of vibration frequency on the ∫EMG of the early component of the finger and wrist flexor muscles. The Δ∫EMGs are averaged across the subjects. For the finger flexor (upper panel) the Δ∫EMG decreases as vibration frequency increases. For the wrist flexor (lower panel) vibration frequency has no significant effect.

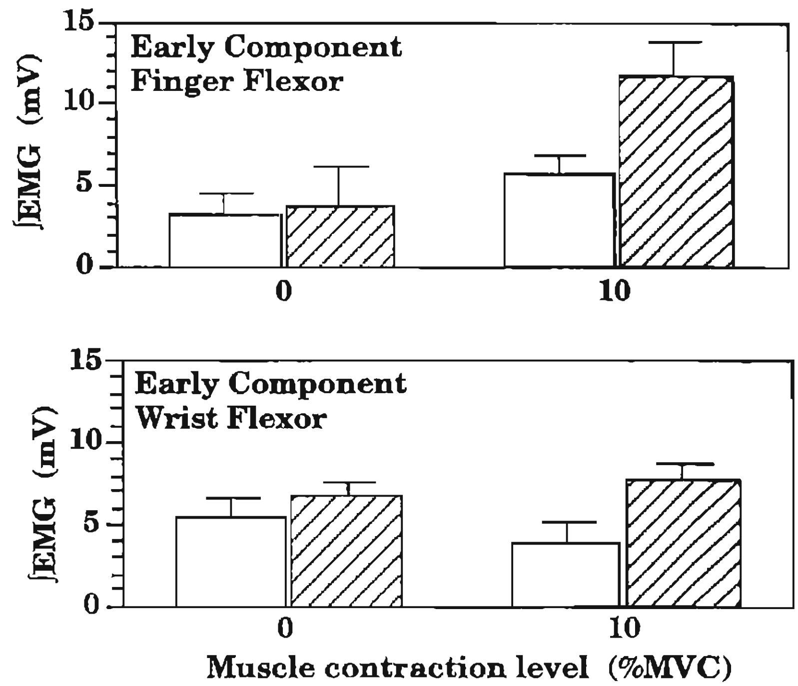

Figure 4. Effect of initial muscle contraction level on the ∫EMGs of the early component of reflex response of the finger flexor and wrist flexor muscles. The hollow an and hatched bars represent the ∫EMG obtained before and during vibration, respectively. The ∫EMGs were averaged across the subjects and frequencies. The higher level of initial muscle contraction resulted in stronger facilitation of the early component.

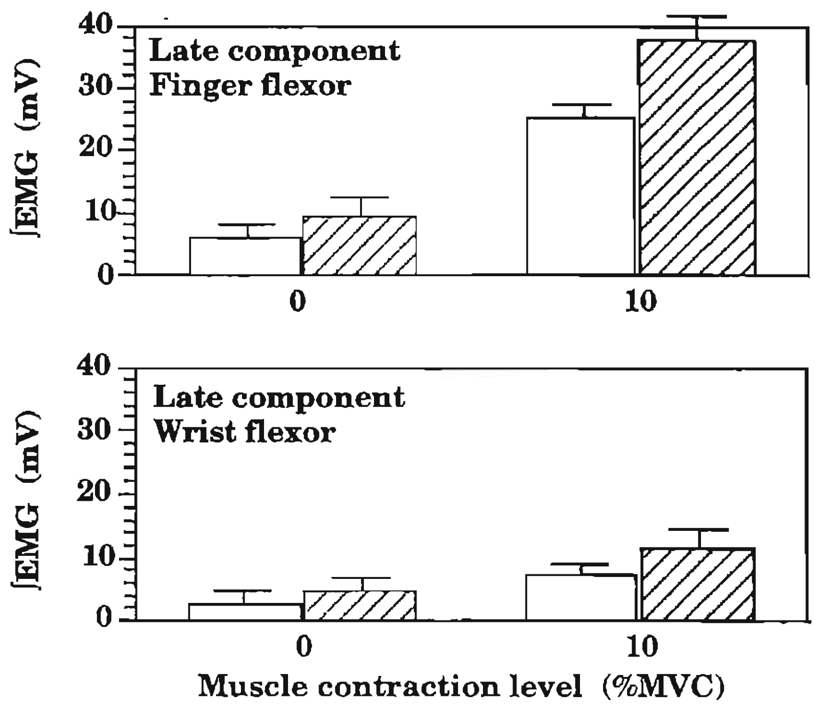

Figure 5. Effects of initial muscle contraction on the ∫EMGs of the late component of the reflex response of the finger flexor and wrist flexor muscles. The hollow an and hatched bars represent the ∫EMG obtained before and during vibration, respectively. The ∫EMGs were averaged across the subjects and frequencies. The higher level of initial muscle contraction resulted in stronger facilitation of the late components.

Late Component. The amplitude of the late components of both flexor muscles increased during vibration (Figure 5). The frequency of the vibration had no significant influence ($p>0.3$); however, vibration-induced facilitation increased significantly with initial muscle contraction ($p<0.05$).

Latency

The intra-subject variations of the latency of the early and late components ranged between 36 and 62 ms, and between 70 and 140 ms, respectively. The ranges of the latencies were much the same for each of the muscles tested. On average, the latency of both components significantly decreased with vibration by 2.5 ms and 4.3 ms (t-test, $p<0.05$), respectively. The results are summarized in Table 2. The ANOVA indicated that neither vibration frequency nor initial muscle contraction level had a significant influence on latency reduction.

Table 2. ANOVA results for latency reduction

Early components of the flexor muscles

Effect	df	P-value	
		Finger	Wrist
Frequency (F)	2	0.207	0.672
Contraction (C)	1	0.511	0.712
F x C	2	0.245	0.812

Late components of the flexor muscles

Effect	df	P-value	
		Finger	Wrist
Frequency (F)	2	0.250	0.598
Contraction (C)	1	0.780	0.751
F x C	2	0.450	0.538

Note: df=degree of freedom

Occurrence Frequency

Early component. Although before vibration the occurrence frequency was less at 10% MVC than 0% MVC, the reflex responses were observed more frequently during vibration exposure. This increase varied from 23% to 86%; however, it was only significant ($p < 0.04$) for the 10% MVC initial contraction. The frequency of vibration did not have significant influence on the increase of the occurrences ($p>0.2$).

Late component. The occurrence frequencies of the late components of both flexor muscles was significantly ($p < 0.05$) higher at 10% MVC than 0% MVC. The occurrence frequency increased with vibration but it was only marginally significant ($p = 0.06$) for the wrist flexor muscle.

Experiment II: Subjective perception
At rest, seven of the ten subjects perceived a decrease in the stimulus intensity during vibration, whereas the remaining three subjects perceived an increase. At 10% MVC, however, only two subjects perceived a decrease in stimulus intensity during vibration, and four subjects perceived an increase. This latter group includes the three subjects who reported an increase at rest. The remaining four subjects showed mixed responses. Repeated measures ANOVA showed that neither the vibration frequency nor the muscle contraction significantly influence changes in perception of the stimulus intensity.

Discussion

Motor Responses

The results indicate that vibration induced a facilitation of the motor responses. The frequency had only a significant effect on the increase of the EMG amplitude for the early component of the flexor muscles; however, the vibration-induced facilitation increased with initial muscle contraction for both components of both muscles. In addition, the latencies of both components decreased and more reflex responses were observed during vibration.

Vibration activates a large number of cutaneous and muscle proprioceptive afferents (mainly Ia-afferents). These latter increase α-motoneurons depolarization principally via a polysynaptic pathway (9). Thus the accessibility of α-motoneurons by cutaneous influences increases and contributes to the increase of the cutaneous reflex components. In addition, animal studies have indicated that tactile afferents contribute to neural networks subserving the nociceptive withdrawal reflex (10, 11). Consequently, an increase of the reflex magnitude, a slight reduction in latency, and a lowering of the threshold of the reflex responses can occur (12). Nevertheless, the latency reduction, of the order of several milliseconds, most probably results from the opening of shorter parallel reflex pathways, whose existence has been proposed by Perl (13).

Vibration frequency had significant effects on the EMG amplitudes of the early component of the finger flexor muscle. This effect is likely to result from the nature of each component. As differentiated by Hugon (14) and Willer (15), the early component is the expression of a tactile response mediated by low threshold $A_{\alpha\beta}$-fibers, while the late component is associated with a nociceptive response mediated by high threshold $A_{\delta}C$-afferents which may share some of the neural mechanisms responsible for feeling pain. Furthermore, vibration is also an extremely powerful stimulus for the cutaneous receptors (16, 17). Therefore, it may be suggested that a spatial summation occurred when the reflex response was elicited. Hence, the early component is more sensitive to the vibration frequency than the late component, which is less dependent on tactile afferents. Finally, the decrease in facilitation of the early component as vibration frequency increases principally results from the behavior of the "frequency response" of the cutaneous receptors. Although these receptors can respond in 1:1 synchrony to vibratory stimuli up to 150-200 Hz, an increasing population starts to misbehave and abruptly fails to respond as the frequency increases beyond that range (5, 17). Hence, the strength of the temporal facilitatory drive decays.

The differential modulation between the two flexor muscles could be explained by the functional differences between the muscles. Indeed, in agreement with Bernstein's hypothesis on the control of the end effectors (18), precise regulation of muscle activity, and thus influence of cutaneous feedback (19), are conceivably more critical for the fingers than intermediate links, such as the wrist. In addition, because of the posture and task required in the experiment, the level of activity was higher for the finger flexor muscle than for the wrist flexor, which influenced motoneuron accessibility, as indicated below.

The facilitation of the withdrawal reflex increased with initial voluntary muscle contractions of moderate level. This effect may result from the combination of several factors.

First, moderate level of voluntary muscle contraction influenced the depolarization and accessibility of the motoneurons (20). This mechanism allowed a stronger facilitation of the cutaneous reflex at 10% MVC. Second, muscle contraction increases vibration transmissibility (21), thus vibration is likely to activate more proprioceptive and exteroceptive mechanoreceptors. Third, habituation of the reflex responses, which is a prominent feature of the reflexes, is likely to be reduced by a steady voluntary contraction of the muscles (22), also contributing to the facilitation of the reflex responses at 10% MVC.

Perception

The overall statistical conclusion that there was no effect of vibration on perception is, at first glance, not compatible with the recent data showing that pain is relieved by vibration and that pain threshold is increased by vibration (23, 24, 25). However, detailed analysis of data for each muscle contraction level leads to a different view of the results.

When the muscles were initially at rest, analysis of individual data revealed that the subjects could be classified into two groups according to their responses to vibration: seven of the ten subjects showed a significantly decreased perception of stimulus intensity during vibration; and the remaining three subjects showed an increase of the perception. The gate control theory proposed by Melzac and Wall (26) suggests that the balance of activity of large-fibers (A_{ab}) and small-fibers (A_{d}) is a key to cutaneous and pain perception. Vibration-induced activity of large-diameter cutaneous afferents (16, 17) is likely to induce an imbalance leading to a greater spinal inhibition of the small-fiber activity, resulting in alleviation of the uncomfortable sensation mediated by this fibers. This theory fits with the general trend of the effects; however, it accounts neither for the increase in discomfort described by three subjects, nor for the discrepancy between perception and motor responses. In this resting condition, a significant influence of the efferent control (corollary barrage) of the afferent information produced by the central command is not expected since the motor command issued to hold the fingers is rather negligible. Such mechanisms would also not account for the facilitation indicated above.

When the subject was exerting a moderate level of voluntary muscle contraction, there was no clear pattern of changes of perception by the application of the vibratory stimuli. Two subjects reported a decrease, four subjects claimed an increase and the remaining four showed mixed responses. Although in the absence of vibration the subjects did not compare directly the sensation at rest and at 10% MVC, this latter condition produced a lower average of the perceived intensity (@ rest PI= 9.3 ± 2.9, @ 10% MVC PI= 7.89 ± 3). The decrease in PI is in agreement with a pain threshold elevation resulting from isometric contraction (27, 28). Gating of sensory responses by the efferent copy of the central command and/or afferent inhibitory mechanisms have been proposed to explain the attenuation of cutaneous sensitivity. In addition, it has been shown that pain sensation can be attenuated by a mental task (29), which was required in the present experiment by asking the subject to maintain a constant grip force. As an increase in PI was reported by four subjects, and four did not clearly distinguished the sensations with and without vibration, it seems that any gating mechanism, taking place at spinal (26) or supraspinal (15, 25, 27, 28, 30) levels is most likely overwhelmed by the afferent outflow generated by the vibratory stimulus. Furthermore, the increase in PI during vibration indicates that small-fibers mediating pain are either less affected by the interactions or that a facilitation can take place. This later phenomenon has also been observed by cooling of the extremities (25).

In the present conditions we suggest that the main interaction is taking place at the central level. A "masking" effect produced by the vibration-induced sensory noise and/or a divergence of attention produced by that noise may blur the sensation evoked by the electrical stimulus and make its interpretation difficult.

Studies have described parallels between the withdrawal reflex responses and nociception in humans. Such studies suggest that sensory and segmental reflex functions of the spinal cord may share overlapping (perhaps common) integrative neural substrates. Willer (29, 31) has reported that the threshold of a painful sensation and that of a nociceptive reflex elicited by electrical stimulation of the ipsilateral sural nerve were both correlated with the intensity of the stimulus. In the present and an earlier (32) study, however, a dissociation between the neurological responses and perception was observed when vibration was applied. This dissociation was obvious even when a background voluntary muscle contraction was exerted, which confirms an interaction of supraspinal origin. In addition, the threshold at which nociceptors begin to fire does not usually coincide with the threshold of pain perception (33), resulting in different modulations of the reflex responses and perception. Furthermore, vibration and muscle contraction are probably contributing to the divergence between the reflex responses and perception, as discussed above.

To conclude, the results indicate that a reflex protective mechanism of the hand is facilitated during hand-arm vibration exposure. Therefore, exposure to vibration may contribute to the exaggeration of the behavioral response while simultaneously decreasing sensorimotor control performance. It is suggested that low level of grip exertion and high vibration frequency could minimize the vibration-induced alteration of the cutaneous reflex. This is in agreement with the results of a previous study concerning vibration-induced motor effects (34). In addition, a poor correlation was found between the motor responses and perception during vibration exposure. This dissociation suggests that subjective evaluation of critical external stimulation may not always be appropriate. As already suggested (32, 35), psychophysical scaling of vibration-induced discomfort or risk should be carefully scrutinized.

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TONIC VIBRATION REFLEX

Aims

The aim of the present study was to determine changes in motor unit synchronization in the finger flexor and wrist flexor muscles according to the following hypothesis:

1) Motor unit synchronization is strongly dependent on vibration frequency and vibration amplitude
2) The tonic vibration reflex can contribute to muscle fatigue

Analysis of the tonic vibration reflex: Influence of vibration variables on motor unit synchronization and fatigue

Abstract

The influence of vibration frequency (40, 80, 100, 120, 150, or 200 Hz) at selected displacement amplitudes (0.2, 0.3 mm) on the tonic vibration reflex (TVR) characteristics was investigated. The degree of synchronization of motor unit activity with vibratory stimuli were determined in humans using the electromyographic (EMG) activity of the finger and wrist flexor muscles when vibration was applied to the distal tendons of the hand flexor muscles. The spectral analysis indicates that harmonic and subharmonic motor unit synchronization mechanisms contribute to modulate the amplitude of the TVR as the vibration frequency increases. Harmonic synchronization decreases while subharmonic synchronization increases as vibration frequency increases. It is suggested that the synchronization process influences muscle fatigue, since it impels motor unit activity and thus contributes to an increase in metabolism. High frequency vibration (>150 Hz) tends to induce less motor unit synchronization in a frequency range beyond known mechanical resonances of biological tissues. These results find application in the design of hand-held vibrating tools.

Background

It is well known that mechanical vibration applied to the muscle belly or tendons can elicit a reflex muscle contraction (13). This response, named the Tonic Vibration Reflex (TVR), results mainly from the vibration-induced activity of the muscle spindle Ia fibers (5, 9, 27), and is mediated by monosynaptic and polysynaptic pathways (10, 21, 29).

The relative roles of the two pathways are of concern in the study of motor control and the relationship between the TVR and muscle fatigue and stress. The TVR may contribute to muscle fatigue and/or increase the risk of cumulative trauma disorders observed after repetitive hand vibration exposure (22). In this type of vibration exposure, the TVR superimposed on ongoing voluntary muscle activity should be minimized or eliminated. Several studies have indicated that the TVR is composed of motor unit activity synchronized and unsynchronized with the vibration cycle (15, 16, 18, 29). Further description of the TVR, and the behavior of motor unit activity as a function of the vibratory stimulus variables, should lead to a better understanding of the reflex responses of proprioceptive origin and the mechanisms of the risks associated with vibration exposure. Risk factors include vibration variables and force exertion, which influence vibration transmissibility to the human body (24, 25, Martin, unpublished results).

In the present study, changes in the TVR and motor unit synchronization in the finger flexor and wrist flexor muscles were analyzed as a function of the frequency and two displacement amplitudes of vibration applied to their distal tendons, and as a function of the initial level of voluntary muscle contraction.

Material and Methods

Subjects

Ten healthy subjects participated in the experiment as paid volunteers and gave informed consent. Their average age was 22.6 years. All of the subjects were free from any known neurological or musculoskeletal disorders.

Mechanical stimulation

The right hand, in slight extension, gripped a vertical handle fixed to a padded arm-rest. An adjustable support helped to maintain the wrist in this position thus imposing an isometric condition. The handle was equipped with a strain gage dynamometer. The height of the arm-rest and the horizontal position of the handle were adjusted to obtain approximately a 120° 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, 203) equipped with a specially designed probe. An accelerometer placed inside the vibrating probe provided feedback to a vibration compressor (Trig-tek 801B) driven by a sinewave generator. The compressor coupled to a vibration monitor (Trig-tek 610B), which computed the 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. Hence, this system allowed the maintenance of a constant displacement amplitude of the probe throughout the vibration period whatever the tendon tension in the range of tested voluntary contractions. The vibrating probe was pressed on the tendons to obtain a 1 mm backward displacement of the probe, which produced an initial force of about 4 N (stiffness of the vibrator suspension guidance: 4N/mm). Vibration variables and initial deformation of the tendon were carefully controlled as mechanical characteristics of the stimulus influence the response of muscle stretch receptors (Matthews, 1963, 1966; Cordo et al. 1993).

Electromyographic recording sites

The electrical activity (EMG) of a finger flexor muscle (flexor digitorum profundus: FDP) and a wrist flexor muscle (flexor carpi radialis : FCR) was recorded by pairs of small cupular surface electrodes embedded in preamplifier devices to minimize noise and wire artifacts. A ground electrode was attached on the radial styloid of the wrist and provided an electrical reference. After localization of the muscles by palpation and resistive maneuvers, best electrode placements were obtained by successive trial and error (with the forearm held in the position of the experimental situation) in order to minimize cross-talk. For the FCR and EDC the electrodes were placed on the bellies of the respective muscles. For the FDP, the electrodes were placed at a location about 1/3 the distance between the olecranon and the ulnar styloid, and 1 cm ulnarly to the ulna shaft; at this location, this muscle lies just below the thin aponeurosis of the flexor carpi ulnaris. The EDC activity was recorded to observe the reciprocal inhibition and ascertain that the TVR did not switched to an "antagonist vibration response" (26) during the experiment, and more specifically in the resting condition. The respective signals were amplified, rectified and integrated to obtain rms values.

Procedure

The level of maximal voluntary contraction (MVC) of the grip was determined before each experiment. The subjects were then trained to maintain a grip force of 10% and 20% of their MVC for 1-min periods, using only the proprioceptive feedback. At first, 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 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 correspond 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 %MVC level was stabilized and the subject felt ready for the trial to begin. Force stabilization was reached within 5 to 10 seconds. No external feedback was provided during the trial.

Data was 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 0.2 and 0.3 mm.

For each subject, the experiment was carried out in two days to reduce any possible effect of boredom and fatigue. Data was collected for a total of 36 trials for each subject (3 levels of contraction x 6 frequencies x 2 displacement amplitudes). Each subject served as its own control. Due to the practical limitations imposed by the setting of the vibration displacement amplitude, trials were randomized only across the frequencies and contraction levels. A two minute rest period separated each consecutive trial. The muscle contraction levels were selected to represent grip exertions during small power hand-tool operation (28).

In a complementary experiment performed by 5 subjects an isometric grip exertion (20% MVC) was maintained for 8 min. with or without tendon vibration (100 Hz, 0.3 mm) in the situation described above.

Data recording and processing

The EMGs of the ECR, FDP and the FCR muscles were recorded simultaneously. The built-in preamplifier minimized noise and artifacts of electrical and mechanical origins. The respective signals were then amplified, rectified and integrated to obtain the rms values. For the raw EMG the signals were low-pass filtered at 300 Hz for anti-aliasing purposes. Raw EMGs, rms EMGs and grip force signals were sampled at 1 KHz for 60-s, as indicated above. The vibration-induced increase in rms EMGs ($\Delta EMG = rms\ EMG_{vib} - rms\ EMG_{ref}$), and the power spectral density (PSD) of the EMG signals computed for the last 15 s of the vibration period were analyzed as a function of initial contraction levels and vibration frequencies for both displacement amplitudes. Fifteen periodograms of 1024 ms covering the 0-256 Hz frequency band with a 1 Hz resolution were averaged; a Hanning window was used. To quantify motor unit synchronization, the area of spectral peaks at the vibration frequency and at the 1st subharmonic frequency were expressed as percentages of the total power of the PSD. The normalized synchronization index (SYNC) at the vibration frequency (VF) or subharmonic frequency (SF) was defined as:

$$\mathrm{SYNC}_{VF} = \frac{\int_{VF-5}^{VF+5} \mathrm{PSD(f)\,df}}{\int_{0}^{256} \mathrm{PSD(f)\,df}} \qquad \mathrm{SYNC}_{SF} = \frac{\int_{SF-5}^{SF+5} \mathrm{PSD(f)\,df}}{\int_{0}^{256} \mathrm{PSD(f)\,df}}$$

The absence of artifacts was systematically verified before each experiment. A spectral analysis of all EMG signals was performed in passive (resting) and active (voluntary contraction) conditions while vibration was turned on. For each condition, the probe was placed close to but not in contact with the muscle tendons, or was applied to several areas away from the tendons. The PSDs were "flat" while resting and did not exhibit "prominent peaks" correlated with the vibratory stimulus during voluntary contraction.

Data analysis

Repeated measures analysis of variance (ANOVA) treating the subject as a random blocking factor was performed on the average ΔEMG, SYNC_{VF}, and SYNC_{SF} to determine the effects of the vibration variables and initial muscle contraction on the TVR and motor unit synchronization.

Results

The strength of the TVR as measured by the ΔEMG averaged over all subjects increased with initial contraction up to 10% MVC for the FDP and FCR, while an increase with vibration amplitude was observed only for the FCR. In addition, the strength of the TVR varied with vibration frequency for both muscles, but in a slightly different way. For the FDP, the TVR increased with vibration frequency up to 100 Hz, increased at a slower rate up to 150 Hz and then decreased beyond with the exception of 20% MVC. For the FCR, the TVR increased with frequency up to 100 Hz, then decreased beyond (Fig. 1). Hence, magnitude changes of the TVR as a function of vibration frequency were dependent on initial contraction and the muscle considered. The grip force did not varied significantly during vibration. These results, presented in a previous publication (22), were mentioned here to help interpret the results that follow.

Furthermore, during vibration the EMG recorded from the EDC decreased with each increment of initial level of flexor contraction; however, vibration frequency did not produce a significant influence.

Spectral analysis

The spectral analysis showed a correlation between the vibratory stimulus and motor unit activity. It should be stressed that spectral peaks correlated with vibration result from the phase shift of a number of synchronized motor units distributed along the vibration cycle. Narrow peaks at the vibration frequency and/or subharmonic frequency were present in the PSD of the respective EMG signals. Examples of typical PSDs of the FCR EMG, obtained from one subject in two conditions, are shown in Fig. 2. For a 100 Hz vibration (Fig. 2, upper panel), a high peak was observed at 100 Hz, indicating a strong synchronization of motor unit activity with the vibration frequency. For a 200 Hz vibration (Fig. 2, lower panel), the main peak was observed at the subharmonic frequency (100 Hz) while a smaller peak was observed at the vibration frequency (200 Hz). This inversion of the relative amplitude of the respective peaks indicates that subharmonic synchronization is predominant for vibration in the high frequency range, which is quantified by averaged data presented below.

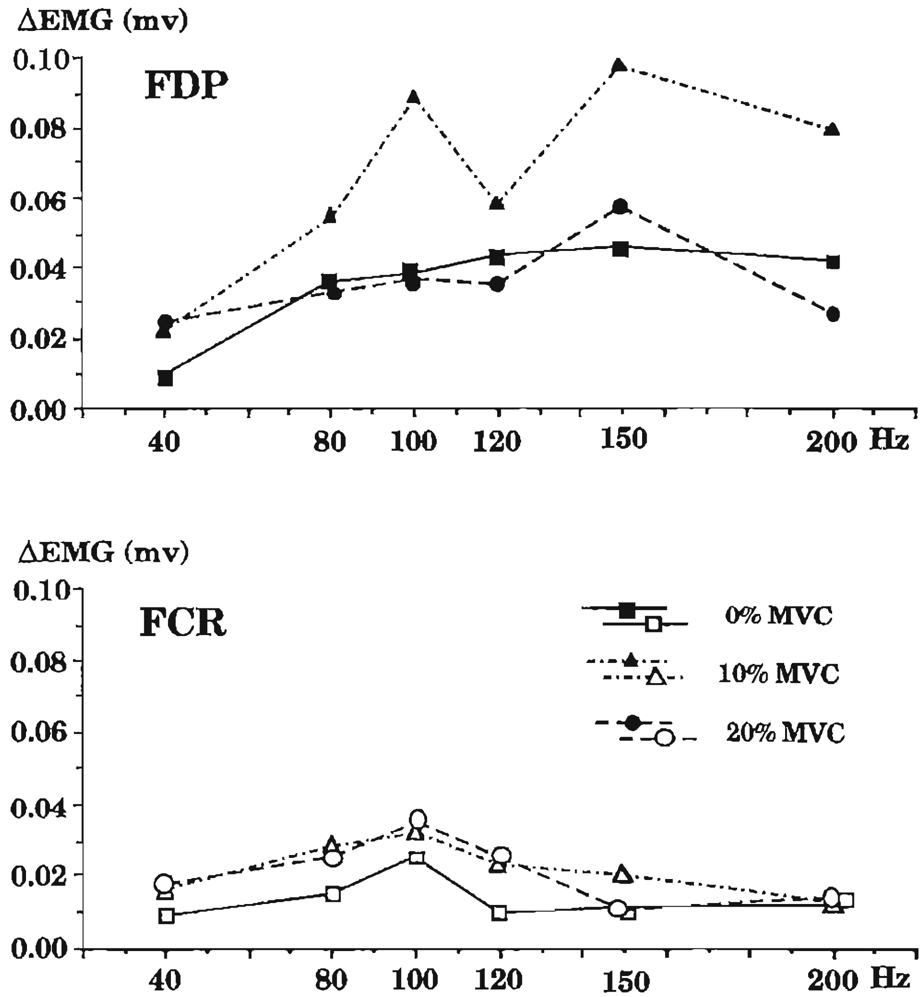

Figure. 1. Effect of vibration frequency on average (10 subjects) TVR magnitude (ΔEMG) of the FDP (upper panel) and FCR (lower panel) for increasing initial muscle contractions (resting, 10% and 20% MVC).

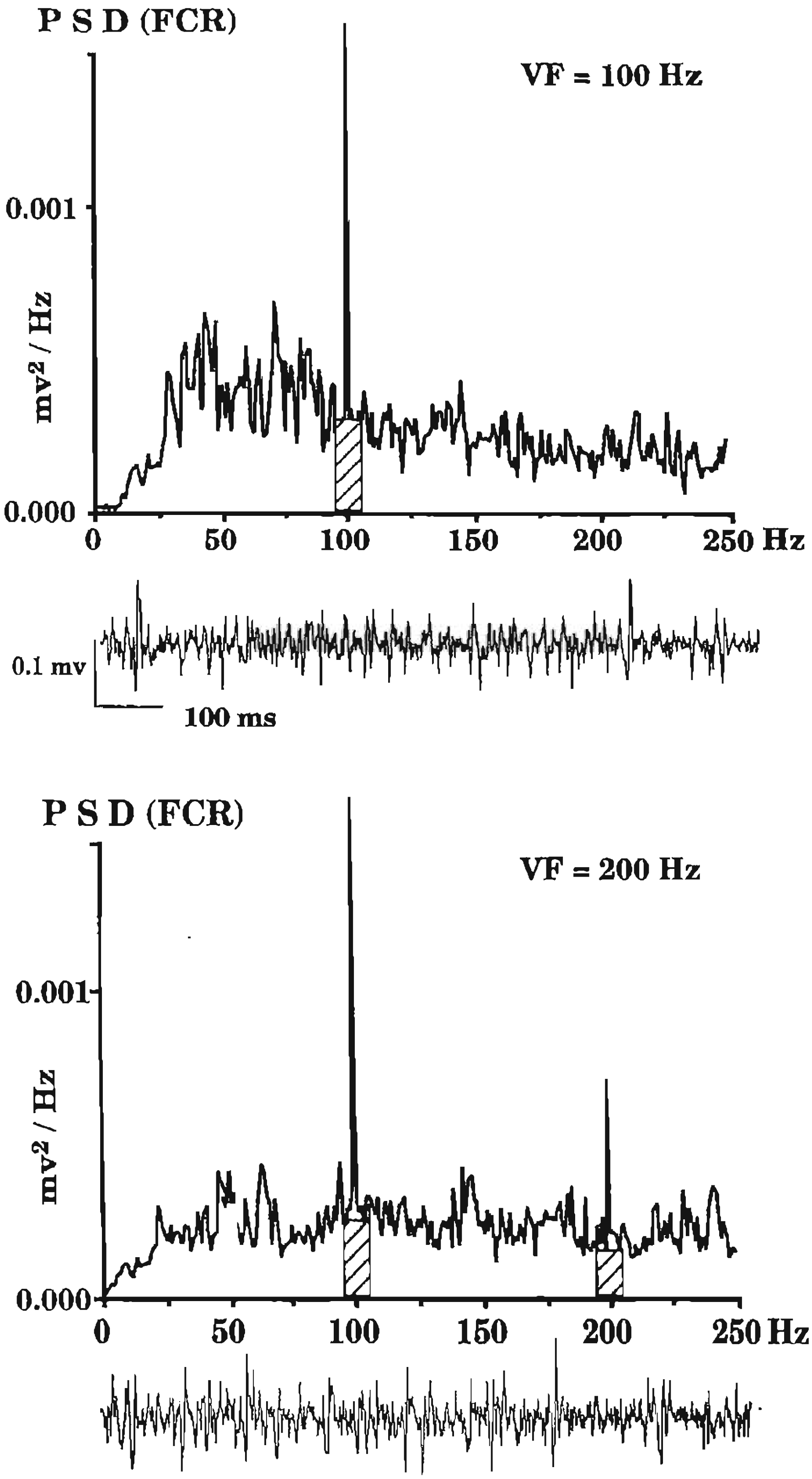

Figure 2. Representative examples of FCR power spectra showing the influence of vibration frequency on the synchronization process (100 Hz, upper panel: 200 Hz, lower panel). A fragment of the corresponding EMG is presented below each spectrum. Each spectrum corresponds to the averaging of 15 periodograms of 1024 ms, obtained for one subject. The hatched areas represent the 10 Hz bandwidths use to compute synchronization indices. The spectral peak of the harmonic component is predominant for the 100 Hz vibration while the subharmonic peak is predominant for the 200 Hz vibration. VF = vibration frequency.

The results of the ANOVA performed on the average indices (Table I) indicate that the tested vibration amplitudes had no effects on any of the indices, while vibration frequency was significant in all cases, and initial muscle contraction was significant in all cases except for the synchronization at the vibration frequency ($SYNC_{VF}$) for the FDP.

Table I. ANOVA results for the motor unit synchronization.

Effect	d.f	P- values			
		Finger flexor		Wrist flexor	
		NSI_{VF}	NSI_{SF}	NSI_{VF}	NSI_{SF}
Frequency (VF)	5	0+*	0+*	0+*	0+*
Displacement (D)	1	.165	.745	.210	.837
Contraction (IC)	2	.483	.002*	.012*	0+*
VF x D	5	.602	.014*	.419	.001*
VF x IC	10	0+*	.435	.011*	.003*
D x IC	2	.471	.854	.017*	.375
VF x D x IC	10	.873	.969	.353	.001*

Note: * = significant

Vibration Displacement Amplitude

It is assumed that the TVR was somewhat stabilized during the last 15 s of the vibration period and that most of the primary endings were recruited even at the lower level of vibration amplitude (Roll et al. 1989). Thus further recruitment of motor units with a small increment in vibration amplitude was limited. Since this variable was not significant (Table I), the indices were then summed across the amplitudes and the subjects, and analyzed as a function of vibration frequency for each initial contraction.

Vibration Frequency

The graphs in Fig. 3 show, for both muscles at each initial contraction, that as vibration frequency increases the normalized synchronization index $SYNC_{VF}$ decreases while the $SYNC_{SF}$ increases. Beyond 100 Hz, the $SYNC_{SF}$ becomes predominant (paired t-test, $p < 0.05$). A "cut off" frequency appears located above 100 Hz. This observation is supported by the Tukey comparisons which indicate that there is a significant difference in $SYNC_{VF}$ either between 80 Hz and 100 Hz or between 100 Hz and 120 Hz for both muscles. These results are compatible with the results on the strength of the TVR presented in Fig. 1.

Initial Muscle Contraction Level

When compared to the resting condition (0% MVC), the initial contraction of 10% MVC resulted in a significant ($p < 0.05$) increase of the $SYNC_{VF}$ for the FCR, and of the $SYNC_{SF}$ for both flexor muscles (Fig. 3-4). The increase in harmonic synchronization ($SYNC_{VF}$) is essentially observed at 40 Hz for the FDP and up to 100 Hz for the FCR, while non-significant changes occur beyond 120 Hz for both muscles. The increase in subharmonic synchronization ($SYNC_{SF}$) is marked at all frequencies but 40 Hz for both muscles. These effects are clearly seen in figure 4, where the indices of synchronization corresponding to each level of initial contraction are overlaid for each of the muscles (FPD, upper panel; FCR, lower panel). The initial contraction of 20% MVC induced similar effects; however, no significant differences in the synchronization indices were observed between 10% and 20% MVC.

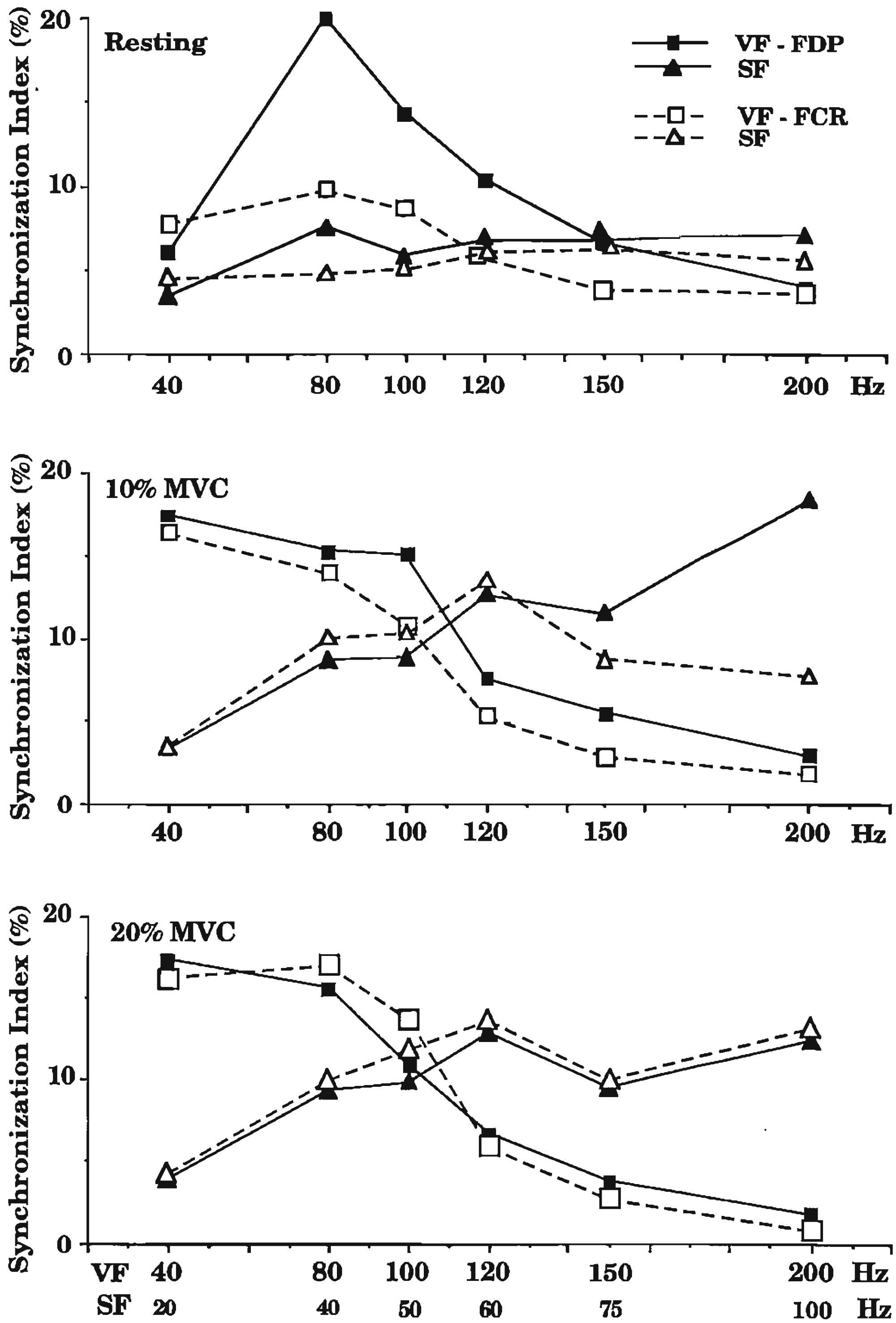

Figure. 3. Influence of vibration frequency on the normalized indices of synchronization ($SYNC_{VF}$, $SYNC_{SF}$) for the FDP (dark symbols) and the FCR (hollow symbols) for each initial muscle contraction (top to bottom). Each data point represents the average over 10 subjects. Harmonic synchronization of motor unit activity decreases while subharmonic synchronization increases as vibration frequency increases. VF= vibration frequency; SF = subharmonic of vibration frequency

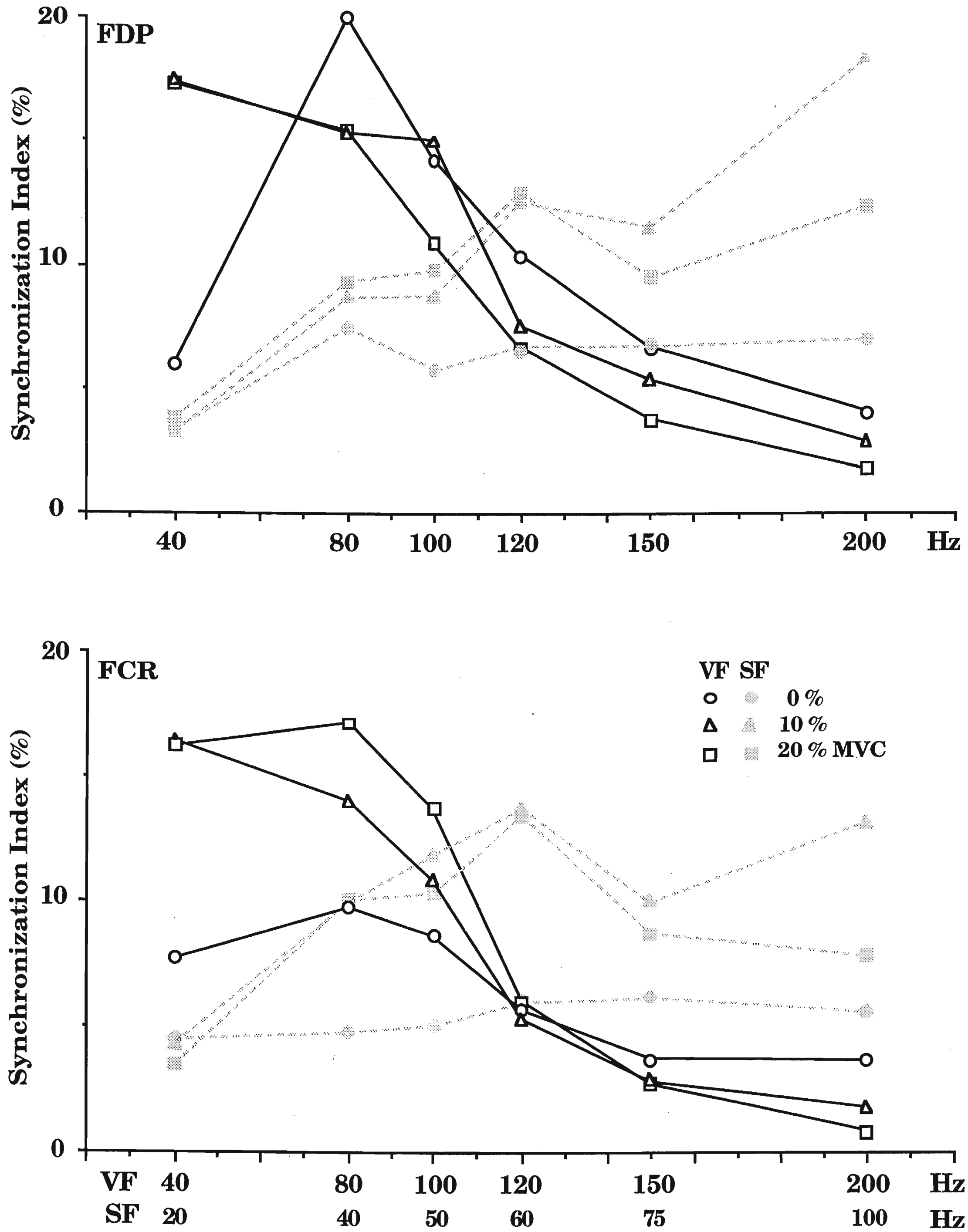

Figure. 4. Influence of vibration frequency and initial muscle contraction on the indices of synchronization ($SYNC_{VF}$, dark lines; $SYNC_{SF}$, gray lines) for the FDP (upper panel) and the FCR (lower panel). Each data point represents the average over 10 subjects (same data as in fig. 3). Synchronization of motor units is enhanced by the initial contractions (see text for detailed description). VF= vibration frequency; SF = subharmonic of vibration frequency

Muscle.

The synchronization patterns of the motor unit activity of both flexor muscles were similar. However, a paired t-test revealed that the magnitude of motor unit activity correlated with vibration frequency was higher for the FDP than for the FCR ($p=0.00$). This difference was more specifically seen at rest (Fig. 3) for 80 to 150 Hz vibration frequencies ($p < 0.05$). There was no significant difference observed at the subharmonic frequency between the two muscles ($p=0.28$). Furthermore, it can be seen on Fig. 3 that the "cut off" frequency is slightly higher for the FDP than for the FCR for initial contractions up to 10% MVC.

Moderate exertion for a Long duration

The results describing changes in grip force, rmsEMG and mean frequency of the PSD as a function of time are illustrated in Fig. 5 for the FDP muscle. Each data point corresponds to the analysis of the preceding 15 s, averaged across the subjects. Without vibration (control), a non-significant ($p= 0.22$) decay of the grip force with time was observed. When the moderate muscle contraction (20% MVC) was maintained during vibration, a significant ($p < 0.01$) progressive decrease in grip force occurred. An abrupt decay of the grip (first half minute) was followed by a decay at a rate higher than the control situation. In both cases the respective rms EMGs and mean frequency of the FDP did not vary significantly over time ($p > 0.1$); however, after 5 min. the EMGs tended to increase (not statistically significant) while the grip forces remained constant. Peaks correlated with the vibration frequency were still present at the end of the vibration period.

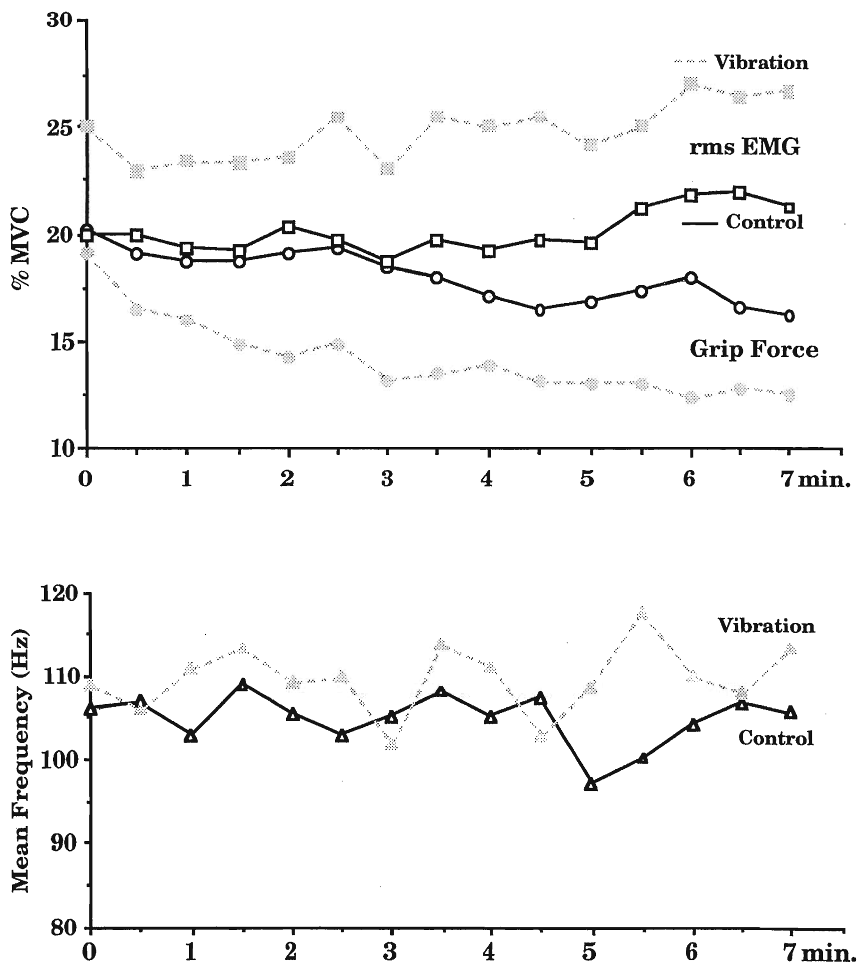

FIG. 5. Effects of vibration on moderate grip exertion of long duration. Grip force (upper panel) decays rapidly during vibration while the rms EMG and mean frequency of the EMG power spectra (lower panel) do not vary significantly as a function of time. Data averaged over 5 subjects.

DISCUSSION

The main results showed that vibration-induced increases in EMG activity and the degree of motor unit synchronization were dependent on the vibration frequency and the initial contraction. Recall that these results correspond to the "steady state" phase of the TVR analyzed during the last 15 s of the vibration period.

Synchronization.

The "frequency response" of the TVR seems highly correlated with a motoneuron recruitment/derecruitment process resulting from the "frequency response" of the primary spindle endings. Indeed, these receptors can respond in 1:1 synchrony up to about 100-150 Hz (5, 27); beyond this "cut-off" frequency most receptors start to respond at subharmonic frequencies and then at random (27). At low vibration frequencies (≤100 Hz), first harmonic synchronization was predominant and the magnitude of the TVR increased with vibration frequency. First, we may assume that almost all Ia afferents were recruited by the vibratory stimulus (27) and that the recruitment did not vary significantly with frequency since the displacement amplitude was the same at all frequencies (19). Second, we demonstrated earlier for the soleus muscle that below 100 Hz the inhibition of the monosynaptic pathway does not vary with vibration frequency at constant displacement amplitude (19). Hence, an increase in the TVR in this frequency range results principally from an increase in motoneuron depolarization with the firing frequency of Ia afferents, which leads to a recruitment of motor units of increasing threshold.

At high vibration frequencies (≥100-150 Hz) most Ia afferents start to "misbehave" (8, 27) and subharmonic synchronization is predominant (Fig. 3). Thus, a derecruitment process affecting the motoneurons in a reverse order is likely to occur, following Henneman's principle (14). The declining excitatory drive of the harmonic response of Ia-fibers is likely to be balanced by the increase in both the subharmonic response (Fig. 2&3) and the asynchronous activity until these components loose their own influences as the frequency increases beyond 200 Hz. This latter effect, due to the decay in firing frequency and in the number of responsive fibers (27) is illustrated in part by a stabilization or a decline in the subharmonic component beyond 120 Hz (Fig. 3).

Aside from the intrinsic bandwidth properties of the primary endings, the weakening of Ia response with the increase of vibration frequency may also have mechanical and reflex origins. First, the visco-elastic muscle-tendon system is likely to behave like a low pass filter in the high frequency range and attenuate vibration transmissibility to the spindles. This filtering results in a decrease in Ia-afferents driving. Second, the strength of facilitatory inputs to the γ-system from several afferents (1, 17, 30) mediating respectively the vibration-induced activity of skin, joint and secondary endings also fades away as vibration frequency increases, due to the low "cut off" frequency of the aforementioned mechanoreceptors (5, 27). Hence, the decrease of the gain of the nested positive reflex loop (group II, joint and skin afferents $\rightarrow$ γ-motoneurons $\rightarrow$ Ia-afferents), affects the sensitivity of primary endings and contributes to the decay of vibration-induced synchronization of α-motoneurones and to their derecruitment.

An alternate explanation can be proposed. The roughly "inverted U" shape of the TVR as a function of vibration frequency may suggest a resonance of the musculo-tendinous system, which would enhance the stretch response of the spindle endings. Hence, under the assumption of a near maximal driving of Ia-afferents indicated above, potentiation of the TVR would essentially result from an activation of the less sensitive secondary endings (8, 27). In such a case or even if more Ia fibers could respond, we should not observe a decrease in $SYNC_{vf}$ for frequencies below the presumed resonance. Although a mechanical resonance cannot be ruled out, it probably does not play a significant role in the present context.

Finally, a greater sensitivity of the Ia-afferent loops (of central and/or peripheral origin) of the FDP than the FCR is suggested by 1) a slightly higher "cut off frequency" of the TVR (22), 2) a greater value of the index of harmonic synchronization up to 10% MVC of initial muscle contraction, and 3) the slightly higher "cut off frequency" (intersection of the harmonic and subharmonic responses) for the FDP than the FCR. The agreement of these data support the hypothesis that the sensitivity of the proprioceptive feedback is more critical for the end effector - the fingers. Furthermore, given the anatomical position of the tendons, the mechanical stimulation was probably slightly less efficient on the FDP than the FCR tendons. Thus, higher sensitivities of FDP spindles to stretch can be suggested.

Localized muscular fatigue

During the whole vibration period, the EMG activity remains 25% higher than the control value. The initial change in force exertion, paralleled by a decrease in EMG (fig. 5; at t= 0.5 min.), is most probably due to the alteration of force perception induced by localized tendon vibration (7). Nevertheless, the continuous decrease in force that follows, not paralleled by a decrease in EMG, but rather concurrent with a constant EMG level exhibiting no change in the mean frequency of the power spectra, suggests a vibration-forced driving of the motor units leading to a decrease in muscle fiber efficiency with a metabolic origin. This hypothesis stems from the organization of motor unit reflex patterns and possible fatigue mechanisms.

First, in the context of an initial contraction (20% MVC), a high vibration frequency (100 Hz), and a steady state of the TVR, this latter is certainly powered by a large proportion of high-threshold motor unit activated predominantly by polysynaptic pathways (6, 18, 29), with a lesser proportion of slow, low threshold motor units activated monosynaptically (29). Also Romaiguère et. al (29) have shown that the polysynaptic components can be phase-locked to the vibration cycle. As motor unit fatigue resistance decreases inversely with the recruitment threshold (31), it seems reasonable to expect that muscle fatigue develops at a higher rate under vibration.

Second, the present results suggest that fatigue compensatory mechanisms of neurological origin, e.g., increase in the discharge rate and recruitment of additional motor units (2, 20), are hindered. On the one hand, the driving process induced by vibration forces the recruited motor unit to discharge at a relatively high rate, above 16 Hz for a 100 Hz vibration inducing a 10% MVC contraction (29), which contributes to precipitate fatigue. On the other hand, most of the pool of motor units that would have been activated by the adjustment of the motor command for the assumed level of effort are already driven by the vibration-triggered mechanisms. Recent studies (3, 4) demonstrate that vibration is indeed able to re-recruit and temporarily increase the firing rate of motor units fatigued by a maximal effort, with a more pronounced facilitatory effects on high- than low-threshold units. Such results suggest that vibration has a greater driving power than fatigue compensatory mechanisms. This power is certainly enhanced by the fusimotor-driven feedback (see nested positive feedback above), which contributes to maintain a high motoneuron discharge rate. In the absence of vibration, a decrease in the gain of this feedback is supposed to contribute to a decrease of the motor output (for review of the "sensory feedback hypothesis" and fatigue see 12). Also, as vibration forces the driving of motor units it would preclude an eventual rotation of motor unit activation, a mechanism suggested to minimize fatigue development by alternation of activity and inactivity periods (11, 23). Finally, the forced driving of motor units is supported by the fact that synchronization observed from individual recordings did not deteriorate significantly over the time period considered here. This latter effect was also observed in a previous study (18).

To conclude, this study indicates first, that the index of synchronization could be used to determine the relative sensitivity of the Ia-afferent feedback. Second, high frequency vibration (>150 Hz) tends to induce less muscle/tendon stress and motor unit synchronization. Third, the vibration-induced stress reaches its maximum at a moderate level of force exertion. These results find application in power hand tool design. As transmissibility of vibration to the forearm system is limited beyond 100 Hz, tools generating low intensity high frequency vibration (>150 Hz) should be preferred, provided mechanical resonances do not occur.

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MANUAL DEXTERITY

The aims of this study were to evaluate the alterations of visuo-manual control resulting from vibration exposure and determine their variation after long term exposure. The following hypotheses were tested :

1) manual dexterity is impaired by high frequency hand vibration
2) the alterations are proportional to the displacement amplitude of the vibration up to 150 Hz, beyond that frequency less significant effects are expected.
3) post-vibration effects vary with the vibration level

Post-effects of long term hand vibration on visuo-manual performance in a tracking task

Abstract

Impaired performance of visually guided motor activities may be an important factor in accidents involving falls, dropping objects and improper use of controls. Although one cannot blame vibration as a common denominator in injuries incurred by workers using hand tools intensively, a significant number are likely to be related to manual control impairment resulting from vibration exposure. The aims of this study were first to determine the influence of vibration parameters on the alteration of manual tasks and second, to emphasize the often ignored or neglected role of movement errors in accidents occurring in vibratory environments.

Movement precision and performance time were evaluated through a visuo-manual tracking task performed before and after long term hand vibration exposure. Constant displacement amplitude vibration of 0.2 mm and 0.3 mm peak-to peak at frequencies of 90, 150, 300 Hz were applied for 10 minutes to the hand along the z axis by a vertical handle. During exposure the subject exerted a grip force of 5% MVC for 5 s and then relaxed for 25 s while maintaining the fingers in contact with the handle. The tracking task consisted in moving a ring (Ø = 9 mm) attached to a thin rod held between the index and thumb finger along a zig-zagged wire (Ø = 3.7 mm) . Alterations of tracking errors (ring-wire contact) and tracking time were analyzed as a function of the vibration parameters. Ten healthy subjects participated in the experiment.

Vibration induced a significant increase in errors and a significant decrease in tracking time. These impairments decayed with time after vibration exposure. The recovery period was greater than 5 min. but less than 10 min. with the exception of 90 Hz vibration, for which recovery could be longer than 10 min. The number of tracking errors was neither influenced by vibration frequency nor by amplitude. The tracking time decreased as frequency increased and recovery was related to the displacement amplitude. The subjective rating of the performance on a visual analog scale indicated that the subjects tended to perceive the task as being easier after vibration exposure. Vibration applied to the non-dominant hand while the subject performed the tracking task had no effect.

These results show that vibration similar to hand-tool vibration affects precision and velocity control of visually guided hand movements. Furthermore, these performance decrements were not consciously perceived.

Background

Manipulating objects or controls under visual control of the hand are familiar and simple behavioral actions of everyday life. These activities require the coordination of complex sensory and motor processes involved in the control of the eye, the head and the hand. Visual and non-visual cues such as proprioceptive (Gauthier and Hofferer, 1976; Gauthier et al. 1988, Vercher and Gauthier, 1992) and exteroceptive (Akamatsu, 1992) information do contribute to the coordinated control of eye and hand movements when they are simultaneously involved in a motor task (Gauthier et al. 1988). Furthermore, the combination of sensory information (auditory, visual, proprioceptive and tactile) about the arm position enhances hand tracking performances (Mather and Lackner, 1980).

Accuracy of limb movement is affected by hand and whole-body vibration (Lewis and Griffin, 1976, 1979; Gauthier et al. 1981, Ribot et al. 1988, Martin et al. 1991). Furthermore, oculomanual coordination can also be affected by hand vibration (Martin et al. 1991). In the high frequency range ($F > 20$ Hz), the source of alteration was suggested to lie principally in the vibration-induced response of somesthetic receptors (Gauthier et al. 1981; Martin et al. 1980, Martin et al. 1991). Although visual cues may compensate to some extent for the vibration-induced alteration of sensory information, they may not be sufficient to fully counteract the deficit incurred by other sensory modalities (Martin et al. 1991). In addition, impairment of sensorimotor activities observed during vibration exposure frequently persist several minutes after cessation of the stimulus (Martin et al. 1980, Roll et al. 1980; Gauthier et al. 1981). Hence, motor control and more specifically visually guided activities, can be significantly impaired during and immediately after vibration exposure and contribute to accidents involving falls, dropping objects and improper use of controls or tools. Finally, vibration-induced changes in the behavior of sensorimotor systems such as spinal proprioceptive reflexes and cutaneous reflexes are frequency dependent (Martin et al. 1984; Park and Martin, 1993;. Martin and Park, 1995). The "frequency response" of the sensory receptors involved in these feedback systems has been suggested to shape the relationship between the motor responses and vibration frequency.

In an attempt to determine first the influence of vibration parameters, such as frequency and displacement amplitude in the impairment of visually guided tasks, second, to determine the duration of eventual post-effects and, third, to emphasize the often ignored role of movement errors in accidents occurring in vibratory environment, continuous manual control was analyzed through the response of the visuo-manual system when the eye and the hand act together in a simple tracking task.

The present study describes changes in tracking error and tracking time after hand vibration exposure as a function of vibration frequency and displacement amplitude. The results point out the role of proprioceptive and exteroceptive inputs in visuo-manual control. They also indicate a divergence between precision and velocity control which could lead to improper control of tools or controls in vibratory environments.

Material and Methods

Subjects

Ten healthy subjects participated in the experiment as paid volunteers and gave informed consent. All subjects were university students. Their age ranged from 20 to 32 years. All of the subjects were free from any known neurological or musculoskeletal disorders. Prior the experiment the subject read and signed an informed consent form.

Experimental situation

The subject was seated on an adjustable chair in front of a table with the arms unsupported. A metallic zig-zagged wire (L = mm, Ø = 3.7 mm) fixed to an adjustable support was placed before the subject in a frontal plane (Figure 1). A ring (Ø = 9 mm) placed around the wire was attached to a thin rod (Ø = 4.7 mm) which was held between the index and thumb finger. Each end of the wire was equipped with a metallic contact insulated from the wire. These contacts areas were connected to the printer port of a computer via a debouncing circuit, and were used to start and stop a timer. The wire was also connected to a printer port input. The ring was connected to a 4.5 v battery. Software was developed to count the number of ring-wire contacts and compute the duration of the tracking task. The chair and device heights were adjusted to match each subject's anthropometry and height level preferences. The tracking task consisted of moving the ring along the wire while avoiding contact. The subject was instructed to perform the task as fast as possible with an emphasis on precision.

Vibration

Vibration was applied to the dominant hand along the longitudinal axis of the forearm (z axis) by a vertical handle adapted on an electromagnetic vibrator placed on the table next to the tracking device. A padded arm rest fixed to the chair was adjusted to support the forearm horizontally, and aligned with the vibrator axis. The handle was equipped with a strain gage dynamometer to measure the grip force. The dynamometer was connected to a digital voltmeter to provide feedback. Three sinusoidal vibrations of 90, 150, 300 Hz and two constant displacement amplitudes of 0.2 mm and 0.3 mm were used, respectively. The exposure duration was 10 min. in each case.

Procedure

To avoid any learning effect during the experiment the subjects were trained to perform the tracking task until their performance plateaued. Training ended when the subject achieved a similar performance for three consecutive trials (less than 15 errors, with a tracking time less than 35 s and, variations limited to $\pm$ 2 errors and $\pm$ 2 s). This level of performance was reached within 20 to 40 min. The average performance over the last three trials was used as the baseline. Then, the tracking task was performed before, immediately after (t_0), and 5 (t_5) and 10 min (t_{10}) after vibration exposure; hence performance was tested in four conditions. The level of maximal voluntary contraction (MVC) of the grip was determined before the test session. During the vibration period the subject grasped the handle and exerted a grip force of 5% MVC during 5 sec and relaxed for 25 sec. This task, which simulated tool grasping, was paced by a brief auditory signal generated by computer. Data were collected for a total of 21 trials for each subject ([3 frequencies x 2 displacement amplitudes + 1 control] x 3 conditions). The control condition was similar to the others, except that vibration was not applied to the handle. Due to the practical limitations imposed by the setting of the vibration displacement amplitude, trials were randomized only across the frequencies. Half of the subjects started with the 0.2 mm amplitude while the other half stated with the 0.3 mm amplitude. The last test of each condition was also used as the pre-vibration test for the following condition; hence, two consecutive vibration periods were separated by a 12 min. interval.

Subjective evaluation

The subjects were asked to rate the difficulty of the task after each trial on a 10 cm visual analog scale . The scale was presented horizontally, the left and right anchor points were labeled to correspond to the least and most difficult task possible. The subjective rating was indicated by placing a vertical mark on the scale.

Data analysis

Repeated measures analysis of covariance (ANACOVA) treating the subject as a random blocking factor was performed on the tracking errors and tracking time to determine the effects of vibration on the visuo-manual task. Tracking time and tracking errors were used alternately as the added regressor. This type of analysis was also performed on the subjective rating of the task.

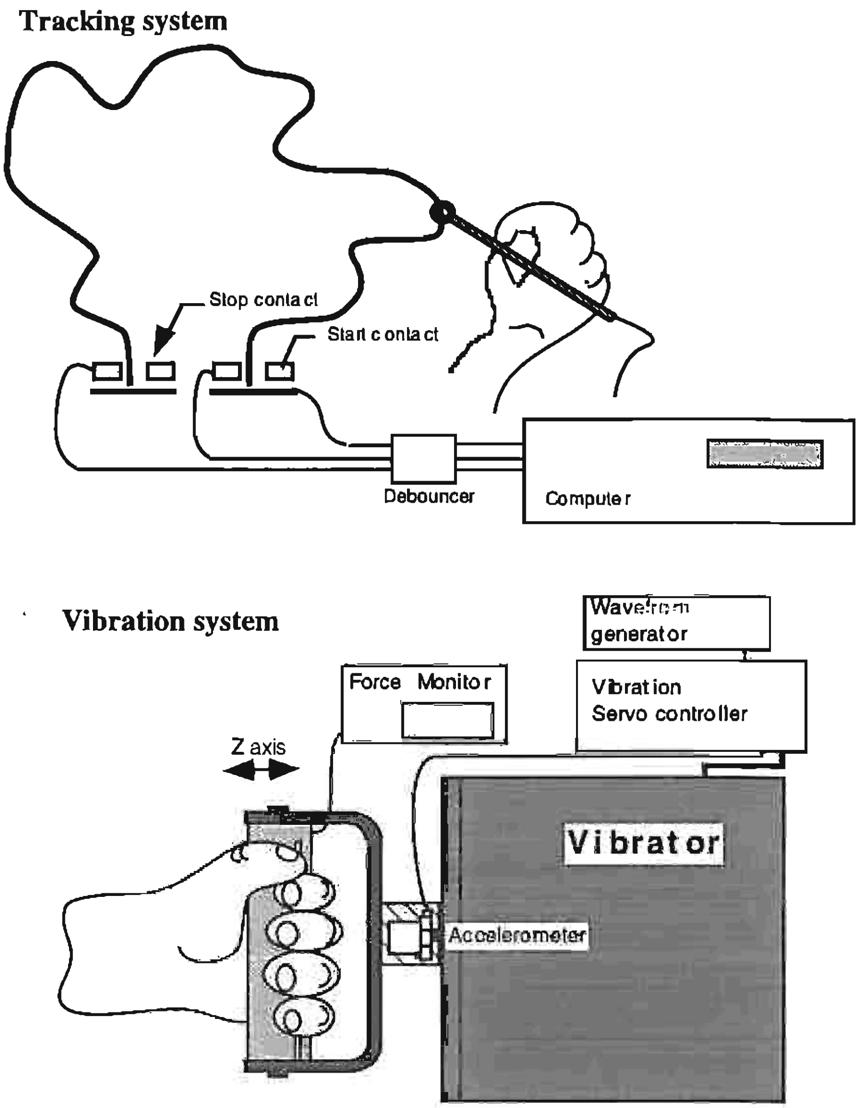

Figure 1. Tracking system (upper panel): A ring is fixed to a thin rod held between the thumb and index fingers. The ring is connected to a 4.5 v battery. Contacts between the ring, the wire and start and stop washers are recorded by a computer via a 3 channel debouncing circuit whose outputs are connected to printer port inputs . Vibration system (lower panel). The vibration level is servo controlled by using a accelerometer in the feedback loop. The force monitor provides a visual feedback of the grip force.

Results

Although a large inter-subject variability was observed, the tracking task was affected immediately after vibration exposure and the recovery time varied with vibration frequency. No changes in performance were observed in the control conditions. The results of the ANACOVA performed on the number of errors, tracking time and subjective rating are presented in Table 1. These data indicate first, that vibration had a significant influence on precision and time. Second, neither frequency nor displacement significantly affected the number of errors; however, these variables significantly influenced the time to complete the task in specific conditions as indicated by the significance of the interactions between frequency and conditions and displacement and condition. The subjective ratings appeared marginally affected by vibration exposure.

Table I. ANACOVA results for the tracking task parameters

Effect	**df**	**P- values**		
		Errors	Track. Time	Rating
Frequency (VF)	2	0.11	0.83	0.94
Displacement (D)	1	0.79	0.052	0.63
Condition (C)	2	0.006*	0.000*	0.06
VF x C	2	0.99	0.006*	0.85
D x C	2	0.94	0.040*	0.85
Track. Time	1	0.02*	•	0.000*
Errors	1	•	0.02*	0.001*
Subject	9	0.000*	0.000*	0.000*

Note: * = significant

Number of errors

Figure 2 presents the averages of the number of tracking errors as a function of vibration frequency and, time after vibration exposure. The gray dot on the left axis indicates the average baseline performance (12.4 ± 6) observed before vibration exposure. Immediately after vibration (t_0) the number of errors (averaged over amplitudes) increases with vibration frequency (15 ± 7.3 @ 90 Hz, 16.6 ± 8.2 @ 150 Hz, 17.5 ± 10.2 @ 300 Hz); however, this tendency was not significant. This change in tracking performance (4 errors) represents a 33% increase.

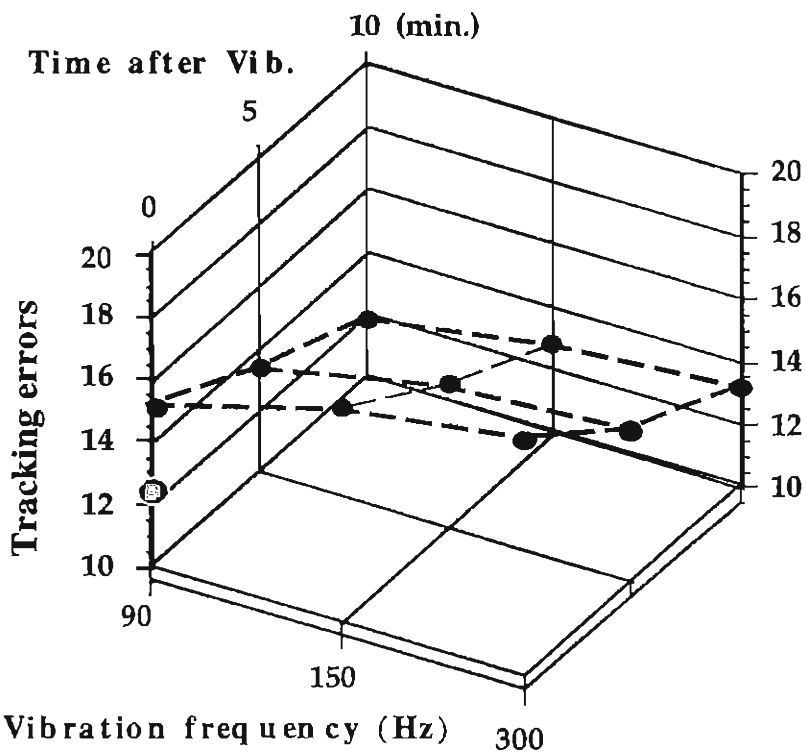

Figure 2. Number of tracking errors as a function of vibration frequency and time after vibration exposure. Tracking precision decreases immediately after vibration exposure (t_0). Ten minutes after vibration exposure (t_{10}) the number of errors is similar to the pre-vibration level.

The number of errors (averaged over frequencies and amplitude) decreases significantly ($p = 0.01$) with time (16.4 ± 8.6 @ t_0, 14.1 ± 5.8 @ t_5, 12.5 ± 6.2 @ t_{10}). As shown on the graph, the number of errors 10 min. after vibration exposure is similar to the baseline level.

Tracking time

Figure 3 presents the averages of the tracking time as a function of vibration frequency and time after vibration exposure. The gray dot on the left axis indicates the average baseline performance (30 .5 ± 5 s) observed before vibration exposure. The tracking time is significantly shorter (4.8 s, $p < 0.01$) immediately after vibration exposure. In this condition, the tracking time decreases as vibration frequency increases and is significantly shorter after the 300 Hz (24.7 ± 4 s) than 90 Hz vibration (28.3 ± 3 s) for the 0.3 mm displacement amplitude. The tracking time decreases significantly ($p = 0^{+}$) with time from 25.7 ± 4.3 s (t_0) to 29.7 ± 4.8 s (t_{10}), after 150 Hz and 300 Hz vibration exposures.; however, the differences in tracking time between t_5 and t_0, and t_5 and t_{10} were not significant. Furthermore, at t_{10} the statistical analysis indicates that the tracking time is 1) longer ($p < 0.05$) for the 0.2 mm than the 0.3 mm displacement amplitude (30.9 s for 0.2 mm, 28.0 s for 0.3 mm) and, 2) shorter ($p = 0+$) for the 90 Hz (27.5 s) than 150 Hz and 300 Hz (30 s and 29.4 s, respectively) vibration. Finally, after the 90 Hz vibration, tracking time (mean across conditions: 27. 6 s) does not vary significantly ($p > 0.1$) with time during the post-vibration period tested. This suggests a recovery period longer than 10 minutes for the 90 Hz exposure.

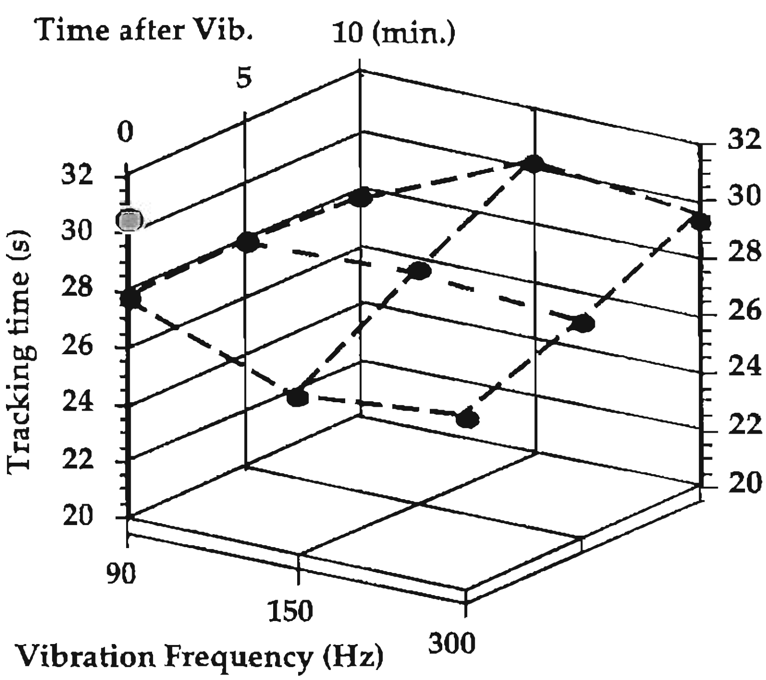

Figure 3. Tracking time as function of vibration frequency and time after vibration exposure. The tracking time decreases immediately after vibration exposure. This increase in movement velocity is higher for 150 and 300 Hz than 90 Hz vibration. The recovery of the pre-vibration level is also frequency dependent (see text for details).

Perception of task difficulty

The results of the ANACOVA performed on the subjective rating indicate that the perception of task difficulty is not directly affected by vibration exposure, despite a tendency ($p = 0.06$) to perceive the task as being more difficult immediately after vibration exposure. The graphs presented in Figure 4 indicate that the subjective rating is correlated with tracking time (r = 0.55), while a weaker correlation is observed with the number of errors (r = 0.30). Furthermore, a multiple regression analysis shows that SR = -4 25 + 0.226 Tt + 0.076 Er, where SR, Tt and Er denote respectively subjective rating, tracking time and number of errors. However, this model explained only 37% of the variance. It is worth noting that eight subjects perceived the task to be less difficult immediately after vibration, while two subjects indicated the opposite. These latter showed an increase or no significant decrease in tracking time concomitant to an increase in tracking errors. These results indicate that perception of task difficulty, which increases as tracking time lengthens, is more particularly influenced by task duration than errors.

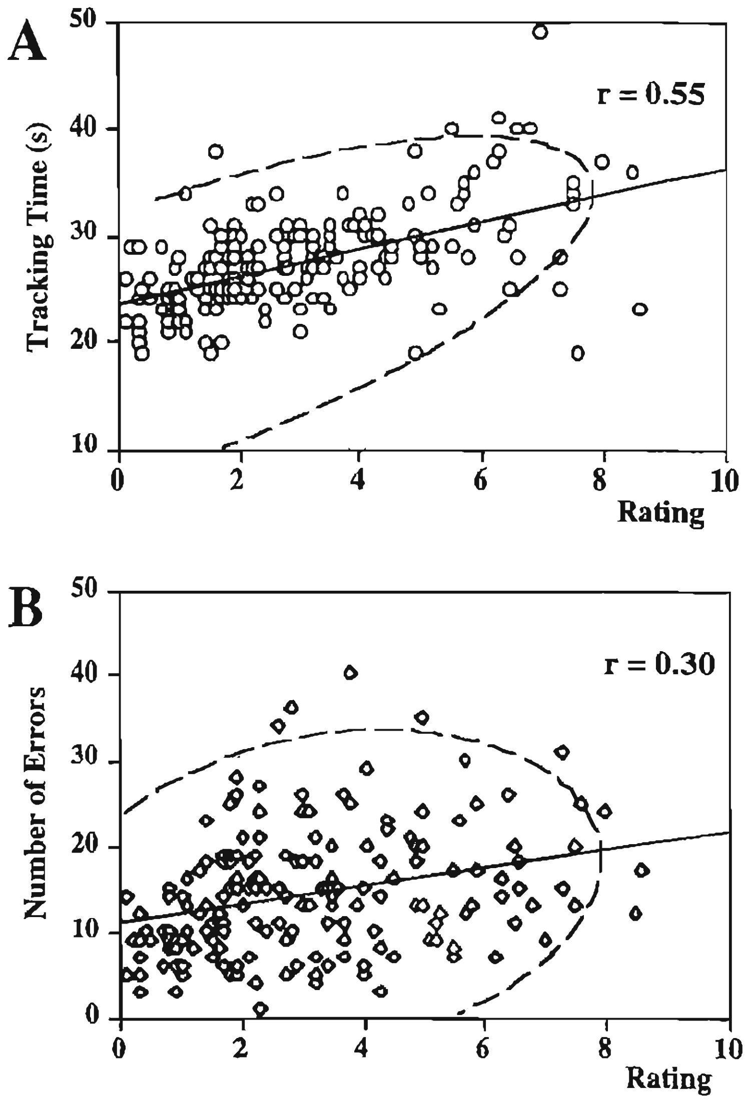

Figure 4. Correlations between subjective rating, tracking time and tracking errors. Perception of task difficulty increases with the tracking time (**A**), while it is much less influenced by the number of errors (**B**). The dashed lines represent the 95% bivariate normal density ellipses.

Discussion

The present study investigated the effects of hand vibration characteristics on a simple visuo-manual tracking task. There were three major findings in this study. First, post-vibration impairment of visuo-manual tracking show a long, frequency dependent recovery time. Despite a moderate influence of the 90 Hz vibration on the tracking time, the recovery time for a "normal" performance is longer for the 90 Hz than the 150 Hz and 300 Hz vibration. This finding suggests that recovery is most likely related to the differential sensitivity to vibration frequency of the sensory systems (proprioceptive and tactile) involved in manual control.
Second, the decrement in tracking precision appears to be related to an alteration of movement speed control which was significantly influenced by vibration frequency. Third, vibration exposure induced a divergence between the subjective perception of task difficulty and the objective measure of performance. This finding, which agrees with previous results, suggests that vibration-induced alteration of manual precision is not properly perceived, which may represent an additional risk during the manipulation of vibrating hand-tools.

Mechanisms of post-vibration effects

The results presented in Figure 2 and 3 show long lasting post-vibration effects. The graph in Figure 3 indicates that the recovery is frequency dependent. Full recovery appears to take place only between 5 and 10 min. after vibration exposure for the highest two frequencies (150 and 300 Hz) and may be longer than 10 min. for the 90 Hz vibration. The time lag of the recovery and the influence of vibration frequency can be explain by the differential sensitivity of the sensory systems activated by the vibratory stimulus and the nature of the mechanisms involved in movement control.

Previous studies have shown that the alteration of continuous manual control resulting from vibration exposure can be attributed to the response of the somesthetic receptors to the vibratory stimulus.(Gauthier et al. 1981, Ribot et al. 1986; Martin et al. 1991). These responses contribute to the alteration of the functioning of peripheral and central neurosensory mechanisms underlying motor control (Goodwin et al. 1976; Martin et al. 1984, Roll and Roll, 1987; Martin et al. 1991). Primary muscle spindle receptors, known to provide position and velocity information, have a frequency response to vibration limited to about 100 Hz (Burke et al. 1976; Vedel et al. 1985; Roll et al. 1989), while tactile receptors, also involved in motor control processes, as discussed below, have a frequency response up to 250-300 Hz (Johansson and Vallbo, 1983; Roll et al. 1989). Thus, effects of proprioceptive origin are more pronounced for frequencies less than 100 Hz, while effects of tactile origin could be stronger for higher frequencies.

The very long time course of the recovery period seems to result from changes affecting peripheral and central mechanisms. First, peripheral mechanisms such as temporal depression of the sensitivity of tactile receptors (Lundström and Johansson, 1986) and neural mechanisms suggested to include recurrent circuits (Rymer and Hasan, 1981) have a short recovery time course (< 2 min.) after vibration exposure. Thus, these mechanisms contribute only to immediate post-effects. Second, long lasting (>> 5 minutes) post-vibration involuntary muscle contractions have been related to changes in central mechanisms (Gilhodes et al. 1992) triggered by the activity of the spindle receptors of the vibrated muscle. These post-effects are not elicited when symmetric vibrations are applied to antagonistic muscles. In addition, it has been hypothesized that intentional motor activity is subtended by a set of non-linear oscillators constituting rhythm generators. Craske (1985, 1986) has suggested that the central structures including these oscillators might generate the so called post-contraction phenomena. Furthermore, tactile sensibility is known to be affected by vibration and the post effects are related to the frequency, amplitude and duration of vibration exposure (Verillo and Gescheider, 1977, Gescheider et al. 1979). The recovery time to perception threshold is about 5 min. for a 10 min. exposure duration, which is longer than the expected recovery time of the receptors themselves (indicated above). Overall, these data do not directly explain the present long duration post-vibration effects; however, they provide evidence of the existence of central structures in which vibration-induced proprioceptive or tactile inputs, could trigger long lasting phenomena. These phenomena would delay the recalibration of the sensorimotor systems.

The respective duration of the post-vibratory response of the mechanisms presented above suggest that the long time course of tracking performance recovery has primarily a proprioceptive origin, which is strongly affected by the 90 Hz vibration. The tactile system may play a significant role in the first five minutes of the post-vibration period. This interaction is mainly acting at the highest two frequencies, for which we observed a slight increase in tracking error and a significant decrease in tracking time.

A significant amplitude effect is observed only 10 minutes after exposure. This phenomenon may result from a possible saturation of the alterations already present for the lowest amplitude level. A desaturation could occur only after several minutes and allow the emergence of an amplitude effect. This result suggest that post-vibration effects on visuo-manual performance are already important at low vibration levels.

Finally, the contribution to post-vibration effects of mechanisms such as the depression of synaptic transmission (Nielsen and Hultborn, 1993) and, acute reduction of blood flow in the peripheral vessels (Welsh, 1980) cannot be ruled out. However, their respective recovery times are not clearly described.

Hand velocity and finger position control after vibration exposure

Previous investigations have indicated that hand tracking can be performed using a velocity control mode based on prediction after training and acquisition of skills (Mc Ruer and Jex, 1967; Martin et al. 1991). In the present experiment, the movement trajectory, represented by the wire, is fully predictable. Although the hand movement was not monitored in this study, we observed that the tracking strategy evolved from a step-by-step mode (position control) to a smoother and more continuous mode (velocity control) with training. After vibration exposure we observed a 33% increase in the number of tracking errors and a 14% decrease in tracking time. The decrease in tracking time represents a 20% increase in the average velocity of the hand. Hence, after vibration exposure, the considerable increase in movement velocity is likely to play an important role in performance decrement.

It seems counter-intuitive to observe an increase rather than a decrease in speed. One may expect a slow down in movement velocity in an attempt to minimize the influence of the vibration-induced alteration of movement precision. However, despite a required emphasis on precision, the deep alteration of velocity control cannot be compensated as it appears that velocity is not properly perceived by the subjects (see discussion below).

In the context of our experiment, hand movement velocity control seems primarily based on kinesthetic information issued from the hand tracking system. This hypothesis is supported by two set of arguments. First, the extent of the post-vibratory effects indicate that kinesthetic information eventually derived from the visual input is not used for hand velocity control or cannot compensate for the vibration-induced alteration of other sensory modalities cooperating to hand movement control (Gauthier et al. 1981, Ribot et al. 1986; Martin et al. 1991). As indicated above, the functioning of proprioceptive and tactile systems have been corrupted by their response to the vibratory stimulus. Hence, in the present context, visual detection of movement inaccuracy may not be sufficient to help a "temporarily impaired hand controller". Second, the effect illustrated in Figure 3 shows that changes in tracking velocity are frequency dependent. This effect finds its origin in the differential sensitivity to vibration of the primary muscle spindles known to contribute to limb position and velocity control, and the tactile receptors, as described above. Furthermore, fast adapting tactile receptors, such as Pacinian corpuscles are most sensitive in the high frequency range (> 80 Hz). In addition, these receptors are extremely responsive to dynamic events such as the movement of an object held between the fingers (Westling and Johnasson, 1987). They may provide appropriate trigger signals to change the motor output in specific movement phases (Westling and Johansson, 1987) and have a proprioceptive response to finger movements (Hulliger et al. 1979). Because of these characteristics Westling suggested their participation in motor control processes. Therefore, we can suggest that as vibration frequency increases, the alteration of the muscle proprioceptive system decreases while the alteration of the tactile system increases (see also previous experiments in this report). These phenomena are responsible for the slight increase in tracking error and the significant decrease in tracking time observed when vibration frequency increases. The interaction of the tactile system can be attributed to changes of the proprioceptive response of tactile receptors located at joint levels and contributing to hand velocity control.

As indicated above, the tactile information issued from the receptors located at the finger tips contributes to the control of finger movement and thus, to the control of the orientation of the ring (rotation about the horizontal axis). Hence, changes in tactile information of vibratory origin are not compensated by the visual detection of the position error. The impairment of this position control also contributes to the decrement of the tracking precision.

Divergence between motor effects and perception

Apparently the judgment on the task difficulty is mostly related to the tracking time. Faster trials are perceived as less difficult than slow trials despite the higher probability of a larger number of errors (see Figure 2 and 3). However, movement speed, per se, does not seem properly perceived after vibration since 1) velocity is not adequately controlled and 2) perception is not significantly differentiated between the experimental conditions. As indicated above, the vibration-induced alteration of sensory information do contribute to changes in the response of peripheral and central sensorimotor mechanisms involved in hand movement speed control. In addition, the kinesthetic information reaching the cortical areas is likely to be misinterpreted by "decalibrated" central structures. Hence, the estimation of the overall tracking time seems to prevail over the velocity alteration of individual movements, which leads to a performance decrement in term of precision.

This observation is in agreement with previous results. It has been shown that alteration of postural stability is not perceived during and after whole-body vibration (Martin et al. 1980). The subjects describe their posture as "perfectly stable" while body sways increase. Furthermore, pain or discomfort induced by electrical stimulation of cutaneous nerves are attenuated by hand vibration (Martin et al. 1991, see also first experiment in this report), while motor activities usually correlated with pain perception are facilitated. Hence, all these results point at the divergence between perception and performance during or after vibration exposure.

Conclusions

Dissociation between performance and perception of performance may have several consequences in workplaces where vibrating powered hand tools are extensively used. First, decrement in performance will contribute to quality problems. Second, as the alterations of movement control (faster and less precise movements) are not properly perceived, they represent a potential risk of accident since the user is not aware of and not prepared for possible tool control problems. For example, inadequate positioning of a tool may result in an abrupt motion of the tool that can either fall on or being pushed against a body part, or require excessive muscle force to stabilize the tool. In the context of the present experiment, the results show that even visual guidance is not sufficient to compensate for the vibration induced alteration of sensory modalities involved in hand and finger movement control.

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OCULO-MANUAL COORDINATION

The aim of this study was to determine the extent of hand pointing errors and the effects on eye-hand coordination caused by vibration transmitted to the hand. The coordination was analyzed through the response of the visuo-ocular and visuo-manual systems while they are acting together in a pointing task. The following hypotheses were tested:

1) Vibration induced alteration of proprioceptive information will affect significantly oculo-manual coordination;

2) Permanent visual control of the hand should compensate to some extent vibration-induced affects of other sensory modalities.

Effects of vibration frequency and duration on eye-hand coordination in pointing tasks

Abstract

Impaired performance of visually guided motor activities during and after hand vibration exposure may be related not only to the alteration of hand movements, but also to the coordination of the eye and hand systems. The aims of this study were first to determine the influence of vibration parameters on the alteration of eye-hand coordination and second, to determine the role of visual information in the eventual compensation of the vibration-induced alterations affecting other sensory modalities.

The effects of high frequency (100, 200 Hz) hand vibration on simultaneous eye and hand pointing performances were investigated in trained human subjects. The pointing task consisted of aiming with the eye and the hand to one of six punctual visual targets spaced by 5° (viewing angle) along a horizontal line. In a first experiment, the pointing task was performed with and without direct visual control of the hand before and during a short term (2 min.) hand vibration. In a second experiment, the task was performed in the same visual conditions before and after a 10 minutes hand vibration exposure. During this exposure the subject exerted a grip force of 5% of the maximal voluntary contraction for 5 s and then relaxed for 25 s while maintaining the fingers in contact with the handle. Alterations of eye and hand pointing performance (constant error, error variability and hand movement time) were analyzed as a function of vibration frequency, exposure duration, visual condition and time after exposure. Ten healthy subjects participated in the experiment.

Vibration induced an increase in hand pointing constant error and error variability. These alterations were more particularly pronounced for the 100 Hz vibration and when the hand was masked. In this latter visual condition, the persistence of the constant error 10 minutes after vibration exposure suggests a loss of the initial pointing reference. The eye gaze constant error and error variability increased during and immediately after vibration exposure. The influence of vibration frequency on eye movements was slightly different during and after vibration exposure. Recovery time of pre-vibration performance is less than 5 minutes for the eye fixation.

These results indicate that vibration similar to hand-tool vibration affects hand movement precision and the coordination of hand and eye movements. The visual control of the hand counteracts, to some extent, the alterations of hand movements resulting from vibration exposure.

Background

Visual control of hand movement is essential in occupational activities requiring precise manipulation. The coordination of eye and hand movements is essential in these tasks. Visual, proprioceptive and exteroceptive information contribute to the control of the complex coordination processes (Gauthier et al. 1988; Vercher and Gauthier, 1992; Gerard and Martin - previous study).

Hand vibration has been shown to alter continuous manual control (Martin et al. 1991, Gerard and Martin - previous study) and oculomanual coordination (Martin et al. 1991). There is evidence that these perturbations of sensory motor activities result from vibration-induced changes in sensory messages (Burke et al. 1976; Ribot-Ciscar, 1988; Roll et al. 1989; Gilhodes et al, 1992), which deeply affect the functioning of the neurosensory mechanism underlying motor control (Gillies et al. 1969; Desmedt and Godaux, 1978, Martin et al. 1984; Martin et al. 1990; Park and Martin, 1993). These alterations were found to be frequency dependent (Martin et al. 1984; 1986; Park and Martin, 1993). In addition, we have shown that visual control of hand movement may counteract vibratory effects in specific contexts (Martin et al. 1991).

The question then arises as to how alterations of manual performances and eye-hand coordination are related to vibration frequency. In particular, which vibration frequencies would have less influence on oculomanual coordination? Furthermore, as visual control may not be efficient in all situations (Gerard and Martin, previous study) it is of interest to assess its role in simple pointing tasks, which are frequently performed under vibration exposure in various powered hand tool manipulations.

The present study describes the changes in coordinated eye-hand pointing tasks during short term and after long term hand vibration exposure for two vibration frequencies. The results confirm that vibration frequencies equal to or above 200 Hz have less influence on motor performances. They also underline the role of the visual feedback of hand movements in the compensation of vibration-induced alterations.

Materials and Methods

Subjects

Ten subjects, six males and four females, ranging in age from 20 to 40 years participated in the experiment as paid volunteers. All subjects were right handed, in good physical condition, free from any known neurological or musculoskeletal disorders and had good vision without optical aide. Prior the experiment each subject read and signed an informed consent form.

Experimental Situation

The subject was seated on an adjustable armchair in front of a display panel placed 57.3 cm from the eye. Eleven green emitting diode (LED) arranged in a cross shape and spaced by 5 cm (5° viewing angle) served as visual targets (Figure 1). The head-target distance was chosen to match 1 cm on the display panel with 1° of eye rotation. The armchair was adjusted to place the subject's eyes at the level of the horizontal targets and to center the head with the central target.

Eye position was monitored using an infrared optoelectronic device derived from an original design by Bach et al. (1983). This device allowed for the determination of the horizontal and vertical coordinates of eye gaze. In brief, a two-dimensional photosensor provided continuous position change of a light spot reflected by the scleral surface while the eye rotated. The light source was provided by 4 miniature infrared emitting diodes. The elements of the eye monitoring device were arranged in a tube mounted in a vertical position on a fixed support. A semireflecting mirror reflecting only the infrared beam going to the eye and reflected by the eye allowed perfect binocular vision. The frequency bandwidth of the apparatus was 0-300 Hz and the linearity was close to 1 within a ± 15° range. The head of the subject was maintained in a steady position using a bite bar fixed to the support of the eye monitoring device.

Hand pointing position was measured by a two-dimensional sonic device fixed to the panel. The pointing device consisted of a handle with a pointer running off the top at a right angle

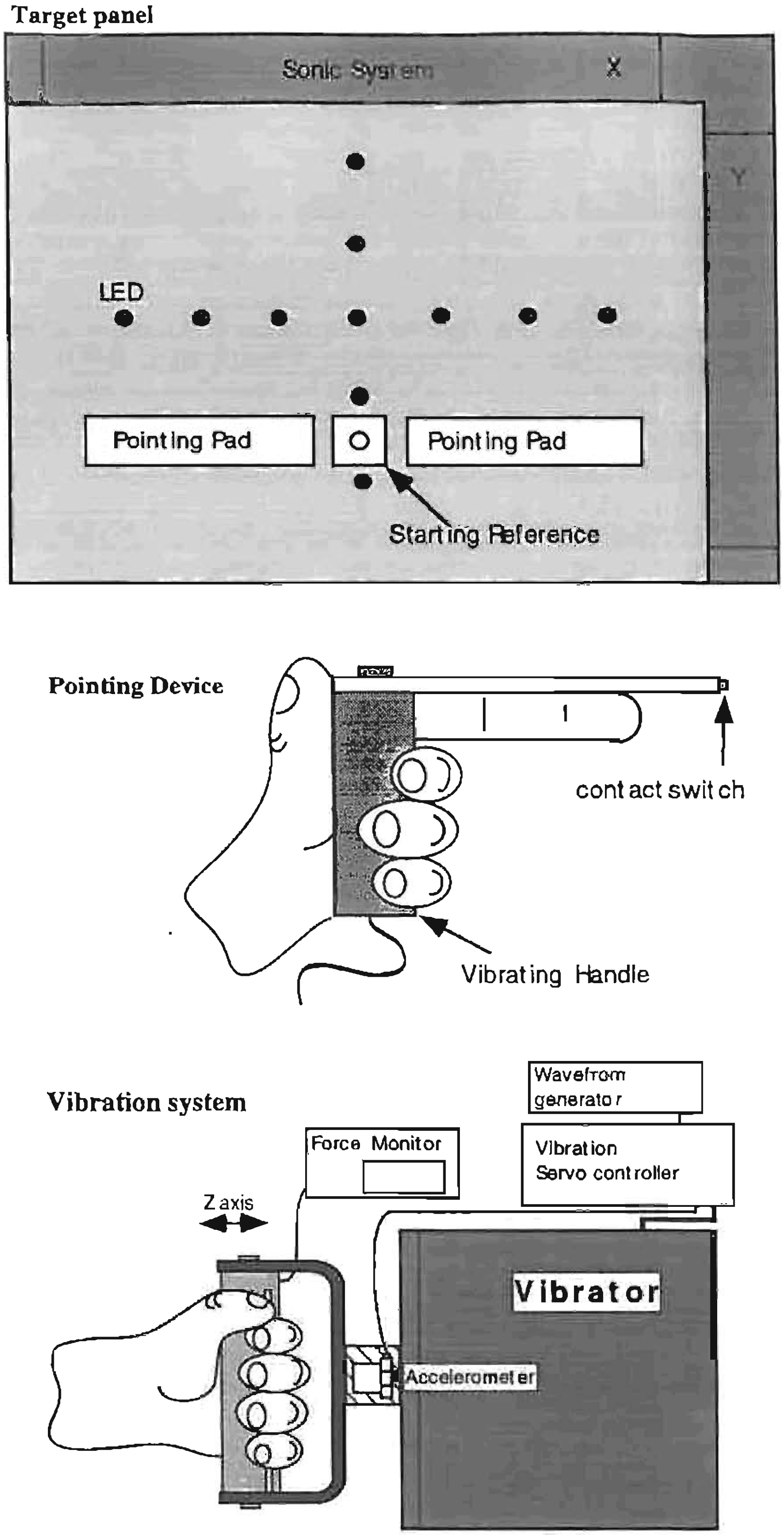

Figure 1. Experimental equipememt. Punctual visual targets are presented on a vertical panel placed 53.7 cm from the eyes of the subject (upper panel). The pointing device (middle panel) is held in the dominant hand. The subject points below the targets, on the pointing pads. Vibration is applied to the hand using the cam load vibrator located inside the handle of the pointing device or an electrodynamic vibrator (lower panel). See text for details.

to the axis of the handle. A contact switch attached to the tip of the pointer was used to trigger a spark between two electrodes located near the switch. The sound generated by the spark was captured by two linear microphones to provide the X & Y coordinates of the pointer. The subject held the handle with the index finger along the pointer extension. The handle contained a cam load vibrator.

Vibration

Vibration was applied to the dominant hand of the subject using either the self-contained vibrator located in the handle of the pointing device or a vertical handle fixed to an electromagnetic vibrator. In this later case, the handle was equipped with a dynamometer to display the grip force on a digital voltmeter. Two sinusoidal vibrations of 100 Hz and 200 Hz with displacement amplitude of 0.2 mm were used.

Pointing Task

The task of the subject consisted of pointing below the horizontal targets with the pointer held in his/her dominant hand. During each pointing sequence, the targets were illuminated ten times in a random order. The target was turned on for one second; three seconds separated two consecutive target presentations. A pad, on which the subject pointed, was located 7 cm below the horizontal LEDs. A circular mark was placed under the center target to indicate the starting location of all pointing movements. The subject was asked to hold the pointing device on the mark until an LED was illuminated and then to return to that location after pointing under the target. The subjects were instructed to simultaneously move the eye and the hand and perform the hand motion as quickly as possible while emphasizing accuracy. The return to the center location was self-paced. The subject was to maintain his/her gaze on the LED without looking down at the pointing device, except at the end of the return movement to verify the hand position.

Procedure

The subject performed three series of practice trail before the experiments. Two sets of experiments were carried out on non-consecutive days: per-vibration and post-vibration pointing. Horizontal and vertical eye movements were calibrated at the beginning, in the middle and at the end of the experiment.

Per-Vibration Pointing. The pointing task was performed before and during hand vibration with the hand in sight or the hand out of sight, masked by an opaque screen. In this latter case, a hole in the screen allowed vision of the center mark. Data was collected for a total of eight trials (2 test situations x 2 frequencies x 2 visual conditions). Vibration frequencies and visual conditions were presented in a random order. A 5 minute rest period separated two consecutive trials (before - during vibration) and a 15 minutes rest period separated two vibration exposures.

Post-Vibration Pointing. The pointing task and visual conditions were identical to the one described above. Here, the pointing performance was tested before (t_c), immediately after (t_0), and 5 (t_5) and 10 min (t_{10}) after a 10 min. vibration exposure (Figure 1). During the vibration period the subject grasped the handle and exerted a grip force of 5% of the maximal voluntary contraction during 5 sec and relaxed for 25 sec. The grip force level was displayed on a digital voltmeter. This task was paced by a brief auditory signal generated by a computer. The maximal voluntary contraction of the grip was determined at the beginning of the experiment. Data was collected for a total of 16 trials (4 test situations x 2 frequencies x 2 visual conditions). Vibration frequencies and visual conditions were presented in a random order. A 15 minutes rest period separated two vibration exposures.

Recording

The horizontal eye position signals were sampled at 1000 Hz and recorded by a computer. The horizontal coordinate of the pointing location and the pointing movement time were recorded simultaneously by another computer.

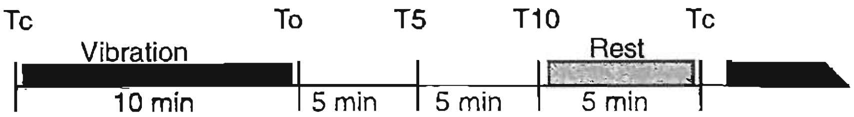

Figure 2. Vibration and test schedule. Vibration period indicated by thick black lines. Tc, To, T5 and T5 represent the testing times before and after vibration exposure, respectively.

Data analysis

Hand and eye horizontal movements (X axis) were analyzed. Repeated measures analysis of covariance (ANACOVA) treating the subject as a random blocking factor was performed on the constant error (mean end-point from the center of a target), error variability (absolute error = |constant error| and std dev. of absolute error), and hand movement time to characterize the effects of hand vibration on the visuo-manual task. Hand or eye errors were used alternately as the added regressor.

Results

Per-vibration pointing

The results of the ANACOVA performed on the hand and gaze constant errors, absolute error and hand movement time are presented in Table 1. These data indicate first, that vibration had a significant influence on hand pointing and eye gaze precision and, eye-hand coordination. Second, the visual condition play a significant role, more specifically during vibration exposure. Third, vibration frequency significantly influenced the task in specific situations as indicated by the significance of the interactions between frequency and condition, and between frequency and target. Because of these interactions an analyses of variance were conducted to compare more easily pairs of situations. Finally, the movement time was also affected by hand vibration.

Table 1. Analysis of covariance of per-vibration pointing performance

Effects	**df**	**P - Values**				
		Hand			**Eye**	
		Constant. Error	Absolute Error	Movement Time	Constant. Error	Absolute Error
Subject	9	0+	0+	0+	0+	0+
Vibration Frequency (VF)	2	0.026	0.231	0+	0.002	0.003
Visual condition (C)	1	0+	0+	0+	0.047	0+
C x VF	2	0+	0+	0.696	0.007	0.004
Target (T)	5	0+	0+	0+	0+	0+
C x T		0+	0+	0.158	0.547	0.016
VF x T		0.001	0.172	0.939	0+	0.165
Hand constant error				0.139	0.001	0.643
Eye constant error		0+	0+			

significance level: $P \leq 0.05$

Hand movements

The graphs presented in Figure 3 (left panels) illustrate the influence of hand vibration on the constant error for each visual condition. First, one can note that in the control situation (no vibration) the constant error increases when the hand is masked. In addition, the statistical analysis conducted on the error variability (absolute error and variance of absolute error) indicates that this type of error also increases significantly when the hand is masked. Second, changes resulting from vibration exposure are as follows:

1) Changes in the constant error were significant only for the most eccentric targets (±10°, ±15°).
2) The constant error is significantly affected ($p < 0.05$) during 100 Hz vibration, this error is larger when the hand is masked (lower left panel). The subject tend to overshoot the targets. The average shift in pointing position induced by the 100 Hz vibration is 1.2 mm when the hand was in the visual field and 3.7 mm when the hand is masked. The absolute error increases significantly ($p < 0.05$) from 4.9 mm to 5.9 mm during 100 Hz vibration when the hand is visible.
3) In the control situation, the standard deviation of the absolute error was significantly ($p < 0.05$) larger for the mask (± 6.6 mm) than the no-mask condition (± 3.5 mm) in the control situation (no vibration). Probably because of this large increase in error variability before exposure, no significant variation in error variability were observed during vibration when the hand was masked.
4) The movement time decreases significantly only during 100 Hz vibration (Table 2).

Table 2. Movement time

Vibration	Hand movement time (ms)	
	No-mask	Mask
Control (no vibration)	635 ± 210	605 ± 193
100 Hz	550 ± 159*	546 ± 139*
200 Hz	645 ± 188	602 ± 187

* significant decrease from control situation ($p < 0.05$)

Eye movements

The graphs presented in Figure 3 (right panels) illustrate the influence of hand vibration on the gaze constant error for each visual condition. Changes resulting from vibration exposure are as follows:

1) The statistical analysis indicates that the constant error changes during vibration exposure; however, these changes are only significant for large amplitude movements (±10°, ± 15°). Average changes in the magnitude of the constant error are 0.25° for both visual conditions (no-mask and mask).
2) The absolute error increases significantly ($p < 0.05$) by 0.2° for the 100 Hz vibration in the no-mask visual condition and is not affected by the 200 Hz vibration. In this condition, a similar effect is observed for the error variability, which increases significantly from ± 0.68 (no vibration) to ± 0.78 (100 Hz vibration). No significant changes in absolute error or error variability where observed when the hand was masked.
3) A visual inspection of the eye movement traces did not reveal a change in the saccade pattern under vibration exposure. Examples of typical saccades recorded in the hand mask condition are illustrated in Figure 4. Four saccades of 15° amplitude are overlaid for the control (upper panel) and 100 Hz vibration situation (lower panel). Correction saccades are frequently present in both situations.

Post-vibration pointing

The results of the ANACOVA performed on the hand and gaze constant errors, absolute error and hand movement time are presented in Table 3. These data indicate first, that vibration had a significant influence on hand pointing and eye gaze precision, and eye-hand coordination. Second, the visual condition play a significant role, more specifically after vibration exposure.

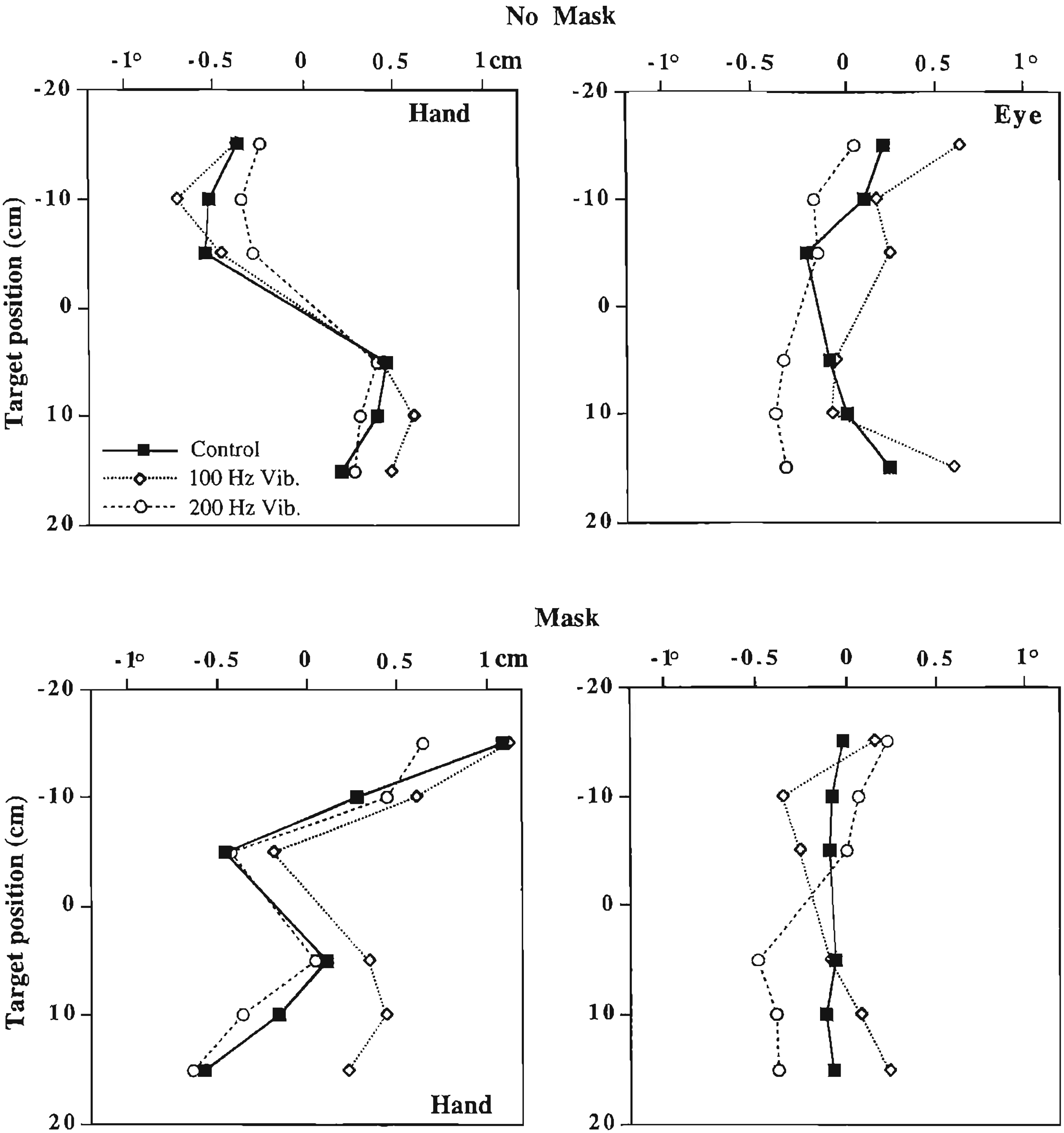

Figure 3. Hand and eye constant errors during vibration exposure. Average changes in the constant error of hand (left panels) and eye (right panels) pointing are illustrated for each vibration frequency in each visual condition: hand not masked (upper panels), hand masked (lower panels). The control situation (no vibration) is represented by the filled square symbols. The errors, displayed along the horizontal axis (1cm = 1°of visual angle), are presented for each target (vertical axis). Each symbol represents the magnitude of the error relative to the center of the target. The average shift in hand pointing position is larger for 100 Hz vibration and for the hand masked condition. A shift in eye gaze is observed during vibration but this error increase is independent of the visual condition (see text for details).

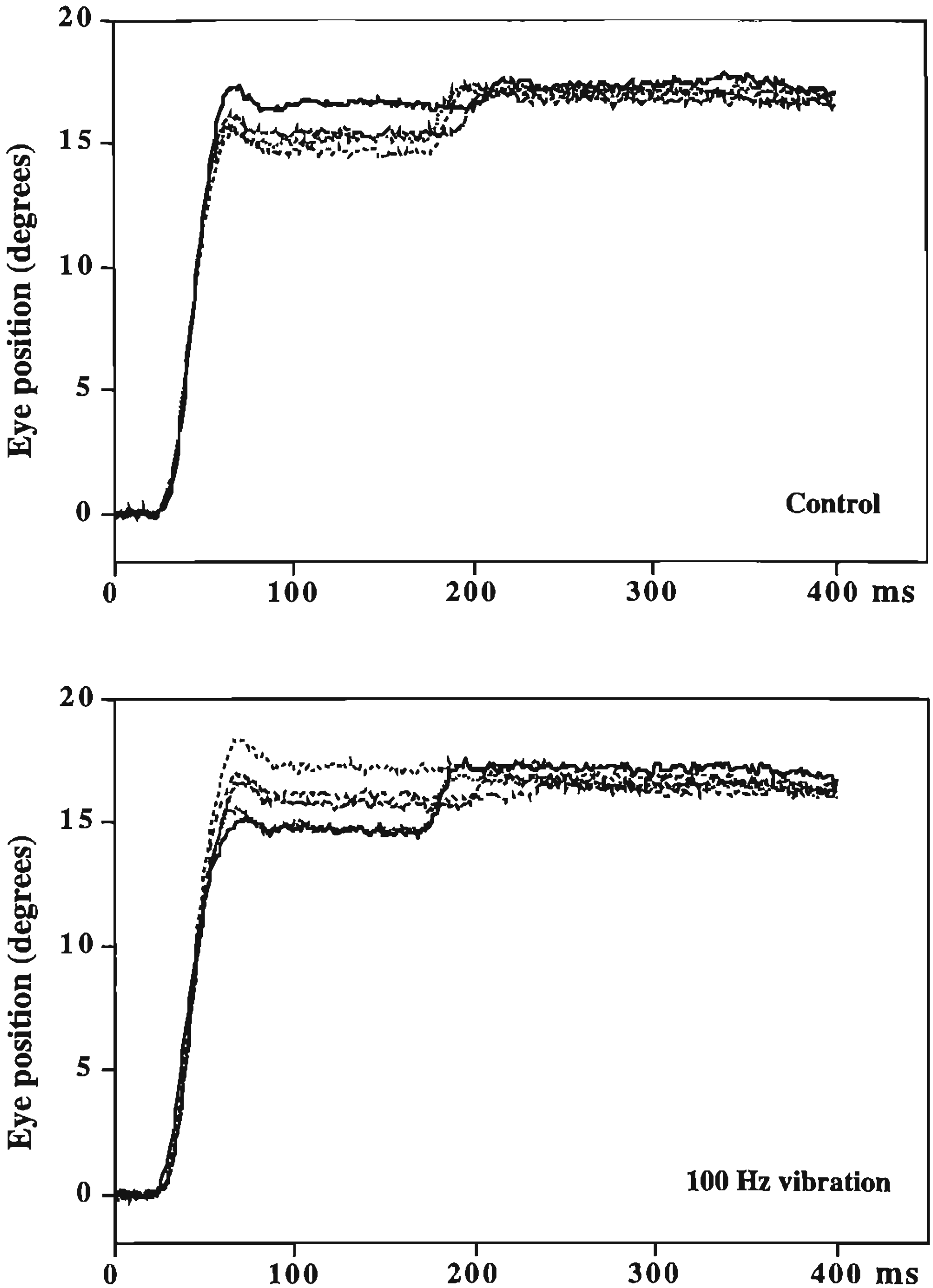

Figure 4. Eye movements. Examples of saccades obtained for one subject in the hand masked condition before (upper panel) and during 100 Hz vibration expsoure (lower panel). The saccades were obtained in reponse to the illumination of the +15° target. The individual traces are overlayed for pattern comparison. The constant error increases during vibration exposure; however, no specific changes in the saccade pattern (number and amplitude of correction saccades) seem to be induced by vibration.

Third, vibration frequency significantly influenced the task in specific situations as indicated by the significance of cross products. Because of these interactions analyses of variance were conducted to compare more easily pairs of situations. Finally, the movement time was not affected after hand vibration.

Table 3. Analysis of covariance of post-vibration pointing performance

Effects	**df**	**P - Values**				
		Hand			**Eye**	
		Constant. Error	Absolute Error	Movement Time	Constant. Error	Absolute Error
Subject	9	0+	0+	0+	0+	0+
Vibration Frequency (VF)	1	0.12	0.07	0.5	0+	0+
Visual condition (C)	1	0+	0.24	0+	0.01	0.10
Time after vibration (Time)	3	0.5	0+	0.28	0.03	0.07
C x VF	2	0.29	0.66	0.83	0.80	0.55
C x Time	3	0.02	0+	0+	0.71	0.16
VF x Time	3	0.35	0.16		0.02	0.11
Target (T)	5	0+	0+	0+	0+	0+
VF x T	5	0+	0+	0.77	0+	0.01
Hand constant error	1			0+	0.04	0.87
Eye constant error	1	0.04	0.551			

significance level: $P \leq 0.05$

Hand movement

The graphs presented in Figure 5 (left panels) illustrate changes in the constant error observed immediately after vibration exposure (t_o) for each visual condition. The horizontal axis represents the error about the center of each target, which corresponds to 0°; the vertical axis represents the target positions, negative values correspond to targets located on the left side of the display panel. A shift in hand pointing position is observed when the hand is masked (lower left panel). This error corresponds to an undershoot of the targets.

The statistical analysis indicates first, that the constant error, the absolute error and error variability are not affected by the visual conditions (mask or no-mask) in the control situation (no vibration). Second, changes resulting from vibration exposure are the following:

1) Changes in the constant error are significant only for the most eccentric targets (±10° and ±15°);
2) The constant error is significantly affected after vibration only when the hand is masked. Vibration frequency does not have a significant ($p >> 0.05$) influence on that type of error. The average magnitude of the shift in hand pointing position induced by vibration, represented by the difference between the constant error observed after and before vibration, is 4.7 mm when the hand is masked. In this visual condition the absolute error increases significantly from 5.1 mm to 7.2 mm.
3) The magnitude of the shift in pointing position observed immediately after vibration (T0) remains approximately the same 5 and 10 minutes after vibration exposure when the hand is masked, while no significant changes are observed when the hand is visible. These effects are illustrated in Figure 6.
4) The error variability (SD of the absolute error) increases by more than 60% after vibration exposure when the hand is masked. This increase in variability persists up to 10 minutes after exposure (Table 4). No changes in variability are observed after vibration exposure when the hand is visible.
5) The movement time is not significantly affected after vibration exposure.

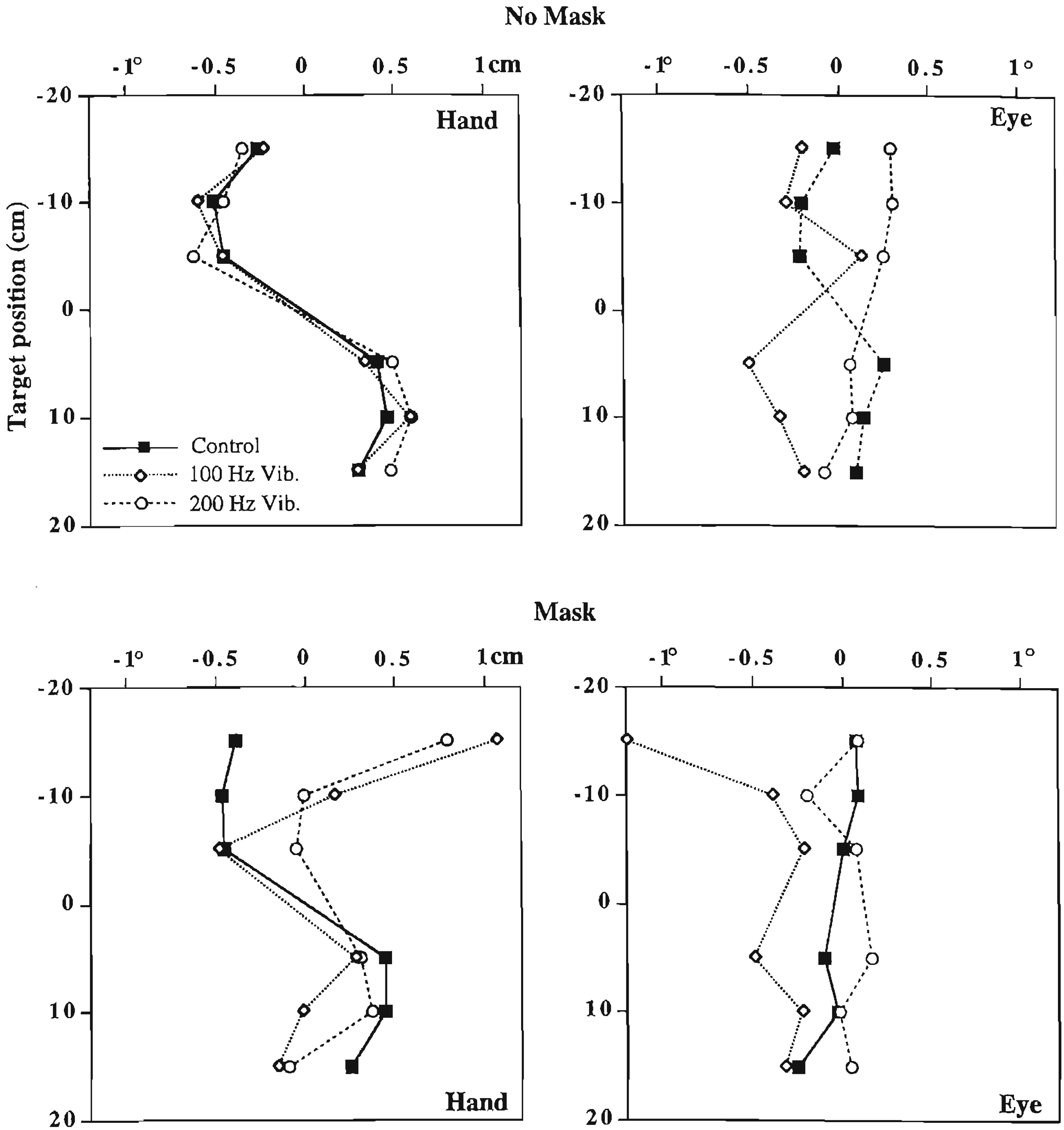

Figure 5. Hand and and eye constant errors immediately after vibration expsosure. Average changes in the constant error of hand (left panels) and eye (right panels) pointing are illustrated for each vibration frequency in each visual condition: hand not masked (upper panels), hand masked (lower panels). The control situation (no vibration) is represented by the filled square symbols. The errors, displayed along the horizontal axis (1 cm = 1° of visual angle), are presented for each target (vertical axis). Each symbol represents the magnitude of the error relative to the center of the target. A shift in hand pointing position is observed when the hand is masked. A shift in eye gaze is also observed after vibration exposure (see text for details).

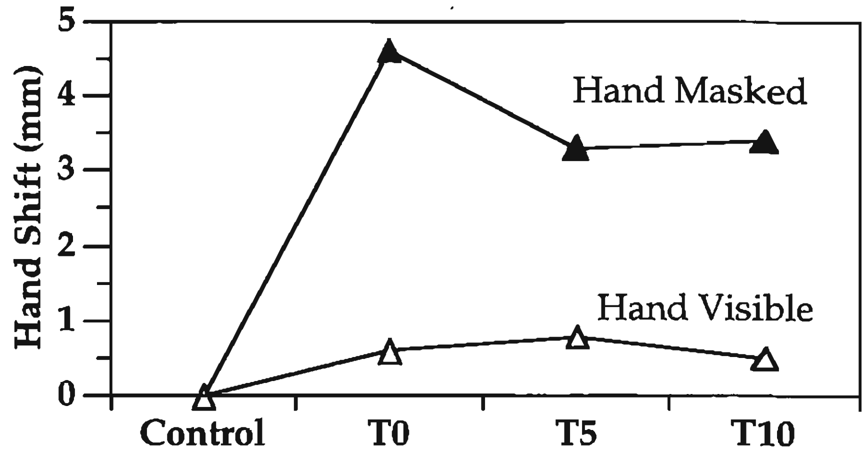

Figure 6. Average shift in hand pointing position observed after vibration exposure. The increase in hand pointing error (hand shift) is plotted as a function of time after vibration exposure. A significant shift is observed after vibration exposure only when the hand is masked. This alteration persists even 10 minutes after the end of the vibration period.

Table 4. Variability of absolute error.

	Absolute error Standard Deviation			
Visual condition	No- Mask		Mask	
Vibration Frequency	100 Hz	200 Hz	100 Hz	200 Hz
Control (before vibration)	.45	.43	.39	.35
T0	.48	.43	.62*	.54*
T5	.48	.44	.59*	.67*
T10	.46	.43	.59*	.60*

* significant increase from control situation ($p < 0.05$)

Eye movements

The graphs presented in Figure 5 (right panels) illustrate the influence of hand vibration on the gaze constant error for each visual condition. the statistical analysis indicates that this type of error changes after vibration exposure. Changes resulting from vibration exposure are as follows:

1) The average shift of the gaze are 0.35° and 0.25° when the hand is not masked and masked, respectively. These shifts mostly correspond to target undershoot when the hand is not masked (Figure 5 upper right panel), while they are not specifically oriented when the hand is masked (Figure 5, lower right panel).
2) The constant error was significantly larger ($p < 0.05$) for 100 Hz than 200 Hz vibration only when the hand was not masked.
3) The absolute error increases significantly ($p < 0.05$) by 0.17° and 0.13° immediately after 100 Hz vibration exposure when the hand is not masked and masked, respectively. Furthermore, the standard deviation also increases in the same situations.
4) No significant changes were observed 5 min. after vibration exposure (t5); hence, hand vibration may not have long lasting effects on the control of eye movements

Discussion

The present study investigated the per and post-effects of hand vibration exposure and on a simple visuo-manual pointing task. There were four major findings in this study. First, impairments of hand pointing and eye gaze show that hand vibration can affect the precision of hand movement and the coordination of the eye and the hand when they are involved in the same task. This finding, which agrees with previous results concerning visuo-manual control, confirms the influence of hand proprioception on eye-hand coordination. Furthermore, only large amplitude movements ($\geq 10°$) are affected. Second, hand and eye movements are generally more strongly affected by 100 Hz than 200 Hz vibration. This finding, showing the influence of vibration frequency, agrees with the results of the previous study. Third, changes in performance observed during and after vibration exposure when the hand is masked underline the role of the visual feedback in vibratory environments. Fourth, the persistence of the constant error of the hand movements 10 min after vibration exposure only when the hand is masked indicate that vibration may lead to a loss of the proprioceptive reference that is not compensated by visual input.

Alteration of eye-hand pointing

The results presented in Figure 3 and 5 show that vibration can induce a shift in hand pointing and eye fixation, before and after vibration exposure. These errors are accompanied by an increase in error variability. The general trend indicates that 100 Hz vibration seems to produce the strongest effects. The vibration induced alterations of coordinated hand and eye movements observed in the present context are in line with previous results showing impairments of continuous tracking movements (Martin et al. 1991; Gerard and Martin, see previous study). They confirm that the vibration-induced alteration of sensory information issued from somesthetic receptors can contribute to a decrease in movement precision and that frequency effects are related to the differential frequency sensitivity of the receptors to such stimulation. Primary muscle spindle receptors, which provide limb position information, are extremely sensitive to vibration frequencies up to 100-120 Hz (Burke et al . 1976; Roll et al. 1989), while cutaneous receptors, also involved in motor control processes (see previous study), are sensitive to vibration up to 250 - 300 Hz (Johansson and Vallbo, 1983; Roll et al. 1989). Thus, the weaker influence of 200 Hz vibration suggests that the impairment of performance has predominantly a muscle proprioceptive origin. Differences in motor activities can explain differences in vibration frequency effects between the current and previous experiments. Here, the handle was controlled with the whole hand with no finger motion, while in the previous experiment, fine finger motions were required to perform the tracking task. In this latter case, tactile information from the tips of index and thumb fingers played a significant role in the control of the tracking device. Hence, this type of control may exhibit more sensitivity to high frequency vibration.

The alteration of eye movements suggest that vibration is able to affect the coordination of the hand and the eye in pointing tasks, despite the fact that the target was always visible. The role of hand and arm proprioceptive afferents in eye movement control, proposed by several authors (Mather and Lackner, 1980; Gauthier et al. 1988, Roll et al. 1988, Martin et al. 1991), suggest that the vibration-induced alteration of the information mediated by these pathways is most likely responsible for the changes in eye fixation error and error variability observed during and immediately after vibration exposure.

In the present context (target visible), it can be suggested that eye movement alterations result most probably from sensory noise generated by the vibratory stimulus. In fact, no specific direction in fixation shift and no obvious changes in eye movement pattern were observed. Furthermore, vibration frequency had a limited impact on eye movements. We assume that the permanent visual feedback provided by the target light counteracted most of the influence of the "distorted" hand proprioceptive information. Nevertheless, a significant decrease in signal/noise ratio introduced by the noisy proprioceptive input affected the gaze and variability of eye fixation. Despite the significance of these alterations it is important to remark that fixation errors are relatively small (0.25°), which do not compromise foveal vision of the targets.

Visual feedback of the hand

The visual feedback of the hand did not totally prevent the alteration of hand aiming position during vibration exposure. Such a "residual" effect is probably due to the fact that the hand aiming location was 7° below the visual target. As subjects were requested to focus on the visual target, the hand was beyond the limit of the foveal field, which corresponds to a solid angle of 2°. Thus, the precision of the foveal system was not available to fully compensate the vibratory effects described above. Nevertheless, peripheral vision did play a significant role, as the alterations of hand movements were more pronounced in the absence of hand visual feedback (hand masked).

Recovery after vibration exposure

The recovery of pre-vibration performance seems to be less than 5 minutes for the hand pointing when the hand is not masked and for eye fixation in all visual conditions. However, the hand pointing constant error and the increase in variability of the absolute error persist throughout the post-vibration period observed. These data show that in the absence of visual feedback, the vibration-induced bias in movement amplitude is not corrected by a recalibration of the hand controller. Such persistence of the error suggests that the pre-vibration reference is lost during vibration exposure. In the absence of a visual information the subject continues to use the last available proprioceptive information. A similar effect has been observed in an earlier study of torque control (Gauthier et al. 1981) without visual feedback. In that study, maintaining a constant torque by pressing with the foot on a pedal was biased by a vibration applied to the whole body. The increase in torque during vibration was not perceived by the subject and the torque remained higher after vibration exposure. We may assume that despite subject training, the subject may use the first series of movements performed immediately after vibration as a calibration for the subsequent series. Furthermore, the existence of long lasting phenomena inducing the persistence of muscle contraction following vibration exposure has been reported by Ghilodes et al. (1992). These authors suggested that these phenomena are related to changes in central mechanisms triggered by the vibration-induced activity of muscle spindle receptors. The contribution of these mechanisms to the delay of a recalibration of movement amplitude cannot be ruled out in the present case.

In the study of manual dexterity described before, changes in velocity control after vibration exposure were not compensated by visual feedback. Thus, since in the present case alterations in position control are compensated by vision after vibration exposure, we may assume that long lasting phenomena are affecting essentially velocity control, which requires a higher level of skill (Mc Ruer and Jex, 1967) and thus may be more easily disrupted by the perturbation of proprioceptive inputs.

Conclusions

The present findings show that hand vibration can affect pointing performance and alter the coordination of hand and eye movements. The absence of visual control of the hand has detrimental effects on aiming precision during and after vibration exposure. Although visual feedback may help to compensate performance decrement induced by vibration exposure, this compensation is not complete during the vibration period. Hence, visual control of the hand appears to be a necessary condition to limit the vibration-induced degradation of manual tasks but this condition is not sufficient. Furthermore, pointing performances seem less affected by high vibration frequencies (200 Hz). These remarks are of particular importance in the design of the workplace and powered hand tools. First, visual control of the hand holding a vibrating tool should not be interrupted in tasks requiring aiming movements. Second, high frequency vibration (> 200 Hz) are preferable since they tend to have less influence on motor performances and are easier to attenuate.

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FINAL CONCLUSIONS

Vibration characteristics and sensorimotor activities

The results clearly indicate that vibration of small amplitude (0.2 - 0.3 mm), in the 40 - 300 Hz frequency range affect the functioning of neurosensory mechanism underlying motor control, impair manual performance and oculo-manual coordination. The degradation of hand movement precision persists for several minutes after 10 minutes of vibration exposure. Furthermore, vibration frequencies greater than 150-200 Hz tend to induce less alterations.

These results indicate that in order to minimize the potential risk of injury resulting from "motor deficiencies" induced by vibration exposure, the following vibration characteristics could be suggested*:

- the displacement amplitude should be less than 0.2 mm
- the frequency should be greater than 200 Hz
- Continuous exposure should be limited in duration

This information finds application in tool and machine mechanical design and work guidelines.

* These characteristics may be context dependent. For example, the results concerning the tracking performance suggest that tasks using primarily tactile information may be less affected by frequencies higher than 300 Hz)

Vision

Visually guided tasks showed performance alterations during vibration exposure; however, visual control was efficient in compensating alterations of pointing performances after vibration exposure.

These results indicate that visual control of the hand appears to be a necessary but not always sufficient condition to limit the vibration-induced degradation of manual tasks.

Perception

Pain or discomfort perception is attenuated by vibration while the associated motor responses are facilitated. In addition, performance impairments are not properly estimated. These results indicate that subjective evaluation of vibration-induced discomfort, risk or self assessment of performance is biased by the sensory noise generated by the vibratory stimulation. Thus subjective rating of vibration exposure or exposure guidelines based on subjective discomfort may not always reflect the potential risks.

PLANNED PUBLICATIONS

Park HS. Martin BJ. Effects of hand vibration exposure on cutaneous reflex responses and stimulus perception. Scand. J. Work, Environ & Health.(submitted).

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