

Power hand tool vibration effects on grip exertions

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Operation of vibrating power hand tools can result in excessive grip force, which may increase the risk of cumulative trauma disorders in the upper extremities. An experiment was performed to study grip force exerted by 14 subjects operating a simulated hand tool vibrating at 9.8 m/s^2 and 49 m/s^2 acceleration magnitudes, at 40 Hz and 160 Hz frequencies, with vibration delivered in three orthogonal directions, and with 1.5 kg and 3.0 kg load weights. Average grip force increased from 25.3 N without vibration to 32.1 N (27%) for vibration at 40 Hz, and to 27.1 N (7%) for vibration at 160 Hz. Average grip force also increased from 27.4 N at 9.8 m/s^2 acceleration to 31.8 N (16%) at 49 m/s^2 . Significant interactions between acceleration \times frequency, and frequency \times direction were also found. The largest average grip force increase was from 25.3 N without vibration to 35.8 N (42%) for 40 Hz and 49 m/s^2 vibration. The magnitude of this increase was of the same order as for a two-fold increase in load weight, where average grip force increased from 22.5 N to 35.0 N (56%). A second experiment studied hand flexor and extensor muscle responses using electromyography for five subjects holding a handle vibrating at 8 m/s^2 using ISO weighted acceleration, with frequencies of 20 Hz, 40 Hz, 80 Hz and 160 Hz, and grip forces of 5%, 10% and 15% of maximum voluntary contraction. Muscle responses were greatest at frequencies where grip force was affected, indicating that the tonic vibration reflex was the likely cause of increased grip exertions.

1. Introduction

1.1. *Cumulative trauma disorders of the upper extremities*

This study investigated the short-term neuromuscular effects of hand tool vibration and their relation to the force exerted in hand-intensive work. Forceful exertions are a commonly cited factor of chronic muscle, tendon and nerve disorders of the upper extremities, or what are frequently referred to collectively as cumulative trauma disorders (CTDs). Strains, aches, muscle fatigue and CTDs in the upper extremities are problems of major concern for manual workers in industry (Hadler 1977, Hershenson 1979, Jensen *et al.* 1983). The costs to employees and employers include sickness, absence, premature retirement, change of job, long-term disability and effects on personal lifestyle (Hymovich and Lindholm 1966, Anderson 1971).

Carpal tunnel syndrome (CTS) is one of a family of CTDs associated with repetitive hand work. Armstrong and Chaffin (1979) showed that the use of forceful exertions, deviated wrist and pinch hand postures such as hyperextension and ulnar deviation, particularly during forceful exertions, were associated with CTS. The prevalence of upper extremity CTDs was estimated by Silverstein (1985) among 574 active workers from six different industrial plants who worked at least one year on jobs that required low or high levels of force and repetitiveness. Hand and wrist CTDs were strongly

associated with forceful and repetitive work and to a lesser extent associated with high repetitiveness or high force alone. The odds ratio for jobs involving high levels of force, repetition and vibration, versus control jobs was 11.3 (Silverstein *et al.* 1986).

Clinical studies by Rothfleisch and Sherman (1978) found a correlation between the incidence of CTS and the operation of power hand tools. Carpal tunnel syndrome was found in 21% of all cases examined in a group of stonecutters, tunnellers, coal miners, forest workers and grinders, having a mean vibration exposure time of 12 years (Lukáš 1982). Another group of ore miners, having 14 years mean exposure to vibration, had a 32.8% incidence of CTS. Cannon *et al.* (1981) found that the use of vibrating hand tools, in combination with forceful and repetitive hand motion, was associated with a greater incidence of CTS than was repetitive hand motion alone. To a lesser extent, repetitive motion tasks involving the wrist were also associated with the incidence of CTS (odds ratio 2.1) but were not as strongly associated with the onset of the disease as was the use of vibrating hand tools (odds ratio 7.0). Cannon *et al.* (1981) concluded that the use of vibrating hand tools and repetitive movements of the wrist jointly contributed to the incidence of CTS.

1.2. Tonic vibration reflex

As early as 1860, Rood (1860) observed that when a rod vibrating at a frequency between 40 Hz and 60 Hz was grasped, a feeling of numbness was reported and the hand muscles involuntarily contracted. Bianconi and Van Der Meulen (1963) reported that primary muscle spindles having high-conduction velocity afferents (above 70 m/s) were highly responsive to vibration. Using decerebrate cat preparations, Matthews (1966) attached a vibrator to the fully innervated soleus muscle tendon. The result was a reflex response producing a contraction of several hundred grams tension. Matthews concluded that primary afferent endings of muscle spindles were the receptors whose excitation leads to the reflexive response.

The motor effects of vibration were confirmed in humans by Hagbarth and Eklund (1965). They observed that if a muscle was initially moderately active, vibrating its tendons caused a gradual increase in activity and a simultaneous decrease in the activity of its antagonists. The result was either slow joint movement or a corresponding change in active tension. Subjects were able to prevent or counteract the movements voluntarily, especially if allowed to see the extremity position during the experiment. However, changes in active force induced by vibration were not correctly perceived and were usually underestimated.

Tonic vibration reflex (TVR) was the term used to describe these phenomena by Lance *et al.* (1966). Tonic contraction usually started a few seconds after application of vibration at a frequency of 50 Hz. The tonic contraction increased progressively until a plateau was reached after about 30 s. The TVR was reported for subjects of varying ages including newborn babies and persons more than 70 years old (Eklund and Hagbarth 1966). A strong TVR in the long finger-flexor muscles was induced if the volar surface of the finger tips was actively pressed against the vibrator. In some cases, the contraction of the finger flexors was so strong that it was hard to overcome by voluntary effort.

Muscular reactions to a pneumatic hammer were studied by Carlsoo and Mayr (1974). Recoil produced muscle stretching, triggering a reflex contraction similar to the monosynaptic stretch reflex. This was frequently observed in the elbow flexor muscles and their presence was dependent upon the posture assumed while operating the tool.

1.3. Confounding CTS and vibration syndrome

Hand and arm vibration syndrome is the collective term for symptoms produced from prolonged and repeated exposure to hand tool vibration. The symptoms include vascular disorders (Taylor and Pelmeur 1975), bone alterations (Kumlin 1970, Kumlin *et al.* 1973), joint deformations, neurological disturbances, soft tissue damage and other miscellaneous abnormalities (Hasan 1970). Often the effects of CTS and hand and arm vibration syndrome are confounded (Brammer 1984). Epidemiological studies of degenerative changes in the hand-arm system caused by vibration have come across problems in differentiating between the effects of vibration and those of heavy manual work involving constant, repetitive movements of the hands and arms to manipulate the tool and work piece.

Peripheral nerve damage may result from a primary lesion caused directly by vibration or indirectly through a secondary disturbance due to damage to the circulatory or musculoskeletal systems (Lukáš 1970). Lukáš used antidromic stimulation of sensory fibres to obtain neurograms from the ulnar and median nerves of workers occupationally exposed to hand and arm vibration. Isolated pathology was often observed in only one of the nerves tested, and seldom in both nerves. The prevalence of mononeural lesions indicated that damage associated with hand and arm vibration is indirectly caused. Awkward hand postures during work may have explained not only the subjective symptoms, but also the pathological changes resulting from compression of the nerve bundles. However, these symptoms did not occur in isolation and were often accompanied by other signs of lesions of the musculoskeletal system. The force applied while holding tools and postural requirements of the job often required a firm grip on the tool handle, subjecting the wrist to considerable stress. Lukáš (1970) questioned if this was the reason why the symptoms of CTS among vibration-exposed workers were often diagnosed.

1.4. Investigative approach

Operation of vibrating hand tools and forceful exertions have repeatedly been shown to be causative factors of CTDs of the upper extremities. Previous investigators studying the biomechanics of human hand vibration transmission have recognized the significance of hand force (Pyykkö *et al.* 1976, Reynolds 1977) but treated force as an independent variable. Teisinger (1972) found that less skilled workers, who grip tool handles too firmly, are more frequently damaged by vibration and attributed such findings to increased transmission to the hand and arm. The literature also indicates that vibration exposure can affect muscular contraction in the form of the TVR. However, quantitative measurements of vibration effects on grip exertions have yet to be studied. This study investigates these effects of vibration on hand force in order to gain further understanding of the relationship between operation of a vibrating hand tool and CTDs.

Two experiments were performed in this investigation. The first experiment measured the effect of hand tool vibration (acceleration, frequency and direction) and tool weight on grip force. The second experiment studied the effect of vibration on the contraction of extrinsic hand flexor muscles and extensor muscles in the forearm while grip force was controlled using electromyography.

The experimental conditions were designed to maximize these effects, representing tools, such as grinders or sanders, that are typically operated for 20 s cycles or longer. Vibration magnitudes, frequencies and load weights were also selected to include a variety of the characteristics of these tools (Radwin *et al.* 1986).

2. Methods

2.1. Apparatus

An apparatus was designed and constructed to simulate power hand tool use under controlled conditions of vibration exposure, frequency, magnitude, direction, posture and load weight. The block diagram of the hand tool simulator is presented in figure 1. Its major components included a vibration generator, vibration control system, counterbalance system, handle and data acquisition system.

A Vibration Test Systems (Aurora, Ohio) model VTS-100 electrodynamic vibrator generated the vibration stimulus. The system power amplifier consisted of a modified Crown-Tecron model 5530 power supply amplifier capable of supplying 310 W power. The vibration control system components consisted of a Trig Tek (Anaheim, California) model 801B controller and a Trig Tek model 610B vibration monitor in the controller acceleration feedback loop. The acceleration feedback transducer was an Endevco model 2217E accelerometer mounted on the vibrator handle platform stage. A Wavetek model 132 signal generator produced the input signal.

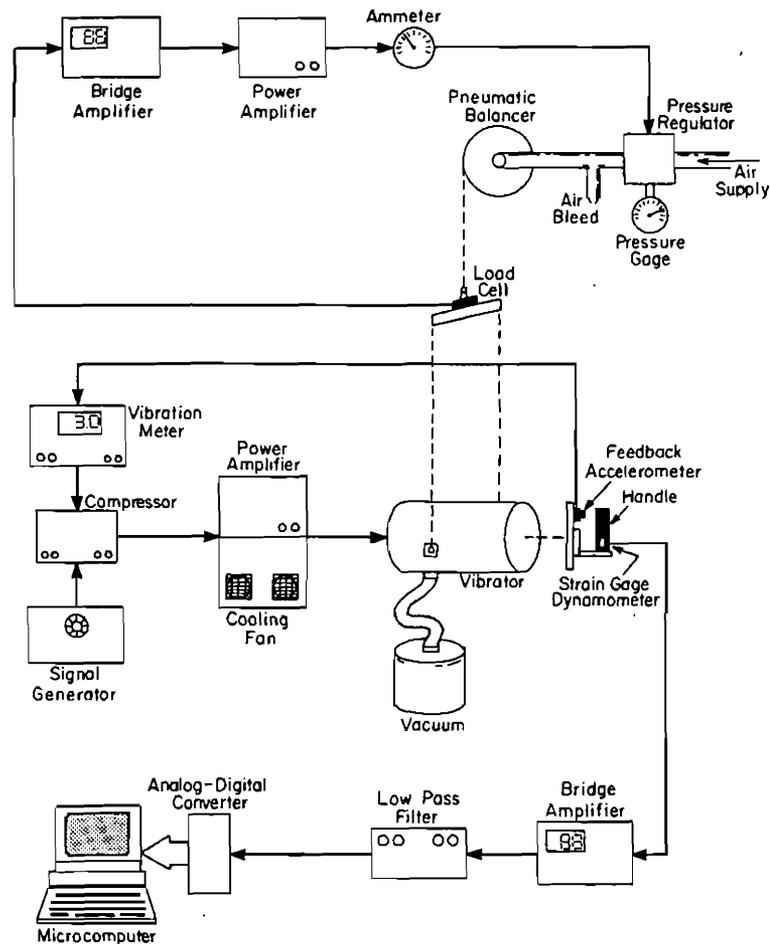


Figure 1. Hand tool simulator block diagram.

Power tool operation often requires support of a load of several kilograms using the hand and arm (Radwin *et al.* 1986). It was important that hand and arm loading resembled musculoskeletal loading when handling power tools. This is because vibration transmission to the hand and arm depends on their stiffness and because muscular responses can depend on muscular loading. Since the vibrator weight was in excess of 26 kg (58 lb), a counterbalance was necessary to simulate loading the hand and arm at portable power hand tool loads. The servo system compensated for external force disturbances at the simulator handle, introduced when subjects handled the apparatus. The balancing system was developed using a Zimmerman (Madison Heights, Michigan) Module-Air pneumatic balancer having 549 N (150 lb) capacity. A pressure regulator attached to the balancer air-inlet controlled the balancing counter force. The vibrator was suspended from the pneumatic balancer wire cable (see figure 2). The load cell provided feedback to the pressure regulation loop to compensate for the effect of friction, which was extremely variable, and other possible external disturbances.

The load weight was adjusted using weights attached to the simulator after the counterbalance was set to its force equilibrium state. Aluminium cylinders were filled with lead shot, calibrated to the appropriate weights, and closed at both ends using

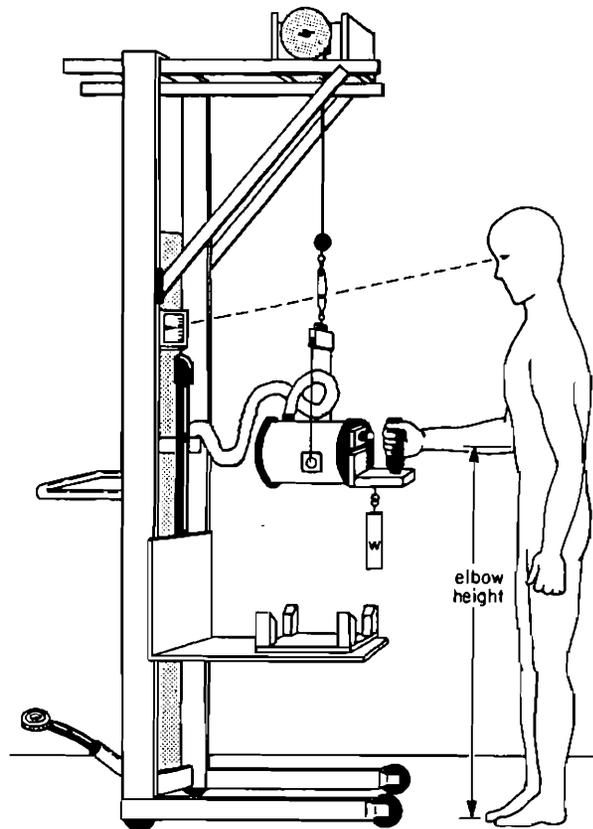


Figure 2. Subjects gripped the simulator handle, which was attached to the electrodynamic vibrator. The vibrator was suspended from the servo counterbalance cable, mounted overhead. Weights (w) were attached to the handle to control load weight.

rubber stoppers. Each cylinder had the same dimensions so that appearance would not indicate the load. Load weights were calibrated into half steps and used in pairs to distribute the load evenly (see figure 2).

The International Organization for Standardization (ISO) basicentric coordinate system (ISO 1984) was used to indicate direction. The coordinates were measured relative to the hand, while it was grasping a cylindrical handle, and in the same plane as the handle. Figure 3 shows the three handle configurations and the corresponding vibration direction coordinates (x , y , z). A quick-release stage was mounted on the vibrator platform to permit handle attachment in any one of the three configurations. The stage was designed using a keyed aluminium block held in position using a cam-controlled jam mechanism. The quick-release stage allowed handle configuration changes in less than 2 min.

Grip force was measured using a strain gauge dynamometer built into the handle. Its design was based on the strain gauge system described by Pronk and Niesing (1981). This strain gage measured the transverse force acting within a beam that caused a

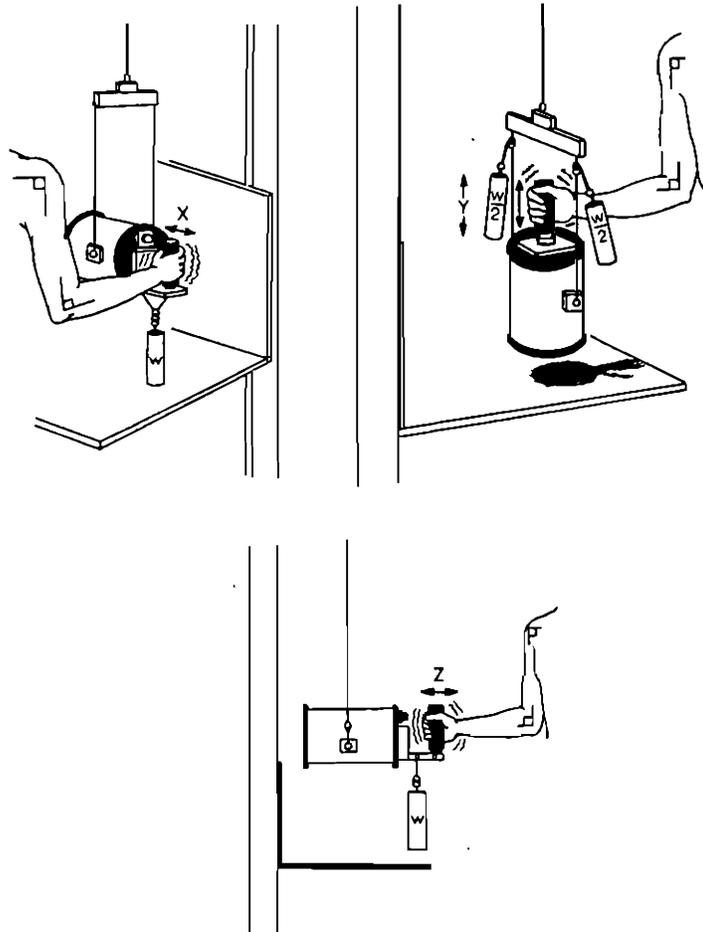


Figure 3. Three orthogonal handle configurations and vibration directions (x , y , z) corresponding to the ISO basicentric coordinate system for hand-transmitted vibration.

shearing stress in the cross-section which was independent of the point of application. The grip compression force output was low-pass filtered using an Ithaco (Ithaca, New York) model 4211 filter, set for a 5 Hz cutoff. This prevented sample aliasing effects during digitization using an analog-to-digital converter (ADC) and eliminated artifacts in the grip force signal caused by vibration of the handle. The dynamometer was calibrated by suspending weights from the handle in the plane of greatest sensitivity. Calibration was performed prior to every experimental session.

2.2. Subjects

All subjects were solicited by posting announcements on bulletin boards in university buildings and classrooms. The criterion of acceptance required subjects who were healthy young adults, had no history of neuromuscular or vascular disorders, had not suffered injuries to the upper extremities and had no prior occupational experience operating power hand tools. Subjects were paid for their participation on an hourly basis.

Each subject was presented with a brief description of the experiment, administered a questionnaire to determine their qualifications and signed an informed consent form. Hand grip strength was measured prior to and immediately following an experimental session. The maximal voluntary contraction (MVC) was measured using a Preston hand dynamometer with a span set to the diameter of the shaker handle and assuming a hand and arm posture equivalent to that experienced in the experimental procedure. Subjects performed two exertions and the average was used.

Fourteen subjects participated in the first experiment. Seven were females and seven were males. Five subjects participated in the second experiment. Three were males and two were females. All subjects were right-handed individuals.

2.3. Experiment 1: hand grip exertions

Mean grip force was measured under controlled conditions of tool weight, vibration acceleration magnitude, frequency and direction, using a $2 \times 2 \times 2 \times 3 + (1 \times 2 \times 3)$ (weight \times acceleration \times frequency \times direction + [no-vibration \times weight \times direction]) factorial experimental design. Each subject experienced each of 30 experimental conditions and served as their own controls. The loads were 1.5 kg and 3.0 kg. Vibration root mean square (RMS) amplitude levels were 9.8 m/s^2 (1 g) and 49 m/s^2 (5 g) for vibration frequencies of 40 Hz and 160 Hz. These conditions were selected because sinusoidal vibration at frequencies between 35 Hz and 150 Hz were considered adequate to represent vibration produced by selected power hand tools surveyed in the automotive industry (Radwin *et al.* 1986). Vibration was delivered in each of the three ISO (1984) basicentric orthogonal coordinate directions. A control condition consisting of *no-vibration* was also included for each of the loads and three handle configurations.

Subjects were instructed to hold the handle with the dominant hand using a power grip. They were allowed to select finger positions that felt comfortable and easily reproduced. The hand grip was inspected to ensure good contact with the palm. Once grip posture was determined, the location of the knuckles was marked using a grease pencil. A thin cord bead was taped to the handle and subjects were instructed to use the bead as a landmark for the underside of the knuckles when grasping the handle to control for dynamometer direction sensitivity variations. The experimenter visually monitored the grip during each trial to check for consistency between trials.

Subjects held the handle while standing in front of the hand tool simulator (see figure 2). A mark was placed on the floor to indicate standing distance from the simulator for each subject. The simulator was held using a 90° elbow angle, measured using a goniometer, with the upper arm parallel to the torso. A marker was suspended from a string to indicate the necessary height to raise the forearm and reproduce the desired elbow angle.

Before the experiment began, a practice session was held consisting of four trials. Each subject practised under the same conditions in the same order. The practice order was the *x*-axis configuration *without* vibration, and the *x*, *y* and *z* axes handle configurations *with* vibration at a magnitude of 29.4 m/s² (3 g) and frequency of 80 Hz. The practice load was 2.25 kg. After practising under all these conditions subjects were questioned whether additional practice was needed. If the answer was *yes* the practice sequence was repeated.

At the beginning of the experiment, subjects were asked to wash their hands using soap and water. They were also provided with paper towels and reminded to wipe their right palm dry before lifting the handle to minimize the effects of frictional changes between the hand surface and the simulator handle due to sweating.

Subjects were instructed to grasp the handle and lift and position the simulator on cue from an audio signal. They were reminded to grip the handle *in the same manner* for each trial. The grip compression force was averaged over a time window starting 20 s after the audio cue and continuing for the next 20 s. The trial proceeded for an additional 20 s, totalling 1 min. Figure 4 represents the grip compression time plot during an experimental trial.

Data from the first and last 20 s intervals were excluded from the analysis. This provided adequate time for the initial grip compression force to settle to a steady state and eliminated possible effects due to anticipation of the end of the trial. The dynamometer output was digitized using an 8-bit ADC at a sample rate of 10 samples/s. The experimenter monitored the grip response during every trial using an oscilloscope.

Each 60 s trial was followed by a 5 min rest period. The experiment totalled 30 conditions and lasted approximately 4 h per subject including preliminaries and training. Experimental conditions were presented randomly to each subject. Grip force data were log-transformed to stabilize the variance and analysed using repeated measures analysis of variance (ANOVA) in which subjects served as random-effect blocking variables.

2.4. Experiment 2: forearm EMG activity

Flexor and extensor electromyograms (EMGs) were measured while laboratory subjects grasped the simulator handle for a 3 × 4 × 3 + (1 × 3) (grip × frequency × direction + [no-vibration × grip]) factorial experiment design. Grip force levels were 5%, 10% or 15% of MVC, while the handle dynamometer vibrated at frequencies of 20 Hz, 40 Hz, 80 Hz or 160 Hz in the *x*, *y* or *z* directions. Vibration amplitude was fixed at an equivalent ISO (1984) frequency weighting acceleration of 8 m/s². The unweighted RMS acceleration amplitudes at each vibration frequency are given in table 1. Gripping a non-vibrating handle at 5%, 10% and 15% of MVC was used for controls. Each subject experienced each of 39 experimental conditions and served as their own controls. Experimental trials were presented randomly to each subject during one session lasting for approximately 4 h.

Bipolar, silver-silver chloride Hewlett Packard model 14240A electrodes were positioned 5 cm apart on the anterior and posterior sides of the forearm. Palpation for

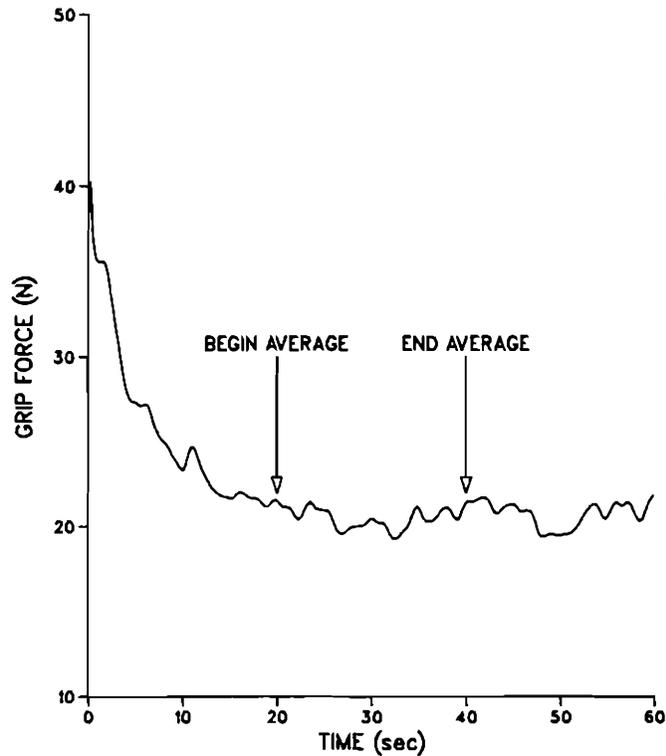


Figure 4. Representative plot of grip force over the 1 min time interval for a trial in experiment 1. Grip force was averaged during the 20 s interval following the initial 20 s of a trial.

Table 1. Equal ISO frequency weighted acceleration used in experiment 2.

Frequency (Hz)	RMS amplitude (m/s^2)
20	10
40	20
80	40
160	80

the flexor palmaris longus and carpi radialis muscles for flexor electrodes, and extensor digitorum communis muscles for extensor electrodes determined placement. EMGs were measured differentially with respect to a reference ground electrode placed on the posterior side of the forearm near the elbow. The signals were recorded using a 12-bit ADC at a sample rate of 1000 points/s for an 8 s period beginning 5 s after gripping of the handle. A Hewlett Packard model 5489A low-pass filter with a cutoff frequency of 300 Hz was used to prevent aliasing of the sampled EMG signals.

Artifacts introduced into the EMG recordings due to induced alternating current produced by the vibrator's powerful electromagnetic field were minimized using 5 cm

long electrode preamplifier cables. The induced artifacts appearing in the EMG power spectrum were typically 10 dB above the signal at the vibration stimulus frequency. A 512 point power spectrum for each EMG record was computed and power at each of the stimulus artifact frequencies, which were harmonics of 20 Hz, 40 Hz, 80 Hz and 160 Hz, including one adjacent upper and lower sideband, was eliminated from the EMG spectra to exclude artifacts at these frequencies. Total RMS power was computed by summing the power spectrum coefficients using Parseval's relation (Oppenheim *et al.* 1983). This resulted in a reduction of less than 5% of the total power spectrum while eliminating the artifact frequencies. The vibrator frequency was controlled using a voltage-controlled oscillator and DC voltage regulator to ensure reproducibility of the signal and artifact frequencies.

Grip force was controlled, providing subjects with visual feedback of the force measured from the strain gauge dynamometer in the handle. Subjects viewed a meter when gripping the handle (see figure 2). The meter sensitivity was adjusted so that it indicated centre scale at the required hand grip force.

This task was practised several times prior to testing *without* vibration until subjects felt confident that they could perform the task. Practice *with* vibration having an RMS amplitude of 40 m/s² and frequency of 80 Hz followed. This was repeated if subjects desired additional practice.

Hand and arm posture were the same as in experiment 1 except that the vibrator was stationary and was resting on the surface of an adjustable table so that load weight was not a factor. The handle location was adjusted by raising the table so that the handle was located at each subject's elbow height.

EMG total RMS was analysed using repeated measures ANOVA with subjects as a random blocking variable. The data were transformed using a square-root transformation to stabilize variances.

3. Results

3.1. Grip force

Figure 5 summarizes the relation of average grip force to vibration frequency, direction, acceleration magnitude and load weight for fourteen subjects. Significant main effects were found for weight ($F(1,13) = 145.88, P < 0.001$), acceleration magnitude ($F(1,13) = 17.73, P < 0.001$), and frequency ($F(1,13) = 48.29, P < 0.001$). No significant main effect was indicated for vibration direction ($F(1,13) = 4.03, P > 0.05$).

Grip force averaged over all experimental conditions of vibration acceleration magnitude, frequency and direction increased from 22.5 N (s.d. = 12.7 N) for the low-level weight to 35.0 N (s.d. = 12.4 N) for the high-level weight. The increase in the grip force geometric mean was 64%, having a 95% Tukey confidence interval between 48% and 80% for a doubling of the load. The magnitude of this change in grip force was equivalent to an average increase of 4% of MVC for the subjects tested.

Grip force averaged over all conditions of acceleration magnitude, direction and weight conditions was 25.3 N (s.d. = 10.1 N) for the non-vibrating handle, 32.1 N (s.d. = 17.5 N) for a handle vibrating at 40 Hz and 27.1 N (s.d. = 13.8 N) for one vibrating at 160 Hz. Averaging for acceleration magnitude effects resulted in a grip force of 27.4 N (s.d. = 13.5 N) for the 9.8 m/s² RMS and of 31.8 N (s.d. = 17.8 N) for the 49 m/s² RMS.

The smallest grip force, averaged over all conditions of weight and direction, was 25.3 N for the non-vibrating handle condition. The greatest average grip force response, 35.8 N, occurred for vibration at 40 Hz and an acceleration magnitude of 49.0 m/s². The magnitude of this increase (42%) was of the same order as that produced

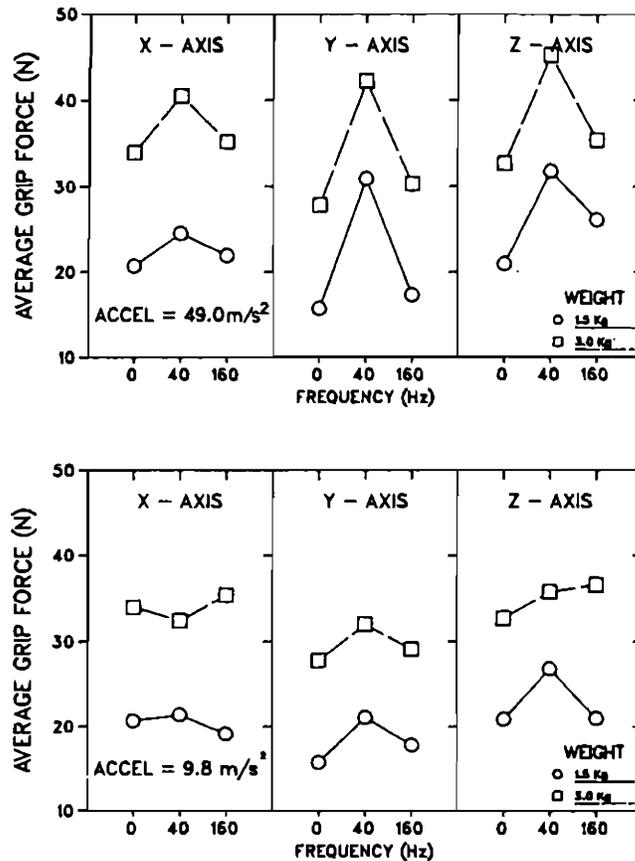


Figure 5. Average grip force (14 subjects) for each experimental condition of frequency, acceleration magnitude, direction and load weight in experiment 1.

by doubling the load weight (56%). Contrast ratios between each vibration condition and the no-vibration control condition, including upper and lower 95% Tukey confidence limits, are given in table 2.

The interaction between acceleration \times frequency was significant ($F(1,13) = 14.43$, $P < 0.01$). Average grip force increased by 7.6 N (24%) when the vibration acceleration magnitudes increased from 9.8 m/s² to 49.0 m/s² at 40 Hz vibration. A much smaller increase in grip force of 1.2 N (5%) occurred with a change in vibration magnitude from 9.8 m/s² to 49.0 m/s² at 160 Hz (see figure 6). This indicated that vibration had a sizeable effect at 40 Hz vibration at the high acceleration magnitude but not at 160 Hz vibration. Contrast ratios between the acceleration \times frequency interaction geometric means including upper and lower Tukey 95% confidence limits are provided in table 3.

The frequency \times direction interaction was also significant ($F(2,26) = 10.24$, $P < 0.001$). The frequency \times direction interaction is plotted in figure 6. Increasing vibration frequency from 40 Hz to 160 Hz was accompanied by a 4.1 N decrease in the average grip force for the y-direction and a 5.1 N decrease for the z-direction. No significant change in grip force in the x-configuration (1.9 N) was observed. This indicated that grip force was sensitive to vibration frequency differences in the y- and z-directions but not in the x-directions. Table 4 lists the contrast ratios between the

Table 2. Mean and 95% confidence limits for percentage differences in grip force between vibration and no-vibration treatments.

CI*	Vibration frequency and acceleration			
	40 Hz 9.8 m/s ²	160 Hz 9.8 m/s ²	40 Hz 49.0 m/s ²	160 Hz 49.0 m/s ²
UCL	0.48	0.35	0.83	0.42
Mean	0.10	0.00	0.36†	0.06
LCL	-0.18	-0.25	0.01	-0.21

* Confidence interval: UCL, upper confidence limit; LCL, lower confidence limit.

† $P < 0.05$.

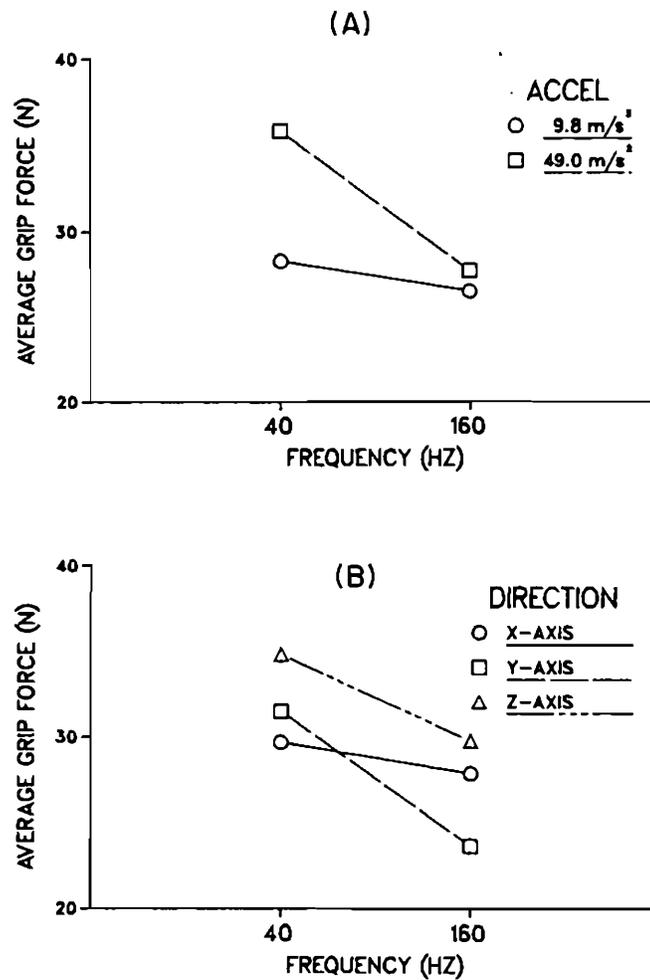


Figure 6. Interaction effects for (A) acceleration \times frequency, and (B) frequency \times direction in experiment 1 (14 subjects).

Table 3. Mean and 95% confidence limits for percentage differences in grip force between A × F interactions.

Vibration frequency and acceleration	CI*	Vibration frequency and acceleration		
		40 Hz 49 m/s ²	160 Hz 9.8 m/s ²	160 Hz 49.0 m/s ²
40 Hz 9.8 m/s ²	UCL	0.47	0.09	0.15
	Mean	0.24†	-0.09	-0.04
	LCL	0.04	-0.23	-0.19
40 Hz 49.0 m/s ²	UCL		-0.12	-0.08
	Mean		-0.26†	-0.22†
	LCL		-0.38	-0.25
160 Hz 9.8 m/s ²	UCL			0.25
	Mean			0.05
	LCL			-0.11

* Confidence interval: UCL, upper confidence limit; LCL, lower confidence limit.

† $P < 0.05$.

Table 4. Mean and 95% confidence limits for percentage differences in grip force between F × D interactions

Vibration frequency and direction	CI*	Vibration frequency and direction				
		40 Hz y-axis	40 Hz z-axis	160 Hz x-axis	160 Hz y-axis	160 Hz z-axis
40 Hz x-axis	UCL	0.38	0.50	0.20	0.03	0.30
	Mean	0.08	0.17†	-0.06	-0.20†	0.02
	LCL	-0.15	-0.08	-0.27	-0.37	-0.21
40 Hz y-axis	UCL		0.39	0.11	-0.05	0.20
	Mean		0.08	-0.13	-0.26‡	-0.06
	LCL		-0.15	-0.32	-0.42	-0.27
40 Hz z-axis	UCL			0.02	-0.13	0.11
	Mean			-0.20†	-0.32‡	-0.14†
	LCL			-0.38	-0.47	-0.32
160 Hz x-axis	UCL				0.09	0.39
	Mean				-0.14†	0.08
	LCL				-0.33	-0.15
160 Hz y-axis	UCL					0.62
	Mean					0.27†
	LCL					-0.01

* Confidence interval: UCL, upper confidence limit; LCL, lower confidence limit.

† $P < 0.10$.

‡ $P < 0.05$.

frequency \times direction interaction geometric means, including upper and lower Tukey 95% confidence limits.

Although the weight \times frequency interaction was statistically significant ($F(1,13)=12.35$, $P<0.01$), it was relatively small in magnitude. The difference in average hand grip force at 40 Hz between the low-level and high-level weights was only 1.2 N greater than at 160 Hz.

3.2. Forearm muscle EMGs

Figure 7 depicts a typical EMG RMS record for a subject gripping the handle at 5%, 10% and 15% of MVC, and vibrating at 20 Hz. Grip force effects were observed in extensor and flexor EMG data for all vibration conditions. Average flexor EMG RMS increased 68% from 0.028 mV (s.d. = 0.011 mV) for 5% of MVC to 0.047 mV (s.d. = 0.012 mV) for 10% of MVC (see figure 8). The average flexor EMG RMS increased an additional 43% to 0.067 mV (s.d. = 0.017 mV) when grip force was increased from 10% of MVC to 15% of MVC. Similarly, extensor average EMG RMS increased 50% from 0.038 mV (s.d. = 0.017 mV) for 5% of MVC to 0.057 mV (s.d. = 0.020 mV) for 10% of

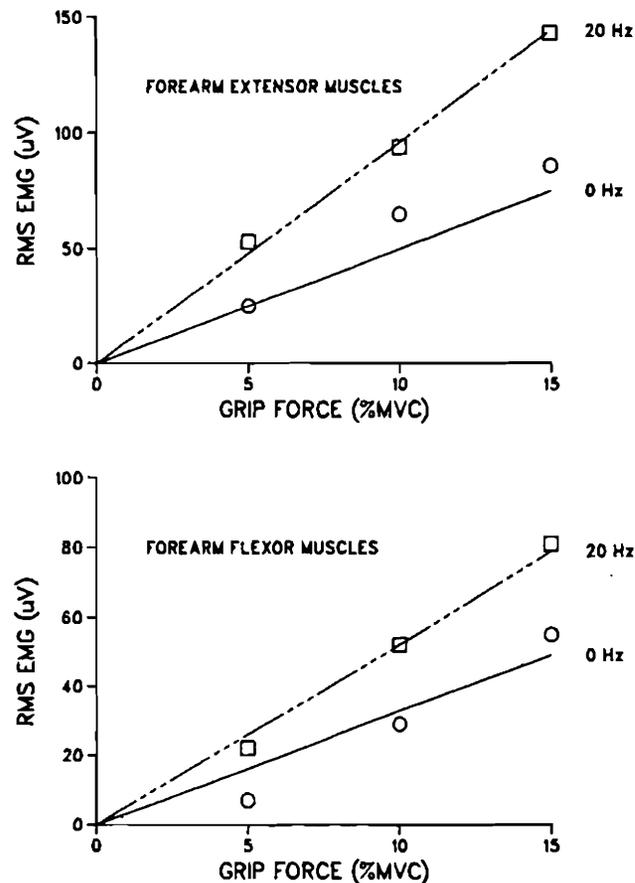


Figure 7. Typical forearm extensor and flexor EMG RMS record for a subject gripping a vibrating handle at 5%, 10% and 15% of MVC grip force in experiment 2.

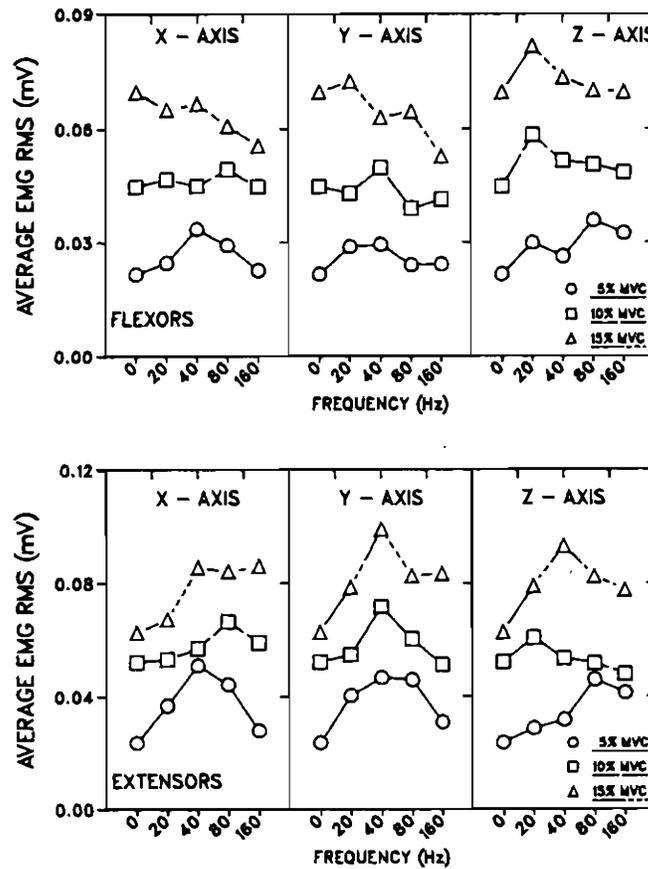


Figure 8. Average forearm extensor (bottom) and flexor (top) EMG RMS (5 subjects) plotted against frequency, direction and grip force.

MVC. Extensor average EMG RMS increased an additional 44% to 0.082 mV (s.d. = 0.028 mV) when grip force was increased from 10% of MVC to 15% of MVC.

The single greatest flexor response (mean = 0.082 mV, s.d. = 0.018 mV) occurred at 15% of MVC for vibration at 20 Hz in the z-direction. Extensors were most responsive at 15% of MVC to vibration at 40 Hz in the y- and z-directions (mean = 0.099 mV, s.d. = 0.024 mV). Smaller responses were present for lower levels of grip force (see figure 8).

A repeated measures ANOVA was performed using logarithms of the ratio between average forearm muscle EMGs recorded *with* vibration and EMGs recorded *without* vibration. These were computed for flexor and extensor EMGs and respective grip forces. The results indicated that extensor muscle EMG RMS, averaged over all conditions of grip force, vibration frequency and direction, increased by 32% (mean ratio = 1.32, s.d. = 1.52) in a forearm gripping the handle *with* vibration compared with that obtained *without* vibration ($F(1,4)=94.4$, $P<0.001$). The magnitude of this increase was comparable to the 44% increase for the effect of increasing grip force from 10% of MVC to 15% of MVC. However, flexor muscle EMG averaged over all conditions only increased 12% (mean ratio = 1.12, s.d. = 1.48) in a forearm gripping a

handle *with* vibration compared with that obtained *without* vibration ($F(1,4)=0.42$, $P>0.1$).

4. Discussion

Since activation of the TVR was considered a contributing factor of grip force, it was necessary to design a grip force measurement procedure which accounts for its presence. Lance *et al.* (1966) observed a variable latent period before tonic contraction started and reported that when the reflex was activated, muscular contraction increased progressively until a plateau was reached after about 30 s. The 20 s delay before measuring grip force allowed for development of the TVR. Results from preliminary experiments and force measurements in experiment 1 verified that grip force has stabilized after the initial 20 s and that there was little variation during the following 20 s sampling window. In addition, holding a tool for this duration was not unlike operating many abrasive hand tools such as sanders, grinders and polishers, which the experimental conditions were selected to represent.

Hagbarth and Eklund (1965) found that when eliciting the TVR by applying vibration directly to muscles, subjects did not correctly perceive changes in force. This was also observed when subjects underestimated limb position during reflex activation of the quadriceps by the TVR (Eklund 1972). In experiment 1 subjects were unaware of grip force changes since they were instructed to hold the handle *in the same manner* for each trial. No mention of grip force measurement was made to subjects who were only informed that the *mechanical system* between the handle and hand was under study to improve hand tool design.

In a previous study (Pyykkö *et al.* (1982) reported unquantified increases in grip force using strain gauges attached to vibrating metal rods occurring at displacement between 500 μm and 600 μm at frequencies between 60 Hz (1.8–2.2 m/s^2) and 250 Hz (31.3–37.5 m/s^2). They observed that a gradual increase in muscle tone developed between 0.5 min and 1 min of exposure. In this study significant grip force increases in experiment 1 occurred with vibration at 40 Hz, but not at 160 Hz for acceleration magnitudes of 49 m/s^2 .

The origin of the TVR has been attributed to the stretch reflex of muscle spindle origin (Matthews 1966). The physiological mechanism that may be responsible for the vibration acceleration magnitude effect in experiment 1 was described by Matthews (1972). Using decerebrate cat preparations and vibrating the fully innervated soleus muscle tendon, Matthews found that increasing vibration amplitude (displacement) between frequencies of 50 Hz and 300 Hz resulted in a reflex response that at first increased in strength but then reached a plateau value. Matthews (1972) speculated that the occurrence of such a plateau shows that the vibration was sufficiently powerful to drive every primary ending in the muscle to discharge an impulse on every cycle of the vibration, so that the overall Ia afferent firing becomes constant in spite of changes in the size of the vibration. Small amplitudes of vibration probably failed to produce secure driving of every ending. It is suspected that in experiment 1 vibration transmitted to the extrinsic forearm muscles had to be great enough to drive the muscle spindles in these muscles for a grip effect to occur. Therefore smaller responses are expected for lower vibration amplitudes.

Westling and Johansson (1984) found that static pinch force was approximately proportional to the weight of the object lifted. They observed that in order to maintain stability and prevent accidental slipping, the grip force had to exceed a minimum level which was determined by the friction between the object and the skin, and the vertical

lifting force. The average grip force similarly increased with increasing load in experiment 1.

In an experiment where subjects were provided with visual feedback to help them to maintain a constant grip force on a vibrating handle, Pyykkö *et al.* (1976) observed momentary changes in grip force at the start of the experiment, especially at acceleration amplitudes of 98 m/s^2 . Any increase in grip force during exposure to vibration rarely exceeded a force of 2 kp (Pyykkö *et al.* 1976). Their data showed unquantified increases in grip force for vibration at 500 Hz and 12–23 μm displacement ($3.0\text{--}5.8 \text{ m/s}^2$), 125 Hz and 130–330 μm displacement ($2.0\text{--}5.2 \text{ m/s}^2$), 80 Hz and 920–1070 μm displacement ($5.9\text{--}6.8 \text{ m/s}^2$) and 40 Hz and 650–1400 μm displacement ($1.0\text{--}2.2 \text{ m/s}^2$). Hence grip force was responsive at 40 Hz for lower acceleration levels than at the higher frequencies. They found that adaptation took place rapidly however, and test subjects did not have any difficulties in maintaining the predetermined grip force using the feedback provided. Pyykkö *et al.* (1976) attributed these observations to activation of the TVR. Increased responsiveness at 40 Hz was similarly observed in experiment 1.

Both flexor and extensor muscle EMG activity in experiment 2 increased with increasing grip force. The relation between integrated EMG and isometric grip force is well known (Lippold 1952, deVries 1968, Bouisset *et al.* 1973). Flexor and extensor muscular activity in experiment 2 were most responsive to low frequency vibration at 20 Hz and 40 Hz respectively, in the *y*- and *z*-directions at grip exertions of 15%, but not 5% or 10% of MVC, or at vibration frequencies of 160 Hz. Moderate muscular activity has been shown to strengthen the TVR (Eklund and Hagbarth 1966, Iwata *et al.* 1972). The effect of pre-loading muscles was observed in this study as well. Significant EMG effects were observed mostly at the 15% of MVC grip force level than at 5% or 10% of MVC grip.

Extensor muscle EMG RMS levels were significantly greater ($P < 0.001$) with handle vibration than without. This effect was not significant for the flexor muscles. One possible explanation is the effect of antagonist inhibition. When the quadriceps muscles were vibrated and tonic contraction was in progress, Lance *et al.* (1966) applied a second vibrator to the antagonist tendons, those of the hamstring muscles. The quadriceps contraction ceased after a short latent period. When the second vibrator was removed, the quadriceps contraction recurred.

Iwata *et al.* (1972) demonstrated that the TVR can be voluntarily inhibited, especially if visual feedback is provided. The absence of flexor effects for overall vibration conditions may also be explained by voluntary inhibition of the TVR. Overall extensor activity increased with vibration present but this did not occur for flexor muscles. Since the task required grip exertion using a constant grip force, a possible explanation for this is that activation of the TVR in extrinsic flexor muscles was inhibited due to visual feedback (Lance *et al.* 1966) and instructions to maintain a constant grip.

Increased extensor activity with limited changes in antagonistic flexor muscle activity while maintaining a constant grip may seem inconsistent at first. Since the dynamometer measured grip force, measurements were the resultant sum of the contribution of all hand and finger joints. Based on EMG studies and anatomic location analysis, Landsmeer and Long (1965) demonstrated that extensor and flexor muscles operate simultaneously during grip. When flexor and extensor muscles are loaded equally, the metacarpophalangeal joint moves towards extension and the interphalangeal joints towards flexion. Chao *et al.* (1976) showed that extensor activity

functions during pinch but acts passively in grasp to enhance joint stability. It is then possible that the resultant grip force was unchanged due to increased extensor muscle contraction.

An *et al.* (1985) measured muscle physiological cross-sectional area (PSCA) using cadaver index finger joint muscles. The flexor profundus and flexor subliminis PSCAs were approximately four times greater than those of the extensor muscles. Therefore, considering that muscle force generating potential is proportional to its PSCA, increased extensor muscle activity should have a less significant effect on grip force than that of flexors because the flexor muscle moment arm is greater than extensor muscles.

Iwata *et al.* (1972) studied the frequency dependency of the TVR in humans at constant acceleration. The vibration stimulus was applied directly to the biceps muscle. Muscular activity, measured using skin-surface electrodes, decreased as the vibration frequency increased from 6.3 Hz to 100 Hz, when low hand grip forces were applied (0–25% of MVC). The strongest biceps activity was observed for 10 Hz vibration at 25%, 50% and 75% of MVC. Dupuis *et al.* (1976) similarly observed muscular activity of the triceps muscle decrease with increasing vibration frequency from 8 Hz to 80 Hz and constant acceleration. These findings were in agreement with the results in experiment 2. Muscular activity was greater in the y- and z-directions for 15% of MVC at the low frequencies of 20 Hz or 40 Hz than at 80 Hz or 160 Hz.

Since the TVR is mediated through primary muscle spindles, a direct relation with vibration displacement was expected, as demonstrated by Matthews (1966). But when a constant acceleration magnitude is maintained and the sinusoidal vibration frequency is increased from 50 Hz to 300 Hz, the displacement decreases by a factor proportional to the square of the frequency. A decrement in muscular activity would then be expected for increasing frequency when the magnitude of acceleration is held constant.

Previous investigations of the TVR in humans were based on direct muscle stimulation, i.e. the application of vibration to muscle bellies or tendons (Eklund and Hagbarth 1966, Lance *et al.* 1966, Eklund 1972, Iwata *et al.* 1972). Eklund and Hagbarth (1966) found that the TVR was elicited most effectively when vibration was applied directly to the tendons or at the muscle bellies if the vibration amplitude was high. When a power hand tool is operated, however, vibration enters the arm through the palm and hand and is transmitted up the forearm. It is likely that vibration affecting muscular activity in the forearm when power tools are being operated depends on vibration transmissibility of the hand and arm.

Pyykkö *et al.* (1976) stated that the TVR was not observed in their study due to the activation of both flexor and extensor muscles in the hand and arm. It was their opinion that the TVR could not play an important role in working conditions as long as the acceleration level was not exceptionally high. However, this study showed an increase in hand grip for vibration levels typically found in vibrating hand tools. Increased contraction of forearm flexor and extensor muscles leads not only to increased grip exertions, but also leads to an increase in stiffness of the hand and arm while a vibrating handle is being held. This can result in increased vibration transmission to the hand and arm (Pyykkö *et al.* 1976, Reynolds (1977).

Vibration transmissibility characteristics of vibration entering the hand, and then being transmitted to the arm, resembles a low-pass filter (Iwata *et al.* 1972, Pyykkö *et al.* 1976, Reynolds 1977). Pyykkö *et al.* (1976) found that vibration attenuation was 3 dB per octave between 20 Hz and 100 Hz and 6 dB per octave between 100 Hz and 630 Hz. Therefore, 160 Hz vibration was much more attenuated than 40 Hz vibration in this investigation, resulting in a smaller response to it than to 40 Hz vibration.

Vibration transmissibility also depends on the location at which vibration enters the hand and arm. Vibration entering the hand is attenuated up the arm and elbow (Pyykkö *et al.* 1976, Reynolds 1977). Frequencies above 100 Hz are more effectively transmitted to the fingers than to the arm. This may explain why muscular response, and hand grip effects were more prevalent at frequencies of 20 Hz or 40 Hz than at higher frequencies. Vibration at these frequencies was more effectively transmitted to the extrinsic hand muscles of the forearm than was vibration at higher frequencies.

Vibration transmissibility has also been shown to be dependent on the direction of vibration. Reynolds (1977) reported that vibration at frequencies of up to 100 Hz was directed unattenuated from the point of contact at the finger and vibrating handle to the middle phalanx for vibration in the *x*-direction and to the proximal phalanx for vibration in the *y*- and *z*-directions. At frequencies above 100 Hz for vibration in the *y*-directions, and above 400 Hz for vibration in the *z*-direction, the vibration amplitudes at the backs of the fingers decreased as vibration frequency increased. The vibration levels at the third metacarpal for vibration in the *x*-direction decreased at an even faster rate, compared with those at the middle phalanx, as the vibration frequency increased. For vibration in the *x*- and *y*-directions, a notable reduction in the vibration levels between the wrist and elbow was evident at all frequencies between 5 Hz and 1000 Hz. For vibration in the *z*-direction this reduction was not present. These observations may explain why the average hand grip force at 40 Hz for the *x*-direction was less than that for the *z*-direction.

The extrinsic muscles of the hand provide the major force in the power grip (Landsmeer 1962, Long *et al.* 1970, Chao *et al.* 1976). This investigation ignored the contribution of the intrinsic muscles. Intrinsic muscles acting on the handle to provide the required grip may have contributed to noise in the flexor muscular activity measurements and to the effects observed in experiment 1.

The experiments in this investigation were performed using subjects from a student population having no experience in operating power tools. It is believed that the results reported here are relevant for a worker population as well. Pyykkö *et al.* (1982) found that activation of the TVR did not differ from that in chain-saw operators and normal control subjects who did not operate vibrating hand tools.

When the TVR was recorded simultaneously with finger pulse plethysmography (Pyykkö *et al.* 1982), the increase in muscle tone did not coincide with vasoconstriction. This led to the conclusion that the activation of muscle receptors is not associated with vibration-induced white fingers. Vibration at 80 Hz elicited a strong TVR but no vasoconstriction was observed, whereas 125 Hz vibration produced vasoconstriction but a weak TVR (Pyykkö *et al.* 1976). The absence of any relationship between vasoconstriction and the TVR suggested that neither muscle spindles nor changes in muscle tone play a major role in the aetiology of vibration white finger. These findings and the results from this study indicate that upper extremity CTDs may result from different origins than vascular disorders.

The prevalence of vibration syndrome was found to be greater among incentive workers than among hourly workers (NIOSH 1984). The characteristics of incentive work are associated with shorter latencies and increased severity of vibration syndrome. The NIOSH report suggested that a possible interpretation of this is that the intensity of incentive work, leading to increased energy transfer from the tool to the hands, contributes to these observations. It can be speculated that vibration effects on hand grip force, under the intensity of incentive work, may also have contributed to increased vibration transmission to the hand and arm, offering an additional explanation for the findings in the NIOSH report.

5. Summary and recommendations

This investigation demonstrated that occupational exposure to power hand tool vibration results in neuromuscular disturbances having potentially undesirable effects on operator health or performance. The results have provided further indication that the origin of CTDs associated with the operation of vibrating power hand tools are secondary lesions, indirectly caused from vibration effects on grip exertions. The magnitude of these effects ultimately on health, safety and performance are yet unanswered. For instance, although most ergonomics practitioners will agree that it is desirable to minimize grip force, it is not known how much grip force can be exerted without excessive risk of incurring a CTD.

This study has dealt with short-term effects of vibration exposure. These experiments did not study the effects of adaptation to the vibration stimulus. The effects of adaptation were minimized in the experimental design by having subjects rest for 5 min in between vibration exposures. It is reasonable to expect that the short-term effects observed can lead to long-term disabilities, CTDs and decreased task performance and product quality. However, the long-term effects are still unknown. An epidemiological study of the incidence of CTDs, of hand tool use, vibration exposure and grip force is recommended for further understanding of these relations and enhancement of hand tool vibration guidelines.

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Les outils manuels vibrants peuvent induire une force d'empoigne excessive et, de ce fait, accroître le risque de cumul des traumatismes des membres supérieurs. On a effectué une expérience pour étudier la force d'empoigne exercée par 14 sujets travaillant avec un outil manuel factice vibrant à des grandeurs d'accélération de $9,8 \text{ m/s}^2$ et 49 m/s^2 , à des fréquences de 40 Hz et 160 Hz dans les trois directions orthogonales et qui pesaient de 1,5 à 3,0 kg. La force d'empoigne moyenne augmentait de 25,3 N en l'absence de vibrations à 32,1 N (27%) pour les vibrations de 40 Hz et à 27,1 N (7%) pour les vibrations de 160 Hz. Cette force augmentait également sous l'influence de l'accélération: jusqu'à 27,4 N pour $9,8 \text{ m/s}^2$ et jusqu'à 31,8 N (16%) pour 49 m/s^2 . On a aussi trouvé des interactions significatives entre l'accélération et la fréquence, d'une part et la fréquence et la direction, d'autre part. La plus forte augmentation de la force (de 25,3 N à 35,8 N: 42%) a été observée pour 40 Hz et 49 m/s^2 . L'ampleur de cette augmentation était du même ordre que celle provoquée par un doublement du poids de la charge où l'accroissement induit était de 50% (de 22,5 N à 35,0 N). Dans une deuxième expérience, on a étudié la réponse électromyographique des fléchisseurs et des extenseurs de la main chez cinq sujets qui tenaient une poignée vibrant à 8 m/s^2 d'accélération pondérée par ISO et à 20 Hz, 40 Hz, 80 Hz et 160 Hz, avec des forces d'empoigne allant de 5%, 10% et 15% de la contraction maximum volontaire. La réponse musculaire était la plus importante pour les fréquences qui affectaient la force d'empoigne, ce qui indique que le réflexe tonique vibratoire est sans doute à l'origine de la force d'empoigne accrue.

Aus dem Handhaben vibrierender Handwerkzeuge können übermäßige Griffkräfte resultieren, die das Risiko kumulativ traumatischer Störungen in den oberen Extremitäten erhöhen können. Zur Untersuchung der Griffkraft wurde ein Experiment durchgeführt, bei dem 40 Personen mit einem simulierten Handwerkzeug arbeiteten: $9,8 \text{ m/s}^2$ und 49 m/s^2 Beschleunigungsintensität, Frequenzen von 40 Hz und 160 Hz, bei einwirkender Vibration in drei orthogonalen Richtungen und mit 1,5 kg und 3,0 kg Lastgewicht. Die mittlere Griffkraft stieg

von 23,5 N ohne Vibration auf 31,1 N (27%) bei einer Vibration mit 40 Hz und 27,1 N (7%) für eine 160 Hz-Vibration. Die mittlere Griffkraft stieg auch an von 27,4 N bei $9,8 \text{ m/s}^2$ Beschleunigung auf 31,8 N (16%) bei 49 m/s^2 . Ebenso wurden signifikante Interaktionen zwischen Beschleunigung und Frequenz sowie zwischen Frequenz und Richtung gefunden.

Der größte mittlere Griffkraftanstieg war von 25,3 N ohne Vibration auf 35,8 N (42%) bei 40 Hz und 49 m/s^2 .

Die Größe dieses Anstiegs war ähnlich hoch wie bei zweifachem Anstieg beim Lastgewicht, bei dem die mittlere Griffkraft von 22,5 N auf 35,0 N (56%) anstieg.

Ein zweites Experiment untersuchte Handbeuger- und Streckermuskelverhalten per Elektromyographie bei 5 Personen, die einen vibrierenden Griff bei 8 m/s^2 mit ISO gewichteter Beschleunigung hielten, bei Frequenzen von 20 Hz, 40 Hz, 80 Hz und 160 Hz und bei Griffkräften von 5%, 10% und 15% der maximalen willentlichen Kontraktion. Die Muskelreaktion war am größten bei Frequenzen, die die Griffkraft betrafen, was einen tonischen Vibrationsreflex indiziert, der wahrscheinlich Ursache für die angestiegene Griffkraft war.

手持振動工具を使用すると、握力が過度になり、上肢の蓄積傷害の危険を高める可能性がある。 $9,8$ と 49 m/s^2 の加速度、 40 と 160 Hz の周波数で3直交方向に振動していて、荷重が $1,5$ と $3,0 \text{ kg}$ の模擬手持ち工具を使用している14名の被験者の握力を調べる実験を行った。平均握力は振動のない場合の $25,3 \text{ N}$ から 40 Hz の振動で $32,1 \text{ N}$ (27%)、 160 Hz の振動で $27,1 \text{ N}$ (7%)に増大した。平均握力はまた $9,8 \text{ m/s}^2$ の加速度での $27,4 \text{ N}$ から 49 m/s^2 での $31,8 \text{ N}$ (16%)に増大した。加速度 x 周波数と周波数 x 方向との間には有意な相関関係が認められた。平均握力の最大増加は振動の無い場合の $25,3 \text{ N}$ から 40 Hz と 49 m/s^2 での $35,8 \text{ N}$ (42%)へであった。この増加は荷重の2倍増加の場合と同程度であった。後者の場合、平均握力は $22,5$ から $35,0 \text{ N}$ (56%)に増えた。2番目の実験では、 8 m/s^2 のISO加重速度、 $20, 40, 80, 160 \text{ Hz}$ の周波数で振動しているハンドルを最大随意収縮の5, 10, 15%の握力で握っている5名の被験者の屈筋と伸筋応答を筋電検査法で調査した。筋応答は握力が影響を受けた周波数で最大であった。これは緊張性振動反射が握力増加の原因と考えられることを示している。

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