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ABSORPTION OF VIBRATION ENERGY IN THE HUMAN HAND AND ARM

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Abstract

The risk assessment of hand-arm transmitted vibration is today based on measurements of the magnitude, frequency spectra and duration of the vibration stimuli. It is, however, reasonable to assume that the detrimental effects might depend on the vibration energy absorbed by the hand and arm. Therefore, the aims of this thesis have been to; (i) examine the mechanical and energy absorbing properties of the hand and arm during vibration exposure, (ii) perform theoretical calculations of the amount of absorbed energy, (iii) compare the calculated results with direct measurements.

The results show that the mechanical and energy absorbing properties depend on the frequency and direction of the vibration stimuli. Higher vibration levels, as well as more firm handgrips, resulted in higher impedance and absorption of energy. The constitution of the hand and arm also affected the results to a large extent whereas the varying hand-arm postures had only a small influence. Using the vibration characteristics for a certain tool and the mechanical properties of the hand and arm, a good agreement between theoretical calculations and direct measurements of the amount of absorbed energy could be established. Furthermore, the shape of the frequency spectra for the energy absorption was found to be unequal for different vibration directions and not in accordance with the currently used frequency weighting routine.

Finally, the findings support the idea that future standards for risk assessment of vibrations should rather be based on the energy absorption concept.

Key words: Vibration, Hand-arm, Energy absorption, Mechanical impedance, Risk assessment, Measurement technique, Standard

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PREFACE

This thesis is based on the following papers, which will be referred to by their Roman numerals:

I Lundström, R. & Burström, L.: Mechanical impedance of the human hand-arm system. International Journal of Industrial Ergonomics 3 (1989) pp 235-242.

II Burström, L. & Lundström, R.: Mechanical energy absorption in the human hand-arm exposed to sinusoidal vibration. International Archives of Occupational and Environmental Health 61 (1988) pp 213–216.

III Burström, L.: Measurements of the impedance of the hand and arm. International Archives of Occupational and Environmental Health (In press).

IV Burström, L: & Lundström, R:. Absorption of vibration energy in the human hand and arm. Ergonomics (Accepted for publication).

V Burström, L.: Measurement of the mechanical energy absorption in the hand and arm whilst using vibrating tools (Submitted for publication).

CONTENTS

APPENDICES (PAPERS I - V)

INTRODUCTION

The Hand-Arm Vibration Syndrome

The term "vibration syndrome" is often used collectively for the symptoms associated with prolonged and repeated exposure to vibration from hand-held tools or industrial processes in which vibration enters the hands. These symptoms, including vascular disorders, bone alterations and joint deformations, neurological disturbances as well as muscle disorders, have also been recognized as an important occupational disease (Taylor 1988).

The conditions known as "Vibration Induced White Fingers (VWF)", "Traumatic Vasospastic Disease (TVD)", "Raynaud's Phenomenon of Occupational Origin" and nowadays "Hand-Arm Vibration Syndrome (HAVS)" is a disease of the fingers and hands with both peripheral vascular and neurological symptoms. The peripheral vascular symptoms commonly known as "white fingers" have attracted most attention and are the best documented of the diseases (Taylor 1974). It has also been suggested that there are synergistic effects between vibration exposure and low temperature, noise, manual static work as well as emotional stress which may contribute to the disturbances (Brammer et al. 1972, Dupuis & Gemne 1985, Pekkarinen & Starck 1986, Pyykkö et al. 1986, Starck 1984a, b).

Neurological disorders, such as disturbances in the sense of touch, decreased temperature sensitivity, as well as fatigue and neuropathy, accompanied by cramp-like pains in the extremities, have been observed in workers exposed to vibration (Bovenzi et al. 1980, Brammer et al. 1986, Ekenvall et al. 1986, Hasan 1970, Klimkova-Deutschóva 1966, Nilsson et al. 1989, Partanen et al. 1970). Histopathologic observations in finger biopsy have also shown that vibration exposure causes degeneration of sensory nerves and tactile organs (Takeuchi et al. 1986). Furthermore, the incidence of carpal tunnel syndrome have been attributed to the use of vibrating hand-held tools and to the position of the hand and wrist during the performance of work (Cannon et al. 1981, Chatterjee et al. 1982, Rothfleisch & Sherman 1978).

Bone and joint disorders is another of the lesions associated with vibration exposure (Bovenzi et al. 1987, Iwata 1968a, b, Kumlin et al. 1973, Laitinen et al. 1974, Malchaire et al. 1986). On the other hand some investigations have found that these disorders are not specific for the vibration exposure (for refs. see Gemne & Saraste 1987).

Muscle atrophy has occasionally been reported in association with vibration exposure, and reduced grip force and abnormal muscle fatigue have been found among users of vibratory tools (Färkkilä et al. 1979, Färkkilä et al. 1980, Färkkilä et al. 1982, Hellström & Lange-Andersen 1972, Korhonen et al. 1977, Leong et al. 1986, Marshall et al. 1954, Matsumoto et al. 1977, Pyykkö et al. 1978). Furthermore, changes in the chemical composition of the blood have been noticed (Hasan 1970, Ivanovich et al. 1985, Iwata et al. 1973, Men'shov & Baranova 1978, Moncada et al. 1977, Okada et al. 1971, Okada et al. 1982).

The risk assessment

Little is known about the pathological basis of the vibration syndrome (NIOSH 1984) or the influence of specific attributes of vibration, for instance the acceleration or the frequency spectrum. Epidemiological evidence has shown, however, that there is a positive correlation between the total time of exposure and the severity of vibration white fingers, which suggests that the trauma could be cumulative (Hempstock & O'Connor 1975, Nilsson et al. 1989, NIOSH 1989, Taylor et al. 1975). Although symptoms of the Hand-Arm Vibration Syndrome have been documented in many occupations, few dose-response relationships have been derived from epidemilogical data (Brammer 1982a, Futatsuka 1984, Griffin 1982). During the last forty years a number of proposals for recommended safe exposure limits have been presented (for refs. see Louda & Lukas 1977). These proposals are most commonly limited to the relationship between the first appearance of white fingers and measurements of the vibration frequency as well as the vibration level of the object that is grasped by the hand (Hempstock & O'Connor 1975).

The establishment of a quantitative relation between the vibration exposure and the development of the vibration syndrome was achieved by frequency-weighting each vibration component with a function based on a contour of equinoxious frequencies (von Gierke 1971). This contour was formed by combination of vibration amplitudes and frequencies that represent equal risk for causing white fingers. By using this frequency-weighting procedure it was possible to develop a fairly good relationship between the vibration exposure and early stages of the vibration syndromes (Brammer 1982a, b).

The International Standard ISO 5349 (1986) "Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration" specifies general methods for measuring and reporting hand-transmitted vibration exposure. The standard also provide guidance as regards the assessment of hand-arm vibration in accordance with the earlier mentioned frequency-weighting procedure and dose-response relationship. According to this standard, risk assessments should be based upon the vibration direction which gives the largest broad-banded frequency weighted acceleration levels within the frequency range of 5 to 1500 Hz. The dose-response relationship presented in the annexes to ISO 5349 is primarily based on the dose of frequency-weighted energy equivalent acceleration for a period of four hours exposure per day and the response, defined as the onset of vascular symptoms in form of finger blanching. The relation between average latency interval for finger blanching and a single value for the frequency-weighted acceleration for population groups has then been calculated.

However, a number of recently conducted investigations have presented results which diverge from the dose-response relationship presented in the standard (Brubaker et al. 1986, Engström & Dandanell 1986, Futatsuka et al. 1984, Nilsson et al. 1989, Pelmear et al. 1986, Rodgers et al. 1982, Starck et al. 1982, Starck & Pyykkö 1986). Some of them have shown shorter and some longer latency intervals for finger blanching than the standard predicts. Furthermore, the higher frequency limit has been questioned, since investigations have shown that vibrations with high frequencies, above

1 kHz, also have a detrimental effect on the operators (Lundström 1985a, Lundström & Lindmark 1982). Some evidence has also been reported which indicates that the impulsiveness of vibration is an additional factor in the development of vibration syndrome (Broyde et al. 1989, Starck 1984b) and that the assessment should be based upon the sum of vibrations in all the three directions (Mishoe & Suggs 1974, Pelmear et al. 1986). NIOSH (1989) has also concluded that the use of the frequency-unweighted acceleration is a more appropriate means of assessing the health risk to exposed workers. Moreover, it has been shown that the neurological and peripheral vascular symptoms may develop independently and at different rates (Brammer 1986, Brammer et al. 1987, Färkkilä 1986, Harada & Matsumoto 1982, Pelnar 1986, Pyykkö 1974, Stewart & Goda 1970).

Another way to develop a relationship between the vibration exposure and caused injuries may be to study the absorption of mechanical energy in the hand and arm. From a hygienic point of view the physical characteristics of vibration (frequency, magnitude, duration) are discussed most often in the literature (for references see Brammer 1982b), although it is stated in ISO 5349 that other factors can influence the effects of vibration. The physical characteristics very much depend on the type of vibration source, the properties of machined materials, and also on the conditions surrounding the vibration exposure, at least with respect to vibration direction, grip force, static force and the posture of the hand and arm as well as the body. Acceleration is a useful and convenient quantity to measure, but the damage done to the hand is more likely to depend upon the rate with which energy is dissipated in the hand-arm system than upon the acceleration alone (Anderson & Boughtflower 1978, Cundiff 1976).

In a couple of investigations, dissipated or absorbed power has been measured and evaluated in order to study the effects of vibration on humans (Lidström 1977, Pradko et al. 1965, Razumov et al. 1967). This energy point of view encompasses a greater complexity of the biological effects of vibration than acceleration does, because the influence of grip force and applied force as well as hand-arm position could partially be taken into account. For whole body vibration at low frequencies a correlation between power absorption and a subjective feeling of discomfort has been shown (Pradko et al. 1965). The same results have also been found for the hand and arm where a correlation seems to exist between subjective annoyance data and absorbed energy (Reynolds et al. 1977). Furthermore, an epidemiological study has shown that the prevalence of vibration induced white fingers was related to the amount of energy absorbed by the operators (Lidström 1976, Lidström 1977). Based on these investigations, it can be concluded that measurements of the energy absorbed in the hand and arm may be a better and more objective method for risk assessment of hand-transmitted vibration.

The energy flow can, from a physical point of view, affect the human hand and arm in two ways, through motion or through heat, depending on the nature of the energy. The hand and arm are elastic systems capable of storing both potential and kinetic energy. Potential energy is stored as a result of the relative compression or extension of tissues. Kinetic energy results from the motion of the tissues in the hand and arm (Miwa 1967a, b, c, Miwa 1968a, b, c, d, Reynolds 1977, Reynolds & Angevine 1977, Reynolds & Jokel 1974). In an ideal system, i.e. without damping, the vibration results in the transfer of energy between the hand-arm system and the tool handle, where the average transfer of energy is zero. However, several investigators have found that the hand and arm in fact constitute a highly damped system (Abrams & Suggs 1971, Reynolds 1977, Reynolds & Soedel 1972). This damping ability results in absorption of part of the energy due to heating effect in the tissues. It is, however, unlikely that sufficient heating would occur to cause the local damages which have been observed after vibration exposure, except during long term exposure or at very specific resonances (Suggs 1974). It is more likely to assume that most of the energy probably is absorbed due to the relative motion between different tissues, muscles and skeletal systems of the hand and arm. This motion leads to an absorption of heat and if the motion is too powerful, physical damage or modification of the system will occur (Reynolds & Keith 1977). In principle it is therefore reasonable to assume that the occupational diseases, associated with work with hand-held vibrating tools, to a large extend must be related to the absorption of vibration energy (Cundiff 1976, Lidström 1977, Pradko et al. 1965).

It should be noted that the terms "power" and "energy" are interchangeably used in this thesis. They are, however, in a strict definition not equivalent, since power is energy per unit time. Therefore, energy absorption means the energy transferred from a tool and absorbed in the hand and arm over a given time (i.e. power).

Theory for vibration energy estimation

The amount of energy the hand and arm are exposed to is equal to the scalar product of the force (F) and velocity (v). The general energy concept is ordinarily used in conditions where the motion is linear (Model & Heimann 1978, Molloy 1957, Weis et al. 1964) and for the sinusoidal vibration expressed as follows:

$$P(t) = \overline{F(t)} \cdot \overline{v(t)} \tag{1}$$

or

$$P(t) = \hat{F} \cdot \sin(\omega t) \cdot \hat{v} \cdot \sin(\omega t + \varphi) \tag{2}$$

where $\hat{F}$ and $\hat{v}$ are peak value for the force and velocity, respectively, φ the phase angle between the force and velocity vectors and ω the angular frequency. The average transferred energy per unit time to the hand-arm system during the time-period T can be expressed as:

$$P_{(avg)} = \frac{1}{T} \cdot \int_0^T \overline{F(t)} \cdot \overline{v(t)}\, dt \tag{3}$$

In the case of sinusoidal vibration the power could be calculated by measuring the parameters needed for solution of the above equation. In the case of non-sinusoidal vibration it is necessary to resolve the force and velocity wave forms into a finite (Fourier) series of sinusoidal components and for transient vibration to break the aperiodic wave form into an infinite series of sinusoidal components (Weis et al. 1964). In the case of random excitation it is necessary to use cross-correlation for determining the power as follows (Bendat & Piersol 1986):

$$R_{Fv}(\tau) = \frac{1}{T} \cdot \int_0^T \overline{F(t)} \cdot \overline{v(t+\tau)}\, dt \quad (4)$$

where τ is the time differences between the force and velocity signal. If the signals are measured simultaneously the time difference τ is zero which gives:

$$R_{Fv}(0) = \frac{1}{T} \cdot \int_0^T \overline{F(t)} \cdot \overline{v(t)}\, dt \quad (5)$$

This is the same as equation 3 and could be presented in the frequency domain as the cross-spectrum. The cross-spectrum is normally complex, with one real and one imaginary component, and could be expressed as:

$$G_{Fv}(\omega) = 2 \cdot \int_{-\infty}^{\infty} R_{Fv}(\tau) \cdot e^{-j\omega\tau}\, d\tau = C_{Fv}(\omega) - jQ_{Fv}(\omega) \quad (6)$$

where C is the coincident spectral density function (co-spektrum) and Q the quadrature spectral density function (quad-spectrum) (Bendat & Piersol 1986). The real component of the equation reflects the energy absorbing part of the system, due to the transformation into heat by inner friction within the tissues. The imaginary component reflects the energy storing part of the system which does not consume any vibration energy (Anderson & Boughtflower 1978). This indicates that if the phase angle between the force and velocity signals is close to zero, most of the energy transferred to the hand is absorbed by the system. On the other hand, if the angle is close to 90° most of the energy is stored in form of kinetic and potential energy.

Another way of estimating the absorption of energy in the human hand and arm is by using the mechanical impedance. The impedance (Z) is defined as the complex ratio of the force vector (F) to the velocity vector (v) (Bekesy von 1939, Hixon 1976, ISO 5982 1981, Keidel 1956):

$$Z(t)= \frac{\overline{F(t)}}{\overline{v(t)}} = \frac{\hat{F} \cdot \sin(\omega t)}{\hat{v} \cdot \sin(\omega t + \varphi))} \tag{7}$$

The equation shows that the mechanical impedance is a complex quantity with magnitude and phase, but it is not a phasor since it does not symbolize a quantity that varies sinusoidally with time. It is instead a function of the parameters of the mechanical system and the angular frequency (ω) of the force input (Coermann & Okada 1964). The mechanical impedance is also deterministic of the mechanical power transferred from the environment to the human, and the impedance is essentially a description of the energy flow. The real and imaginary parts of Z have significant meaning as regards power dissipation in the physical system. The real part of Z, i.e. $Z \cdot \cos(\varphi)$, which is related to the damping coefficient, is proportional to the amount of power which is actually dissipated by the system in the form of heat. The imaginary part of Z, i.e. $Z \cdot \sin(\varphi)$, is due to components of the system which dissipate no power but simply store and release energy, either in the potential or the kinetic form.

For random excitation the impedance can be determined by use of the auto- and cross-correlation (Bendat & Piersol 1986):

$$Z(t) = \frac{\overline{F(t)}}{\overline{v(t)}} = \frac{\frac{1}{T} \cdot \int_0^T F(t) \cdot v(t+\tau)\, dt}{\frac{1}{T} \cdot \int_0^T v(t) \cdot v(t+\tau)\, dt} = \frac{R_{Fv}(\tau)}{R_{vv}(\tau)} \tag{8}$$

One main application of impedance testing is as a basis for identifying resonances, stiffness, damping characteristics and other system dynamics in order to construct analytical models to represent the vibration response of the structure. This is possible because the modulus of the impedance can be decomposed into a large number of separate elements, consisting of masses, springs and viscous dampers. Mechanically, the human body, as well as the human hand and arm, can also be broken down into a numerous number of separate elements consisting of masses of various structures and sizes, i.e. different bone structures, muscle groups, blood vessels etc., held together by different kinds of springs and viscous dampers (Coermann & Okada 1964, Hixon 1976, Lundström 1984, Olesen & Randall 1979, Reynolds & Keith 1977). It would be a hopeless task to give an exact description of this complex system with respect to all kinds of excitation of the whole frequency range, not forgetting the fact that there is a great variation as to the individual. Biodynamic models for the human body have, however, been constructed by several authors (for example Coermann 1962, Coermann & Okada 1964, Dieckmann 1958, Dieckmann 1959, Edwards & Lange 1964, Franke 1951, Muksian & Nash 1974, O'Hara 1966, Sandover 1971, Suggs et al. 1969, Vogt et al. 1968, Vogt et al. 1973, Weis et al. 1964) and have also been authorized in two international standards (ISO 5982 1981, ISO 7962 1987). For the hand and arm no international standard has been presented, but in the working-group ISO/TC 108/SC 4/WG 5 - "Biodynamic modelling" - such a standard is in preparation. In the literature, many more or less sophisticated hand-arm models can be found (Abrams & Suggs 1971, Abrams & Suggs 1977, Agate et al. 1946, Byström et al. 1978, Calado 1985, Cronjäger & Hesse 1990, Daikoku & Ishikawa 1990, Dieckmann

1958, Dieckmann 1984, Hesse 1989, Jahn & Hesse 1986, Jandák 1990, Kuhn 1953, Lundström 1984, Meltzer 1981, Meltzer et al. 1979, Meltzer et al. 1980, Mishoe & Suggs 1977, Miwa 1964, Miwa 1975, Nilsson & Olsson 1978, Norman 1979, Popov 1979, Reynolds & Angevine 1977, Reynolds & Falkenberg 1982, Reynolds & Keith 1977, Reynolds & Soedel 1972, Suggs 1974, Suggs & Abrams 1971, Wood & Suggs 1977, Wood et al. 1978). Although these models are simplified they still give a lot of information about how the hand and arm behave when exposed to vibrations and can also be used in the computer and analytical design of isolation systems.

The mechanical impedance of the human hand and arm is normally determined by measuring the force and velocity (or acceleration) at the same point and in the same direction. This impedance is called driving point impedance, to distinguish from transfer impedance which is based on measurements of the force and velocity at different points. The accuracy of these measurements has also been determined (Håkansson & Carlsson 1987). A knowledge of the mechanical impedance of the hand-arm system will help identify the relative importance of different frequencies, but will hardly clarify any dose-response relationship. From the definition of impedance it is, however, possible to rewrite the power equation 1 as:

$$P(t) = \overline{F(t)} \bullet \overline{v(t)} = Z(t) \bullet |v(t)|^2 \tag{9}$$

or in the frequency domain:

$$G_P(\omega) = 2 \bullet \int_{-\infty}^{\infty} Z(\tau) \bullet |v(\tau)|^2 \, d\tau =$$

$$= 2 \bullet \int_{-\infty}^{\infty} Z(\tau) \bullet R_{vv}(\tau) \bullet e^{-j\omega\tau} \, d\tau \tag{10}$$

This equation shows that the power involved in the dynamic situation is a function of the impedance and the auto-spectrum of the velocity. By combination of equations 6, 8 and 10 it can also be shown that the phase angle of the cross-spectrum is equal to the phase angle of the impedance, i.e. the angle between the force and velocity signals.

Determination of mechanical energy absorption

From the earlier presented equations two different techniques for determining the amount of absorbed energy in the hand and arm could be distinguished. The first technique is based on direct measurements of the force and velocity, and the corresponding phase angle between these parameters. This method is henceforth called the direct technique. The second technique uses the determined mechanical impedance for the hand and arm and measurements only of the velocity level are necessarily. This method is called the indirect technique.

The direct technique is applicable to sinusoidal as well as random vibration and has no demands as concerns a linear mechanical behaviour of the hand and arm (Johnson 1975). The indirect technique is, however, based on the assumption that the hand and arm act almost like a mechanical linear system for every frequency, in the meaning that a the impedance would be independent of the vibration level or, in other words, the force would increase linearly with the vibration level. The trend of non-linear behaviour is quite evident for the human body and has been shown in a number of investigations (Clark et al. 1962, Edwards & Lange 1964, ISO 5982 1981, Krause & Lange 1963, Perng 1970, White et al. 1962, Wittman & Phillips 1969). For the hand and arm a somewhat non-linear behaviour has also been noticed (Panzke & Balasus 1985, Suggs & Abrams 1971, Suggs et al. 1969, Zaveri 1974) but other results indicate that the non-linear behaviour is small and that there is an acceptable agreement between mechanical impedance measured with sinusoidal and transient vibration, respectively (Weis et al. 1964).

Studies using one or the other of the techniques are found in the literature. For the direct technique fewer studies have been found (Anderson & Boughtflower 1978, Burström & Lundström 1985, Lidström 1977, Lundström 1986) than for the indirect technique (Hansson et al. 1987, Hempstock & O'Connor 1986, Jandák 1990, Mishoe & Suggs 1977, Reynolds & Basel 1980, Reynolds et al. 1982, Reynolds et al. 1984, Taylor et al. 1984, Wasserman et al. 1981). It is difficult, if not impossible, to make a comparison of the results of these studies. This is due to the fact that investigators in general have used different measuring techniques or experimental conditions as regards vibration levels, vibration directions, hand-arm postures, grip force etc. Furthermore, differences in the impedance angle, especially for the indirect technique, could give large divergences of the results. The direct technique is normally technically very complicated and therefore mostly suitable for laboratory experiments. For many applications the indirect technique would be to prefer, partly because of its simplicity and partly because measurements of the magnitude of the vibration stimuli is commonly used today. In the literature, no comparison of the two techniques could be found, however.

AIMS OF THE PRESENT INVESTIGATION

As previously mentioned, working with vibrating hand-held tools or workpieces may cause an occupational disease known as the "Hand-Arm Vibration Syndrome". The main emphasis in many studies has therefore been on establishing a connection between the characteristics of the vibration stimulus and generated disturbances. Several of these investigations have, however, produced conflicting results. One reason may be that the risk assessments according to ISO 5349 are based on vibration measurements conducted directly on the vibrating handle, which in fact may give a false reflection of the actual vibration dose attributed to the exposure. In principle, it is reasonable to assume that the detrimental effects are better related to the amount of vibration energy transmitted to the hand and arm where it is absorbed. Therefore, measurements of the energy absorbed in the hand and arm should be a better and more objective method for risk assessment than the currently used standard - ISO 5349.

Against this background the aims and purposes of the present investigation have been to:

1. examine the mechanical and energy absorbing properties of the human hand and arm and to study how these properties are influenced by different factors involved in a vibration exposure situation,

2. investigate the possibilities to make theoretical calculation of the amount of absorbed energy in the human hand and arm by using vibration magnitude and frequency data together with data of the mechanical properties of the hand and arm,

3. compare the results obtained with the two different techniques, by direct measurements and by indirect determinations.

METHODS

Design of the studies

Study I

This study was designed to describe the mechanical properties of the human hand and arm exposed to sinusoidal vibration within the frequency range of 20 to 1500 Hz expressed in terms of the mechanical impedance. The mechanical impedance has been calculated by measuring the transmitted vibration force and velocity as well as the phase between these parameters. The influence of different experimental conditions on the mechanical impedance, such as hand-arm postures, grip forces adopted by the subjects, velocity amplitudes and vibration directions, were studied. The study was carried out on eight male subjects.

Study II

The objective of this study was to investigate the energy absorbing properties of the hand and arm during exposure to sinusoidal vibration by measuring the force, velocity and phase between these factors. The experimental settings used in the study were the same as for study I also using the same eight male subjects.

Study III

Based on study I this investigation was designed to obtain more information in detail of the mechanical properties of the hand and arm exposed to sinusoidal vibration. The frequencies were chosen to cover a lower frequency range than in study I, from 2 to 1000 Hz. The studied variables were; different vibration directions, handle grips, grip forces, flexions of the elbow, abductions of the shoulder, hands, velocity levels as well as sex and anthropometric data for the subjects. The study was carried out on ten subjects, five males and five females.

Study IV

The energy absorption in the hand and arm were investigated in this study for a frequency range of 4 to 1000 Hz. The investigated factors were the same as in study III. Ten subjects took part in this study, five males and five females, the same as in study III.

Study V

In this study the absorption of vibration energy in the hand and arm during exposure to simulated vibrations from five common types of hand-held tools within the frequency range of 5 to 1500 Hz was studied. The effects of different tools, vibration directions and frequency weighted acceleration levels as well as different grip forces were investigated. Furthermore, the aim was to compare the results obtained with two different techniques, by direct measurements and by indirect determination. Ten subjects (five males, five females) participated in this study.

Apparatus

Handle

The technique used to determine both the mechanical impedance and the amount of absorbed energy in the hand-arm system in all studies is based on measurements of vibration force and velocity as well as the phase between these parameters, made as closely as possible to the surface of the hand. This was obtained by using a handle specially constructed for this purpose. The handle consists of two parallel beams mounted between two U-shaped holders with a clearance of 2 mm. Both beams and holder were made of duraluminium to get a rigid and stiff construction in order to avoid distortions and artifacts due to resonances within the analysed frequency range. At both ends of each beam, strain gauges were glued to measure both grip and pull/push forces applied by the subject to the handle. The strain gauges were connected in accordance with a Wheatstone-bridge circuit to avoid influence of both heat and static deformations of the beams. In study I and II the static and dynamic forces from these strain gauges were separated by a filter. The DC-component of the filtered force signal then reflects the static forces applied by the subject, and correspondingly the AC-component the dynamic forces involved in the vibration exposure. The handle was modified after study I and II by separating the measuring handle from the holders by two force transducers. This arrangement was made mainly to get a possibility to examine a vibration exposure in the transverse direction. The handle was also equipped with a small piezo-electric accelerometer for vibration measurements. The weight of each beach-covered beam was 90 g and the weight of the handle, above the force transducers, was 225 g. The handle had an elliptic size and the dimensions were chosen as far as possible from recommended design criteria of tool handles (Chapanis 1972).

Signal generating and measuring equipment

Study I and II

The handle was mounted on an electrodynamic shaker driven by a power amplifier and a signal generator. Sinusoidal vibrations were delivered to the handle with an increasing frequency (sweep rate 50 s/decade). During the experimental series the measurements of the force and velocity were made on either the upper or lower half of the handle to reduce the possibility of erroneous interaction between the strain gauges. The output from the accelerometer was amplified and integrated to velocity by a charge amplifier before it was fed to a phase meter. The velocity signal was also fed to a feed-back network facility on the signal generator in order to maintain the velocity amplitude at a constant level independent of test frequency, static and dynamic load. The outputs from each of the strain gauges were amplified by a strain gauge' bridge and fed to the phase meter. The measured dynamic force, the velocity and the phase relationship between these parameters were registered on a level recorder. The signals from the strain gauges corresponding to the static forces (grip, pull and push forces) were monitored with an oscilloscope in order to give the subjects the possibility of both achieving and maintaining the grip and pull/push forces at the given level.

Study III and IV

The instrumentation used in study III and IV was quite similar to that of in study I and II except that the handle was also equipped with two force transducer, as earlier mentioned. The outputs from each of these force transducers were amplified by an charge amplifier and afterwards summarized. The summarized force signal was then fed to the phase meter. Furthermore, the grip and pull/push forces were monitored with pointer instruments for the subjects. In order to collect data for different vibration directions of input to the hand, two different orientations of the handle were also used.

Study V

In contrast to study I - IV, in this study recorded signals from five different types of hand-held tools were delivered to the handle through a spectrum shaper. It was then possible to achieve an almost identical frequency spectrum (1/3-octave bands) from the vibrator compared to the original recording. The output from the charge amplifiers was fed to a dual channel real time analyser. All the other used instrumentation was the same as in study III and IV.

For all studies the experimental system was also calibrated by using an accelerometer calibrator and by loading the handle, both statically and dynamically, with known weights.

Signal analyses

Study I and II

Twenty-three discrete frequencies, in the range of 20 to 1500 Hz, were chosen for data analysis. Directly from the charts of the level recorder both force and phase values were determined. These data, together with corresponding velocity amplitudes, were transferred to a computer which calculated the mechanical impedance and the energy absorption per unit time.

Study III and IV

The measured dynamic force, velocity level, phase relationship and test frequency were during each experiment transferred to an on-line personal computer by use of an Analogue/Digital-converter. The computer calculated the mechanical impedance and the amount of absorbed energy per unit time in the hand-arm system.

Study V

For the direct measurements of the power absorption the measured cross-spectrum and phase relationship between the force and velocity signal were after each experiment transferred from the dual channel analyzer to a Personal Computer for calculations. For the indirect determination the measured auto-spectra for the velocity signal were transferred to the computer for later analysis.

Studied variables

Study I and II

In these studies three different hand-arm postures were used. According to ISO 5349 two of these postures represent a vibration exposure in the X_h-direction, one with the arm straight and one with a 90° flexion of the elbow and abduction of the shoulder. The third posture represents a vibration exposure in the Z_h-direction.

Three grip force levels, 25, 50, 75 N, were used in the experiments as well as three different velocity levels, 27, 38 and 53 mm/s. These velocity levels represent frequency-weighted levels of 12.6, 17.8 respective 25.1 m/s^2 in accordance with ISO 5349. During the experiments no pull/push forces were applied on the handle.

Study III and IV

Three hand-arm postures were used in order to give a vibration exposure in the three orthogonal directions; vertical, transverse and proximal-distal. In accordance with ISO 5349 these directions refer to an excitation of the hand and arm in X_h-, Y_h- and Z_h-directions.

Three grip forces were used in the experiment, 25, 50, 75 N. The influence of the angle between upper arm and forearm (the flexion of the elbow) was studied for five positions, 60°, 90°, 120°, 150°, 180°. Moreover, the influence of a 90° angle between the shoulder and upper body (the abduction of the shoulder) was investigated as well as the differences between left and right hand-arm systems. Furthermore, two different handle grips were used in the study; from above and from below. The effect of the vibration amplitude on the energy absorption was also investigated by using four different velocity levels, 8, 14, 25 and 45 mm/s. These velocity levels represent frequency-weighted acceleration levels of 0.8, 1.4, 2.5 and 4.5 m/s^2 within the frequency range of 16 to 1000 Hz in accordance with ISO 5349. Furthermore, some anthropometric parameters for the subjects' hands and arms were measured in order to study the influence of these variables. The subjects were asked to control that no pull/push forces were affected the handle during the experiments.

Study V

In this study, simulated vibrations from five common types of hand-held tools were used (vibration sander, gig saw, impact drill, angle grinder, chipping hammer). The influence of two frequency weighted acceleration levels, 3.1 m/s^2 and 9.3 m/s^2, on the absorption of vibration energy was investigated in the experiments for all tools.

The effect of different hand-arm postures was studied in order to give a vibration exposure in the three orthogonal directions; X_h, Y_h and Z_h. Furthermore, the influence of two grip forces were investigated, 25 and 50 N. Two different descriptions of the mechanical behaviour of the hand and arm were used in the study. For this purpose earlier obtained impedance data have been used (Study III). These data were determined for the three orthogonal directions during both sinusoidal and random vibration exposure. During the experiments the subjects were asked to control that the pull/push forces were 20 N.

Experimental procedure

All studies were carried out in a laboratory at the National Institute of Occupational Health (NIOH) which gave the opportunity to undertake the experiments without any disturbances at approximately the same temperature (21 to 24 °C). The studies were carried out by the same investigator and according to standardized protocols. To avoid the risk of introducing systematical errors, all separate tests within each study were conducted randomly. For all the studies the number of tests for each subject were limited to 1-2 per day (rest period 4-6 hours) in order to eliminate any possible effects of fatiguing.

All subjects were asked before each experiment to wear normal office clothes (without jackets) and were also asked to remove rings, watches etc to minimize any possible effects of clothing. The subjects were then placed in one of the postures, gripping the handle with a given force. To accomplish the right posture reference models were used. After the correct posture and grip force was accomplished, the vibration exposure was started. The subjects were requested to keep the grip force on a constant level during the sweep by looking at a monitored force signal. Furthermore, the subjects were asked to control that the correct pull/push forces were affecting the handle. The test was restarted if the subject for any reason failed to retain the hand-grip force or posture.

The total number of test periods for each subject in study I and II were 36 and in study III and IV 22. In study V the number of test-periods for each subject were 24 (every test-period included exposure of five tools). The total number of received individual data files was therefore 2312.

Data analysis and statistics

In study I and II the results for each subject were obtained for the upper and lower half of the special handle separately. The total impedance or energy absorption has therefore afterwards been determined by vectorial addition of these two components.

For all studies the computer calculations also included a vectorial subtraction for the additional dynamic force produced by the handle itself, i.e. mass cancellation. The dynamic force of the handle was determined by vibrating the unloaded handle at least twice a day. These measurements revealed that the handle behaved as a rigid mass with the force remaining in 90 degrees out of phase with the velocity in the frequency range investigated. The handle data were also used to compare instrument calibration and to serve as a permanent indication of possible errors in gain settings.

Since the data for each subject (after mass cancellation) were in form of both magnitudes and phase relationships for different frequencies, the average values for each experimental condition have been determined by so-called vectorial averaging. This means that the average of the real and imaginary part for all subjects has been calculated and has been used to determine both the resulting impedance and absorption as well as the phase relationship.

The total amount of power absorption has been calculated by both using Simpson's formula for numerical integration as well as by using digital computerized 1/3-octave band filters.

In the calculations of differences between the experimental conditions, all comparisons were made on the assumption that each subject was used as his own reference. Tests on paired observations were therefore performed with both parametric and non-parametric methods. The performed tests gave the same results. Therefore, parametric paired t-tests have been presented throughout the whole series of studies. A P-value of <0.001 was considered significant. For calculations of correlations between parameters, the Sperman Rank Correlation Test and linear regression analysis were used (Box et al. 1978, Feldman et al. 1987).

RESULTS

Mechanical impedance (study I and III)

The results from various combination of variables were composed in order to determine how the mechanical impedance for the hand and arm is influenced by different experimental conditions.

Vibration direction

The influence of the vibration direction on the mechanical impedance is shown in Figure 1.

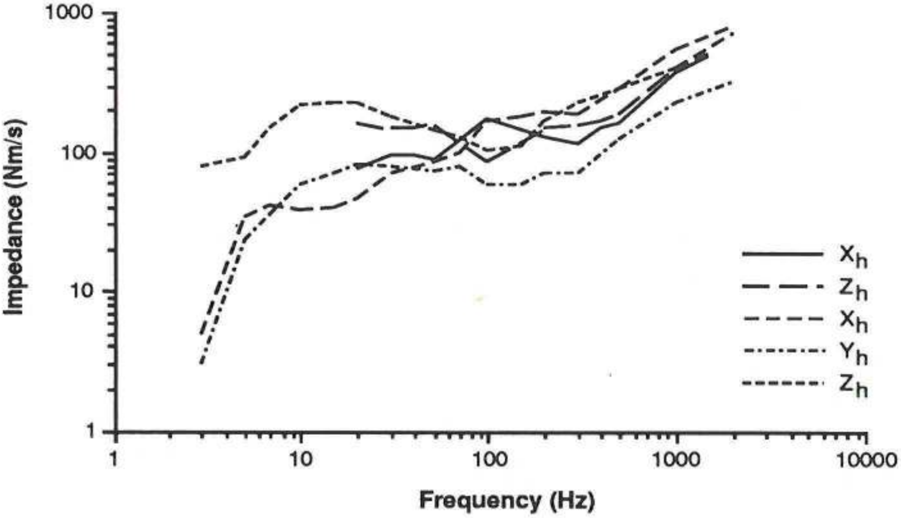

Figure 1. Comparison of hand-arm impedance curves for the three different vibration directions, as defined in ISO 5349, according to results found in study I and III.

The outcome of these investigations, presented in Figure 1, clearly shows that the mechanical impedance of the human hand and arm is strongly dependent on the frequency of the vibration stimuli and that the frequency dependence differs between the three orthogonal vibration directions; X_h, Y_h, Z_h. Furthermore, it can be concluded that the hand and arm have a high vibration damping ability which increases with the frequency. In the low frequency range the hand-arm system reacts more or less like a pure mass for the X_h- and Y_h-directions and like a spring in the Z_h-direction. The "spring behaviour" is due to the fact that the whole hand and arm as well as the body are involved in the damping. When the frequency increases the body's "spring behaviour" decreases and the hand-arm system reaches a more mass-like behaviour above 200 Hz. In the Y_h-direction the hand and arm behave more or less like a damper in the frequency range of 40 to 600 Hz and like a mass for frequencies above. Moreover, it was found that for all directions there are frequencies where the impedance has a low point, probably due to different resonant frequency areas for the hand and arm.

Vibration level

The velocity level had a strong influence on the magnitude of the impedance but only a small influence on the phase relationship. In study I the influence of the velocity level was investigated for the Z_h-direction and in study III for the X_h-direction. For the Z_h-direction it was found that in the low frequency area the magnitude of the impedance was somewhat higher for the low stimulus level. For higher frequencies lower impedance was connected to lower stimulus. For the X_h-direction the magnitude of the impedance increases slightly when the vibration level increases and observed differences are specially pronounced in the frequency region above 200 Hz. For both directions the phase of the impedance was almost the same. An increase of the stimulus amplitude leads to a corresponding increase of the force component provided that the mechanical properties of the hand and arm are linear within the amplitude range in question. According to the definition of mechanical impedance, the magnitude of the impedance will therefore not be influenced. The results from these investigations show, however, a clear tendency towards a non-linear behaviour, especially at high frequencies.

Grip force

The results show that there is a clear relation between the hand grip force applied by the subject and the magnitude of the impedance. Firmer hand grips lead to higher impedance. The increase of the impedance magnitude seems also to be higher at the lower velocity level. There is, however, a tendency in the frequency region of 50 to 80 Hz for the impedance to be independent of the grip force. At lower frequencies this effect is less pronounced compared to the higher frequency region. The phase of the impedance for different grip forces and velocity levels only show small differences.

Hand-arm posture

The influence on the mechanical impedance of different hand-arm postures was studied for three cases, with different flexions of the elbow, abductions of the shoulder and handle grips.

The angle between upper arm and forearm (the flexion of the elbow) has an influence on both the magnitude and phase of the impedance. A clear tendency is that an increase of the angle gives a higher impedance. For the phase of the impedance the differences are specially pronounced in the frequency region below 20 Hz. The angle between shoulder and body (the abduction of the shoulder) has almost no influence on the impedance or phase relationship. Furthermore, the grip direction of the hand has only a small influence on the mechanical impedance. The most pronounced differences could be found below 100 Hz, and handle grips from below give a higher impedance of the hand-arm system.

Sex and anthropometric data

The results show that females have a lower mechanical impedance of their hand and arm than males and the differences are specially pronounced in the frequency region above 20 Hz. These differences are significant and the average difference was found to be about 20% for magnitude of the impedance. The phase of the impedance does not show the same divergence. Furthermore, the mechanical impedance in the X_h-direction had the highest correlation to the volume of the whole hand-arm system in the low frequency region. Above 15 Hz, however, factors describing the hand had the highest correlation against the impedance. Furthermore, in the frequency range of about 200 to 300, where the impedance has a low point, the highest correlation was found for the grip force applied by the subject. Moreover, it was found that the subjects' left hand-arm showed a slightly higher magnitude of the impedance than the right.

Absorption of power (study II and IV)

The different experimental variables' influence on the energy absorption per unit time has been investigated by comparing the magnitude and the shape of the frequency spectrum for the absorption. To estimate the relative importance of each combination of variables the total amount of absorbed energy has also been calculated, although no broad-banded vibration exposure has occurred. To show how the absorption is influenced when a variable is changed the results have also been quoted. In the quotation, the lowest broad-banded absorption for each combination of variables has been used as reference. For study II the total absorption have been calculated within the frequency band of 20 to 1500 Hz. For study IV the total absorption within the 1/3-octave band, having centre frequencies from 6.3 to 1250 Hz, is summarized. The results from these calculations are shown in Figure 2.

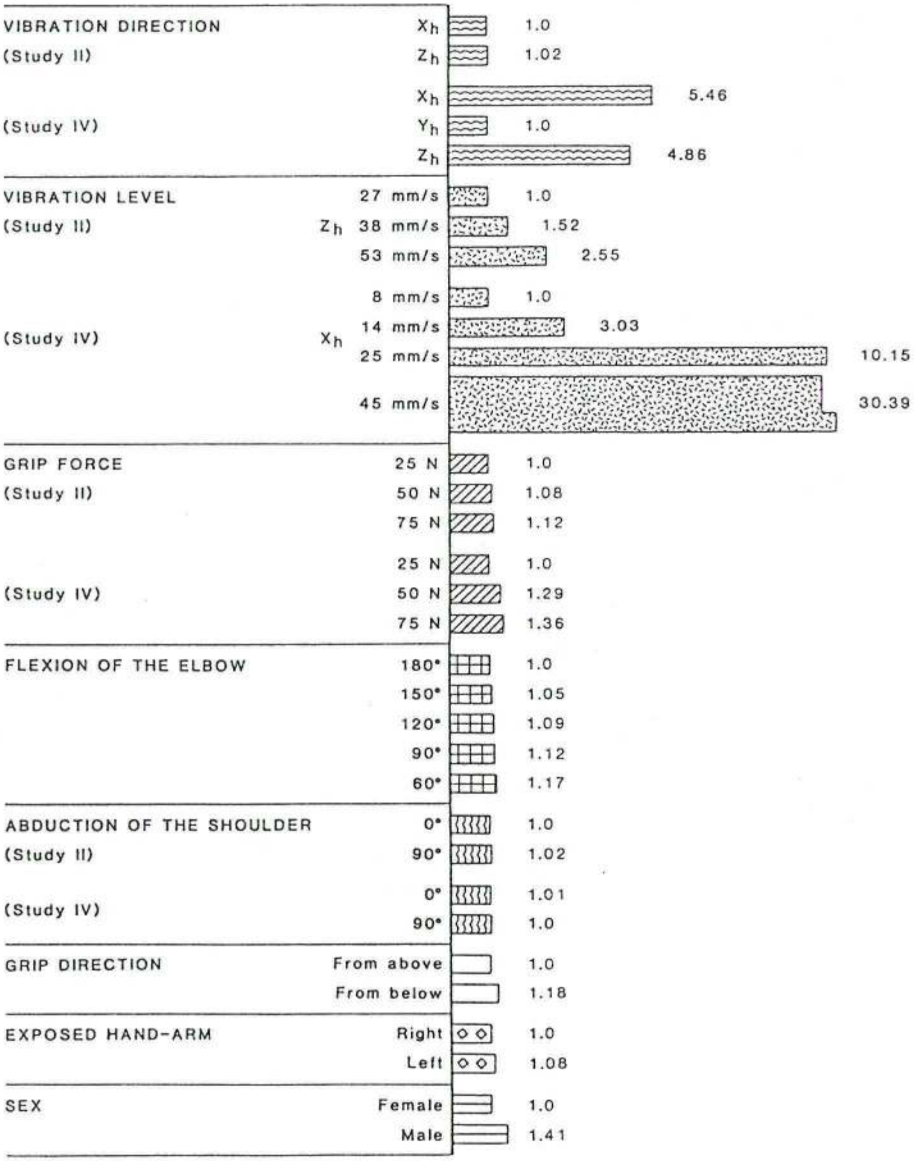

Figure 2. Bar chart showing the quote of the total energy absorption for each combination of variables (Study II and IV).

Vibration direction

The influence of the vibration direction on energy absorption per unit time from both studies is shown in Figure 3.

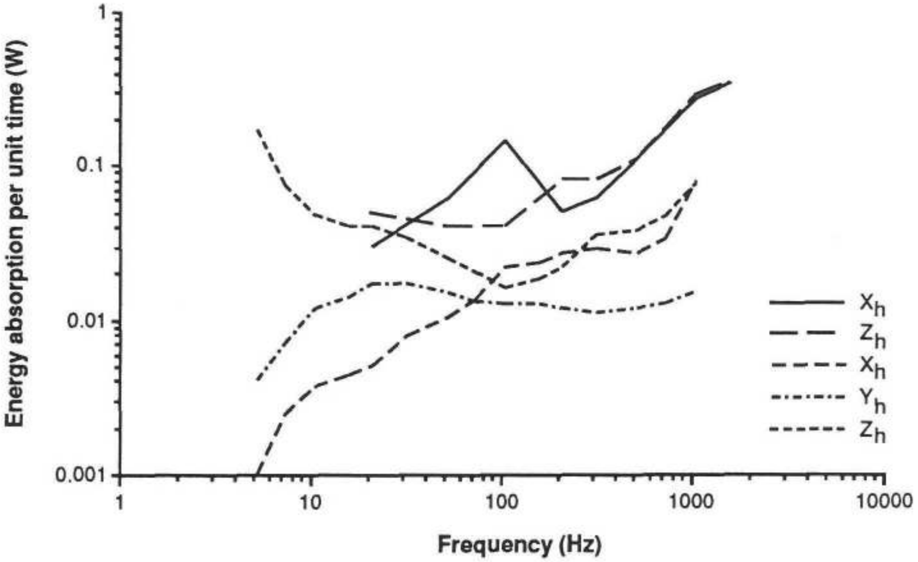

Figure 3. Comparison of the absorption av energy in the hand and arm for the three different vibration directions, as defined in ISO 5349, according to results found in study II and IV.

Figure 3 shows that the absorption of energy is dependent on the frequency of the vibration stimuli. Furthermore, the results show that the energy absorption properties, or in other words the damping ability of the hand and arm, are quite different in the three vibration directions. For vibration exposure in the X_h-direction the absorption increases with the frequency towards a high point at about 100 Hz followed by decrease towards a low point in the region of 200 to 300 Hz. Above 300 Hz the absorption roughly increases with the frequency. The Y_h-direction is characterised by an energy absorption which increases with the frequency towards a maximum at about 20 to 30 Hz, followed by an almost flat response for the rest of the frequency range. For the Z_h-direction the absorption decreases with the frequency towards a minimum at about 100 Hz followed by an increase with the frequency similar to the X_h-direction. In Figure 3 it can also be noticed that to minimize the energy absorption in the hand and arm the vibration input should be in the X_h-direction for frequencies below 30 Hz, and in the Y_h-direction for frequencies above 70 Hz. The vibration input should in no cases be in the Z_h-direction for which the transmission of vibration into the body tends to be more than from the other directions. Figure 2 shows that the Y_h- and X_h-direction lead to the lowest and highest total energy absorption, respectively. The variation is about five times. Furthermore, it can be observed that vibration exposure in the X_h- and Z_h-direction gives about the same absorption.

According to the frequency weighting routine described in ISO 5349 the hand-arm system is considered to be equally sensitive to a constant vibration velocity level for all frequencies above about 16 Hz. For lower frequencies, higher velocity levels are however accepted. On the basis of how the hand-arm system mechanically responds to a vibration stimulus, it is possible to establish a new ISO weighting curve expressed in terms of absorbed energy instead of vibration magnitude.

Absorbed energy is related to the real component of the mechanical impedance of the system multiplied by the velocity level squared. By using the results achieved in study I and III for all three directions, an average value for this component of the impedance at 16 Hz has been calculated. This average value has then been used for determination of the relative position of a new energy absorption curve at this particular frequency. For reasons of simplicity, the damping features of the hand-arm system are held constant over the entire frequency range. The new ISO weighting curve, as well as the results obtained in study IV (Figure 3) for the three different exposure directions are illustrated in Figure 4 for a frequency weighted velocity level of 14 mm/s.

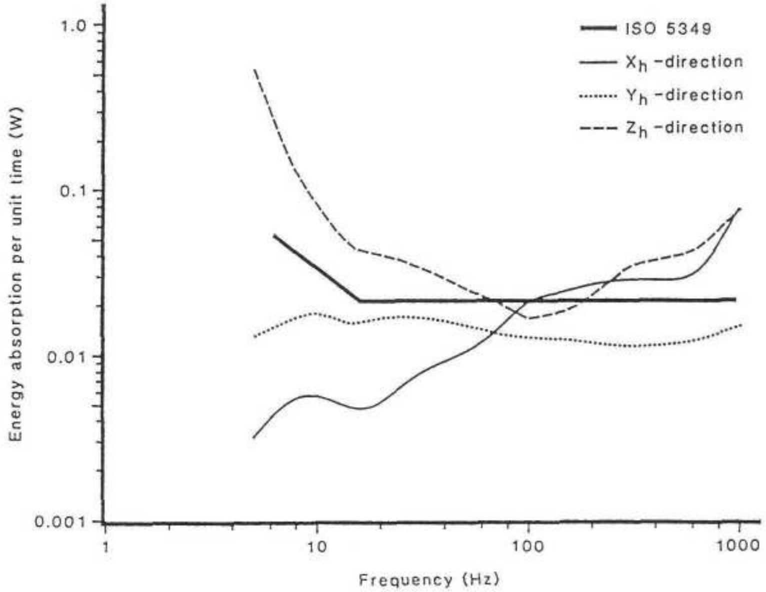

Figure 4. Comparison of hand-arm energy absorption curves for the three different vibration directions and a corresponding ISO weighting curve expressed in terms of absorbed energy (study IV).

As can be seen in Figure 4, the shape of the calculated ISO risk assessment curve is about the same as the energy absorption in the Y_h-direction for frequencies above 16 Hz. For the other two directions, greater divergences from the weighting curve can be observed. Thus the international standard underestimates the energy absorption for exposure in the Z_h-direction as well as for frequencies above 100 Hz in the X_h-direction. On the contrary, for frequencies below 100 Hz and 16 Hz the standard overestimates the absorption for vibration exposure in the X_h- and Y_h-direction, respectively.

Vibration level

The amount of energy absorption increases quite rapidly when the vibration level increases but the curves have similar frequency appearance. If the velocity level is changed from 8 mm/s to 14 mm/s the amount of absorbed energy increases with a factor 3.0 in the X_h-

direction (Figure 2). From 14 mm/s to 25 mm/s or from 25 mm/s to 45 mm/s the corresponding factors are 3.3 and 3.0 respectively. In the Z_h-direction it was found that an increase of the velocity level from 27 to 38 mm/s leads to an increase of the absorption with a factor 1.5 and from 38 mm/s to 53 mm/s with a factor 1.7. From these values the relation between velocity level changes and corresponding changes in the energy absorption can be calculated. The relation is given by; $\Delta P = 10^{\Delta dB/10}$ ($r^2 = 0.98$) where ΔP is the change of absorption factor and ΔdB is the change in velocity level expressed in dB (rel 10^{-9} m/s).

Grip force

From the results it can be concluded that firmer hand grips lead to a higher absorption of energy. The increase of absorption also seems to be relatively higher at the lower velocity level. The amount of absorbed energy increases with a factor 1.3 when the grip force increases from 25 N to 50 N (Figure 2). The corresponding factor is 1.1 when the grip force increases from 50 N to 75 N. In study II the results indicate that firmer grip forces lead to a higher energy dissipation for frequencies above 75 Hz. At lower frequencies, however, the opposite was found.

Hand-arm posture

From study IV, the results (Figure 2) indicate that the angle between upper arm and forearm (the flexion of the elbow) has an influence on the average amount of absorbed energy and it is specially noticeable in the frequency region of 4 to 50 Hz. A clear tendency is that an increase of the angle gives a higher energy absorption. Moreover, it was shown that the angle between shoulder and body (the abduction of the shoulder) has no influence on the energy dissipation, except in the low frequency region. Furthermore, it could also be stated that the grip direction have only a small influence on the energy absorption. Hand grips from below tend to give a higher amount of absorbed energy per unit time (Figure 2).

Sex and anthropometric data

Study II shows that there are clear differences between individuals as regards both the total amount of absorbed energy and the frequency appearance for the energy absorption curve. Study IV shows that females overall have a lower absorption of energy than males and that the average difference for all variable combinations were about 30% (Figure 2). Conducted t-tests also show that these differences are significant. Furthermore, it can be noticed that the magnitudes of the "within subjects" standard deviations were in the range of 5% and the magnitudes of the "between-subjects" were about 25%.

Performed correlation analyses between individual anthropometric data and the energy absorption shows that for the X_h-direction the energy absorption is highest correlated to the volume of the whole hand and arm in the low frequency region. Above 50 Hz factors describing the hand have the highest correlation to the absorption. Furthermore, no differences were found between the subjects' left and right hand-arm as concerns the amount of absorbed energy (Figure 2).

Energy absorption whilst using vibrating tools (study V)

The influence on the absorption of vibration energy per unit time by the different experimental conditions during exposure for simulated vibration from five types of tools (vibration sander, gig saw, impact drill, angle grinder, chipping hammer) was studied by comparing results from various combination of variables and from the two techniques, the direct and the indirect. For the indirect technique a comparison of the results to the different impedance data has also been performed.

Vibrating tool

The gig saw and the vibration sander, respectively, caused the highest and lowest amount of absorbed energy of all the tools, although the frequency weighted acceleration levels were the same. The difference was about three times. Conducted t-tests also show that there are significant differences between all tools except between the saw and the chipping hammer.

Vibration level

The results shows that the shape of the frequency spectrum for the absorption of energy, for each tool, was almost the same in all three exposure directions. However, the level differs somewhat, with the highest absorption in the Z_h-direction and the lowest in the Y_h-direction. Conducted t-tests show that the differences between all three directions are significant. It was also noticed that the highest absorption for each tool is correlated to the frequency band in which the main operational frequency varies. For the different types of tools the operational frequency caused between 51 % and 97 % of the total amount of absorbed energy. Moreover, a tendency in the results was that lower operational frequency corresponds to a greater part of the total amount of absorbed power. The amount of energy absorption undergoes a quite rapid growth with the vibration level. The absorption increases with a factor of 1.5 to 3.2 when the frequency-weighted acceleration is changed from 3 to 9 m/s^2. The increase is, however, dependent on frequency spectra for the tool and on the vibration direction, and it is specially pronounced for the chipping hammer. As expected, the increase of the total amount of energy was significant for all types of tools when the value of the frequency weighted acceleration was enhanced.

Grip force

There is a clear relationship between firmer hand grips and higher absorption of energy. The amount of absorbed energy increase with a factor 1.1-1.3 when the grip force increases from 25 to 50 N. The greatest differences were found for the Y_h-direction and the smallest for the Z_h-direction. Conducted t-tests show that the influence of the grip force on the total amount of energy was significant only for the Y_h-direction. Furthermore, concerning the amount of absorbed energy, it was found that the influence of the grip force was more pronounced for lower operational frequencies of the tools than higher.

Technique

A comparison of results obtained with the two techniques are illustrated in Figure 5. For the indirect technique, the impedance determined during exposure both to sinusoidal and random vibration has been used. In the Figure a quotation of the total absorption for the two techniques within the one-third octave band, having centre frequencies from 6.3 Hz to 1250 Hz, is presented in form of frequency diagrams (Box et al. 1978).

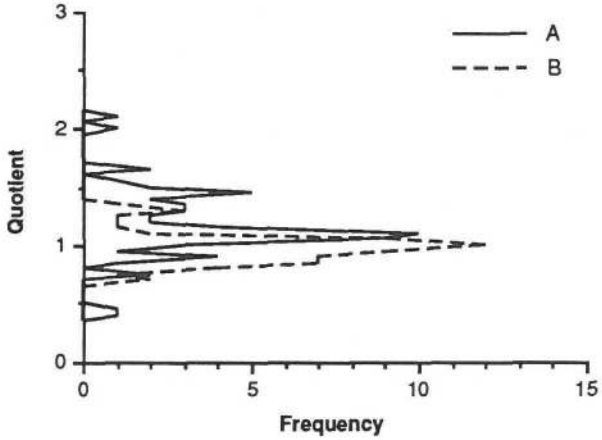

Figure 5. Frequency diagrams of the quotation for the energy absorption in the hand-arm obtained with the direct and indirect technique. For the indirect technique impedance data obtained with sinusoidal vibration have been used in diagram A and random exposure in diagram B.

As can be seen from Figure 5, diagram A, the indirect technique in general gives higher absorption values than the direct technique. The correlation between the two techniques is rather small with a correlation coefficient of 0.67. On the contrary, from diagram B a rather good agreement could be observed between the direct technique and the indirect technique. The correlation coefficient was found to be 0.96.

DISCUSSION AND CONCLUSIONS

When considering the effect of hand-arm vibration it is valuable to have an understanding of the mechanical characteristics of the hand and arm. The information on the mechanical properties, given in the form of mechanical impedance, can be used for computer and analytical design of new tools or equipment. Furthermore, a knowledge of the mechanical impedance for the hand and arm will help identify the relative importance of different frequencies. However, it is not yet possible to use dynamic response data as the sole basis for assessing the injury potential of tool vibration (Griffin 1990). The effects are more likely to depend upon the rate of which the vibration energy is absorbed in the hand and arm (Anderson & Boughtflower 1978, Cundiff 1976).

The severity of the effects from hand-transmitted vibration is influenced by physical, biodynamic and individual factors. Physical factors are for instance the frequency, magnitude, duration and direction of the vibration exposure. Biodynamic factors can be for example hand grip forces, pull/push forces, postures of the hand, arm and body during exposure, as well as the area and location of the parts of the hand which are exposed to vibration. The severity of individual factors may be influenced by biological susceptibility to vibration, agents affecting the peripheral circulation, such as low temperature, noise, smoking, medicines and chemicals. Furthermore, earlier disease or prior injuries to the fingers or hands, the size and weight of the hand and arm as well as working methods can influence the severity of the effects from vibration.

Monitoring all these variables for each worker has been considered impractical (Starck 1984a). Therefore, it has been necessary to reduce the number of variables to manageable proportions. In ISO 5349 the magnitude, frequency spectra and duration of the vibration stimuli have been considered as the most important variables for the risk assessment. The other variables have been assumed to contribute relatively small differences at any amplitude-frequency-duration combination and are not included in the risk assessment (Starck 1984a). The outcome of the present studies clearly shows that measurements of the energy absorption in the human hand and arm is not only dependent on magnitude and frequency of the vibration stimuli but also on other factors which influence the severity of vibration, at least with respect to vibration directions, grip forces, flexions of the elbow as well as individual factors. Therefore, measurements of the energy absorption as presented here may be a better and more objective method for risk assessment than the current standard. As concerns the unsubstantiated premise that a higher amount of absorbed energy per unit time represents an increased risk of vibration injuries or reduction in comfort, it can be concluded that almost all the studied variables have a significant influence on the risk assessment.

Ever since the frequency weighting routine, described in ISO 5349, was first proposed, several investigators have tried to correlate vibration measurements of tools to generated injuries. Many of these investigations have, however, led to contradictory results as earlier mentioned. There are, of course, several possible explanations for these discrepancies, for instance inadequate vibration measurements or incorrect determination of the exposure time. Another explanation could be that the guidelines given in the standard, and consequently the dose-response model, are based on a wrong assumption, namely equal sensitivity for frequencies above 16 Hz. As has been shown in the present studies, and several others, the hand and arm do not respond equally from a mechanical and energy absorbing point of view within this frequency range. If the assumption is correct that an increased absorption of energy will reflect an increased risk of injury, the obtained results show that the shape of the ISO risk assessment curve mostly reflects the energy absorption in the Y_h-direction for frequencies above 16 Hz. For the other two directions the weighting curve does not seem adequate. One conclusion is therefore that the weighting curve should be different for different vibration directions.

The discrepancy between the frequency weighting curve and the corresponding energy absorption curve could explain why an equal increase of the frequency weighted acceleration for simulated vibrations from different hand-held tools did not correspond to an equal increase of the absorbed energy. Furthermore, the fundamental operational frequency of the tool was found to cause the main part of the amount of absorbed energy. These observations correspond to results reported by Reynolds et al (1984). Lower operational frequency of the tool seems also to correspond to a greater part of the total energy absorption. This is rather unfortunate since a large part of the hand-held tools in use today have an operational frequency in the frequency range of 35 to 100 Hz (Lundström & Burström 1984).

In ISO 5349 it is also specified that the risk assessment should be based upon the vibration direction which has the highest acceleration value. The results in the present studies have shown, however, that the hand and arm do not respond equally from a mechanical point of view for these different exposure directions. These differences imply that it could be questioned whether the assessment should be based upon the total sum of vibrations in all three vibration directions instead. Furthermore, it can be noticed that to minimize the energy absorption, the vibration input from a tool in no cases should be in the Z_h-direction.

The vibration level, has as expected, a strong influence on the magnitude of the amount of absorbed energy. The reason for this is probably changes of the dynamic mass of the hand-arm system. When the stimulus amplitude increases, a larger part of the hand-arm system is in consequence mechanically activated. The energy consuming part, i.e. damping mechanisms, of the system increases therefore, leading to the possibility of more energy dissipating. The increase of the energy absorption seems, furthermore, to be linear but this probably holds only for the linear range of the hand and arm. It is also note worthy that the amount of absorbed power is proportional to the amplitude of velocity squared. Thus, every doubling of the velocity amplitude will result in a four-fold increase in the energy absorption in the hand.

The biodynamic and individual factors will, as shown, influence on the amount of absorbed energy. Relatively small changes in position and posture can appreciably affect the transmission of vibration as well as the vibration energy to the hand and arm. For instance, bending the arm at different angles between upper arm and forearm, will significantly affect the magnitude of the energy absorption and should consequently affect the risk assessment.

An increased handgrip force leads to an increase of the effective stiffness of the tissue. This is subsequently followed by a greater transmission of vibration and a corresponding increase of absorbed energy. This may be an explanation to the observations that less skilled workers, gripping the tool handle too firmly, are more frequently damaged by vibrations (Teisinger 1972). Somewhat surprisingly, the results have indicated that the grip force at lower frequencies does not lead to higher energy absorption. It is also worth noticing that the relation between grip force and absorption does not seem to be linear. One reason could be that the energy absorption depends on the amount of viscous elements in the hand-arm system. This amount of viscous elements is influenced by the tension of the muscles and a higher tension enables the vibrations to put a larger part of the hand-arm system in motion, which causes the apparent mass of the system to increase. The reason for the non-linear behaviour could also be that the amount of viscous elements is limited in the hand and arm. With an increased grip force the muscles do not strain a corresponding amount of viscous elements. This might explain the comparatively smaller increase. Furthermore, in these studies it was found that the dependence of the grip force on the total amount of absorbed energy differs between different vibration direction. One reason could be that the amount of viscous elements, which can absorb energy, is unequal for the hand and arm depending on the exposure direction.

In study II and III the results give an indication of a large inter-subject variability of the magnitude of absorbed energy and impedance but a small intra-subject variability. The sources of inter-subject variability are presumably differences in the construction of the subjects' hands and arms and not the sex of the subjects. Findings in these studies suggest that larger biological size of the hand, arm etc, gives a higher mechanical impedance and energy dissipation. On the contrary, however, the results show that the amount of absorbed energy per volume tissue decreases when the anthropometric data increase. This could explain why females have a lower absorption of energy than males. These results also outline that the frequency appearance of the mechanical impedance or energy absorption is highly characteristic for the individual. At a particular frequency where the vibration stimulus has a significant effect on one subject, there could be no such overall effect for a group of subjects. In study I and II the subjects were a relatively homogeneous group of male but in study III and IV the group was less homogeneous and covered both males and females. The observed differences are probably due to these inter-individual variations. It would therefore be necessary to have a large number of subjects to get a reliable mean value. On the other hand, the small intra-individual differences make it more easy to perform individual risk assessments.

The hand-arm system normally has a high shock absorbing ability which increases with the frequency. In the low frequency range the hand-arm system reacts more or less like a pure mass for the X_h- and Y_h-directions and like a spring in the Z_h-direction. When the frequency increases the transmission of vibration up the arm decreases due to decreased influence of mass elements which are most distant from the vibration source. With a progressively increased frequency, the final effect will be that the vibration tends to be more and more localized to the fingers and cutaneous tissues (Dupuis 1975, Hansson et al. 1987, Reynolds & Jokel 1974, Reynolds & Soedel 1972, Reynolds et al. 1977, Suggs 1970). The obtained results indicate that for frequencies above 50 Hz, large amounts of energy are consequently dissipated in small volumes of tissues in the hand, resulting in heat and motions between different bone structures, muscle groups, blood vessels, nerves etc. Vibration frequencies above 50 Hz have also been found to be most troublesome for the development of cold induced vascular disorder in the fingers (VWF) (Griffin 1982, Lundström 1985b, Streeter 1970). The absorption of energy will stimulate an increase in the flow of blood into the area and can result in a tingling and burning sensation, according to Reynolds (1977). Most of the tissues in the hand are, however, highly elastic and can therefore absorb large amounts of energy before fatiguing and ultimately being damaged (Reynolds & Jokel 1974). If the motions of the tissues are out of phase, the relative motion between different tissues can be larger than the individual motions of each tissue. Furthermore, resonances can cause high loads on the tissues and if the loads are powerful enough physical damages or modifications will occur (Mishoe & Suggs 1977, Reynolds &

Keith 1977). The elasticity of the tissues also depend on individual factors, as well as climate and working conditions. For individuals susceptible to hardening of the arteries, work in cold climate and for instance high grip forces will reduce the elasticity of the tissues leading to increased risk for injuries. It is therefore reasonable to assume that the absorption of vibration energy is responsible for the effects associated with the vibration syndrome.

The effects of the time history of vibration have been studied only in a few investigations. Very little is known about the human response as far as this is concerned (Griffin 1974). Evidence has been presented in which in some cases the vibration response characteristics of the hand and arm differ, depending upon whether the signal is a discrete frequency signal or a signal consisting of several frequencies (Reynolds 1977). In study V, two different techniques were used to estimate the amount of absorbed energy in the hand and arm, direct measurements and indirect determinations. From a comparison of the two techniques it is obvious that a correct description of the hand-arm system's mechanical response to vibration is necessary. By use of the impedance data from the random excitation, a far better correlation between the direct and indirect technique could be obtained, compared to impedance data determined by sinusoidal vibration. Furthermore, from the results it can be concluded that it is possible to calculate the amount of absorbed energy in the hand and arm by using the indirect technique. This technique does not take into consideration the intrinsic variables like grip force, hand-posture, individual factors etc. Some of these factors have, on the other hand, been examined in the present studies and a correction for their influence is possible. For more exact measurements of the amount of absorbed energy the direct technique is still to prefer.

The effects of vibrations from hand-held tools or industrial processes in which vibration enters the hands seem to a large extend to depend upon the rate of absorption of vibration energy in the hand and arm. Further studies of the relation between absorbed energy and generated disturbance are desirable to obtain reliable data which clarify the dose-response relationship. Furthermore, it has been shown in the present studies that the shape of the frequency spectrum for the energy absorption is not in agreement with the frequency weighting curve, proposed by ISO 5349. Considering the present results, it seems resonable to conclude that there are strong reasons for changing the shape of the weighting curve and furthermore that the weighting curve should be different for different exposure directions. The obtained results also indicate that the hand and arm have a very high absorption of energy at high frequencies. This absorption should be taken into consideration and more investigations of the effects of high frequency components are necessary. Moreover, the found agreement between the direct and indirect technique outlines new possibilities for the indirect technique to estimate the amount of absorbed energy by using vibration characteristics for the tool and the mechanical properties of the human hand and arm. Further investigations of other factors which influence the severity of the effects from hand-transmitted vibration are of utmost necessity to make the technique more practically useful. Finally, the present findings support the idea that future standards for risk assessment of vibrations should rather be based on the energy absorption concept.

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PAPER I

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MECHANICAL IMPEDANCE OF THE HUMAN HAND–ARM SYSTEM *

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ABSTRACT

The mechanical impedance of the human hand–arm system was measured within the frequency range of 20–1500 Hz. A handle, specially designed for such measurements, was used. The studies were carried out on eight healthy male subjects during different experimental conditions defined by three different hand–arm postures, hand grip forces (25–75 N) adopted by the subjects, the amplitude (27–53 mm/s_{rms}*; 1.4–2.8 g at 80 Hz) and direction of the vibration stimuli. The outcome shows that the mechanical impedance of the hand–arm system depends on the frequency of the vibration stimuli. Above 200 Hz, the impedance, in general, increases quite rapidly, from about 150 Ns/m up to about 500 Ns/m at 1500 Hz, with the frequency. At lower frequencies, however, various shapes of the impedance curves were found which were most pronounced between different hand–arm postures. For the transverse direction, the impedance increased from about 50 Ns/m at 20 Hz to maximum about 100 Hz followed by a slight decrease. For the proximal–distal direction the impedance decreased from about 150 Ns/m at 20 Hz to minimum at about 100 Hz. More firm hand grips, as well as higher vibration levels, resulted in higher impedance magnitudes for frequencies above about 100 Hz. Remarkably enough, for lower frequencies an almost opposite relationship was found. Furthermore, the results indicate a non-linear relationship between mechanical impedence and the studied experimental variables. Therefore, prior to setting up future standards, the mechanical properties of the hand–arm system should be taken into careful consideration.*

INTRODUCTION

It is known that a complex of neurological, vascular and musculoskeletal disturbances can appear among workers who operate hand-held power tools or other industrial processes in which vibration enters the hand and arm. These disturbances are becoming widely recognized as an important occupational disease known as the vibration syndrome (for a review see Taylor and Brammer, 1982).

The determination of correlation between generated disturbances and the characteristics of the vibration stimulus has proved to be a very complex problem. Man's response to vibration exposure depends on several factors, such as frequency, direction, intensity, duration of vibration and grip force when tools are used. Furthermore, this problem is accentuated by large inter-individual variabilities as regards vibration sus-

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ceptibility (for a review and references see Brammer, 1982; Griffin, 1982). In order to understand, or predict, how humans are influenced by vibration, basic knowledge regarding human–machine interaction, is needed.

From a mechanical point of view, the hand and arm can be regarded as a system, consisting of a large number of homogeneous masses of various size and structure, i.e. different bone structures, muscle groups, blood vessels, nerves, etc., held together by different kinds of springy and viscous tissues (Hixon, 1976; Olesen and Randall, 1979). When describing the biodynamic characteristics of the hand–arm system, the mechanical impedance may serve as a good measure of how the system reacts to a vibration stimulus.

The mechanical impedance, Z, can be described as a mechanical structure's resistance to vibrate according to an applied vibration. The dynamic force, F, applied to the structure, divided by the obtained velocity, v, defines the mechanical impedance, i.e. $Z = F/v$. If the force and velocity are measured at the same point, it is called 'point impedance' and describes the resistant and absorbing properties of the structure. The absolute size of the mechanical impedance is dependant not only on the amplitudes of F and v but also on their reciprocal phase relations. When F and v are in phase with each other, the impedance reaches its maximum value. Furthermore, the impedance can be divided into two components—one real (Z_{Re}) and one imaginary (Z_{Im}). Their size can be determined exactly when the phase relationships are known. A mechanical system can be decomposed into separate elements consisting of masses, springs and viscous dampers. Together they constitute a "mass-spring" system.

The published literature indicates that several investigators have conducted impedance measurements on the hand–arm system. However, the results from these studies do not lead to a consensus (Kuhn, 1953; Dieckmann, 1959; Coermann and Lange, 1967; Abrams and Suggs, 1970; Suggs and Abrams, 1971; Reynolds and Soedel, 1972; Miwa, 1975; Mishoe and Suggs, 1977; Reynolds, 1977; Reynolds and Angevine, 1977; Reynolds and Keith, 1977; Wood et al., 1978; Meltzer et al., 1979; Byström et al., 1982; Reynolds and Falkenberg, 1982; Lundström, 1984; Panzke and Balasus, 1985; Hempstock and O'Connor, 1986). While the reasons for these disagreements are not clear, it may be that different experimental techniques, hand–arm postures and grip forces adopted by the subject, are the causes for different findings that have been reported.

The objective of the present study was to perform repeated measurements on a limited number of subjects in order to investigate the effects of hand–arm postures, grip forces, directions and vibration levels on the mechanical impedance of the hand–arm system.

METHODS

Apparatus

On an electro-dynamic shaker (Ling Altec 7/600), a handle, specially designed for impedance measurements, was mounted. The design of the handle is shown in Fig. 1. The handle consists of one upper and one lower beam, covered with beech. The two parallel beams are mounted between two U-shaped holders with a clearance of 2 mm. Beams and holders are made of duraluminium which has a high stiffness. High stiffness is needed to avoid output distortion and artifacts due to resonances within the frequency range of interest in this study, i.e. below 1500 Hz. The weight of each beach-covered beam is 90 g.

Strain gauges were affixed on both ends of each beam and connected in accordance with a Wheatstone-bridge circuit for measurementing static and

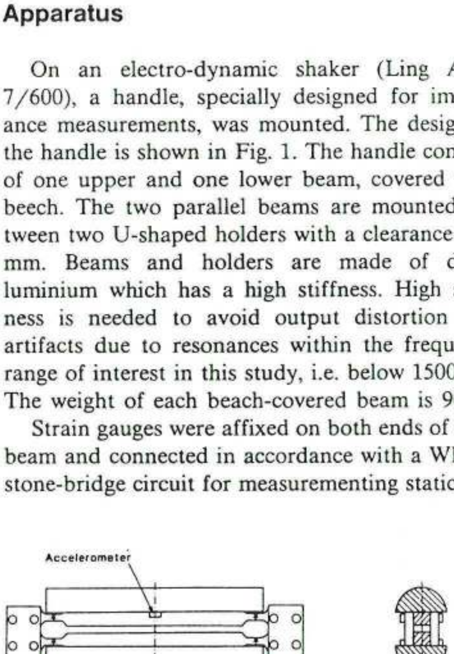

Fig. 1. Schematic drawing showing the design of the impedance handle and the location of the accelerometer and the strain gauges. More detailed information is also given in the text.

dynamic forces that are applied to the handle. The handle was also equipped with a small piezo-electric accelerometer (Endevco 2222 B) for vibration measurements. The location of the accelerometer is shown in Fig. 1.

The shaker was driven by a power amplifier (Ling Dynamic System, LDS 300) and a signal generator (Bruel & Kjear 1027). The signals from the accelerometer were amplified and electrically integrated to velocity signals by a charge amplifier (Bruel & Kjear 2635) before it was fed to a phasemeter (Bruel & Kjear 2971) and a level recorder (Bruel & Kjear 2305). Furthermore, the signals were fed to a feed-back network facility on the signal generator, which made it possible to maintain the amplitude of the vibration velocity at a constant level independent of the test frequency, static and dynamic loads.

The handle was designed for measuring the dynamic force, which mechanically activates the hand–arm system, and the grip, pull and push forces exerted by the subject. The dynamic force signals were amplified by a strain gauge bridge and fed to a RMS-recorder (Bruel & Kjear 2309) and a phasemeter (Bruel & Kjear 2971), showing a level proportional to the magnitude of the impedance and the phase relation between the force and velocity signals, respectively. From these data, together with the information about the stimulus amplitude, the mechanical impedance of the hand–arm system was determined.

Signals corresponding to static forces (grip, pull and push forces) were monitored on an oscilloscope in order to allow the subjects to achieve and maintain static force levels specified by the experimenter. Three grip force levels 25 N, 50 N, and 75 N, were used in the experiments. These hand grip forces were considered to be within the normal range during regular use of vibratory tools (Mishoe and Suggs, 1977). The subjects were instructed to apply no push and pull force during the test.

The vibration amplitude's effect on the hand–arm impedance was investigated by using three different velocity levels: 27 mm/s, 38 mm/s, and 53 mm/s. These velocity levels represent frequency-weighted acceleration levels of 12.6, 17.8, 25.1 m/s^2 in accordance with the International standard ISO 5349 (1986).

The test system was calibrated by using an accelerometer calibrator (Bruel & Kjear 4291) and by loading the handle, both statically and dynamically, with known weights.

Experimental procedure

Sinusoidal vibrations were delivered towards the right hand–arm system of eight male subjects (age 28–42 years, height 164–188 cm, weight 60–72 kg) with an increasing frequency from 20–1500 Hz (sweep rate: 50 s/decade). The subjects were asked to place themselves in one of the three postures shown in Fig. 2, while gripping the handle with a given force. Once the correct posture and grip force were achieved the frequency sweep was started. The subjects were asked to maintain constant level of the grip force during the sweep by looking at the monitored force signal on an oscilloscope. The test was restarted if the subject, for any reason, failed to maintain the specified hand grip force or posture. The test took about eight minutes and was repeated three times for each subject and variable combination. Altogether, it took 45 min, including pauses and repositioning. For each subject the number of tests was limited to two per day (rest period 4–6 h) in order to eliminate any possible effects of fatigue. Moreover, to avoid the risk of introducing systematical errors, tests were conducted randomly.

Twenty-three discrete frequencies, in the range of 20–1500 Hz, were chosen for data analysis. Directly from the charts of the level recorder both force and phase values were determined. These data, together with corresponding velocity amplitudes, were transferred to a computer which calculated the mechanical impedance of the

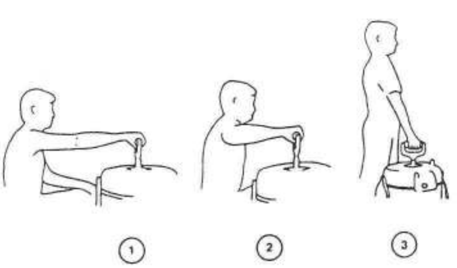

Fig. 2. The mechanical impedance of the hand–arm system has been studied as regards three different hand–arm postures. The postures have got a numerical code of 1–3 in the text according to the figure.

hand–arm system. A vectorial subtraction, i.e. mass cancellation, was performed for the entire frequency range for the additional impedance produced by the stimulus handle itself. The impedance of the handle was determined by vibrating the unloaded handle.

RESULTS

The results from various variable combinations were composed in order to determine how the mechanical impedance for the hand–arm system is influenced by different experimental conditions. Figures 3–5 show the average magnitude and phase of the impedance for each of the variable combination studied. As can be seen, a total spread in impedance magnitude of about 50–650 Ns/m was found. In general, the impedance increased rapidly with frequency above approximately 300 Hz, i.e. close to 24 dB/octave. For this frequency region, only small differences in impedance and phase relationships were observed to exist between all studied variable combinations.

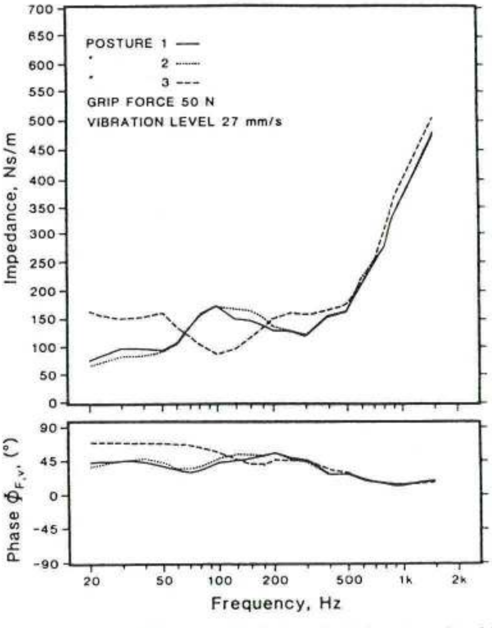

Fig. 3. Average impedance graphs for all subjects ($n = 8$) with respect to both magnitude and phase for different hand–arm postures (for more information, see text).

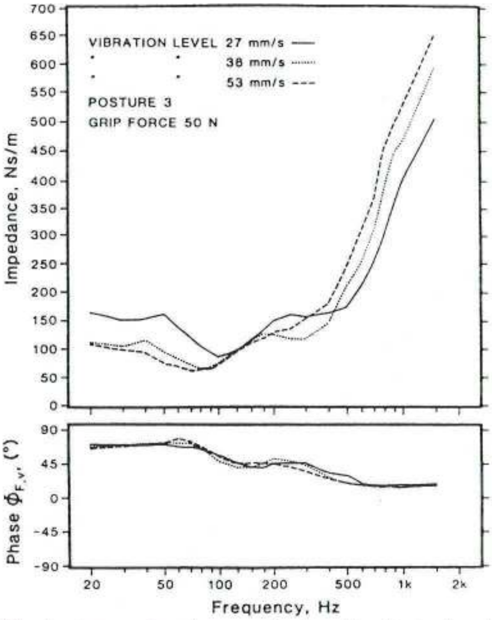

Fig. 4. Average impedance graphs for all subjects ($n = 8$) regarding both magnitude and phase for different stimulus amplitudes (for further information, see text).

For the lower frequency region, i.e. below about 300 Hz, more pronounced differences between impedance curves were observed. This was particularly true for different hand–arm postures (Fig. 3). For postures 1 and 2, the impedance first increased with the frequency from 20 Hz to up to about 100 Hz, and then decreased to a minimum in the region of 200–300 Hz. For posture 3, the impedance decreased with the frequency to a minimum at about 100 Hz; after that it increased again. There was, however, a tendency to peak at about 50 Hz for this posture. The peak seems to be especially pronounced at the lowest stimulus amplitude (Fig. 4).

When comparing impedance graphs, obtained with equal postures and grip forces but with different vibration levels as shown in Fig. 4, some interesting results are worth noticing. At low frequencies, the magnitude of impedance was found to be somewhat higher for low stimulus amplitude. The impedance magnitude, however, was lower for

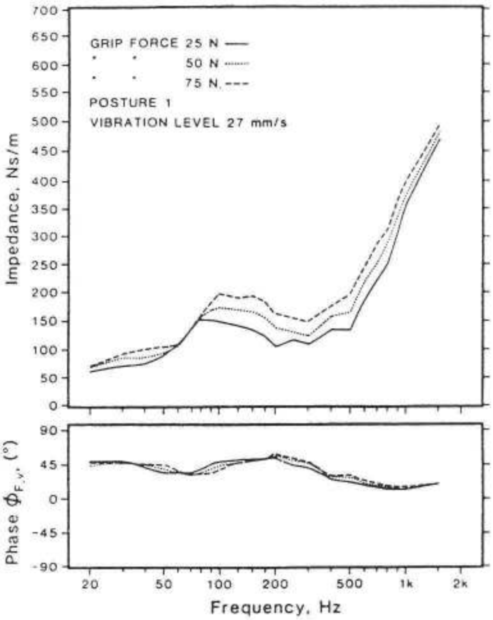

Fig. 5. Average impedance graphs for all subjects ($n = 8$) with respect to both magnitude and phase for different handgrip forces (for further information, see text).

low stimulus amplitude at higher frequency (Fig. 4). Furthermore, this figure also indicates a tendency to two minima, once close to 80–100 Hz and the other close to 300 Hz. This may be due to two different resonant frequency areas for the hand–arm system.

An increase of the stimulus amplitude leads to a corresponding increase in the force component provided that the mechanical properties of the mechanical system are linear within the amplitude range in question. According to the definition of the mechanical impedance, the magnitude of the impedance will therefore not be influenced. As mentioned earlier and as also shown in Fig. 4, this was not the case here. It can be stated, therefore, that the impedance of the hand–arm system is non-linear.

As expected, the results show that a clear relationship between the hand grip applied by subject and the magnitude of the impedance exists (Fig. 5). In general, the firmer the hand grip the higher the impedance. There is however a region close to 50 Hz where the impedance seems to be independent of the grip force. At lower frequencies the effect is less pronounced compared to the higher frequency region.

In this paper only average data for the hand–arm impedance, with respect to both magnitude and phase, is shown. No information has been given regarding the variability within and between subjects. At the compilation of data it was found that the magnitudes of the "within-subjects" standard deviations were quite small (within the range of ±25 Ns/m). Corresponding deviations for the phase angles were within ±10 deg. The magnitude of the "between-subjects" standard deviations was as expected more pronounced, up to about ±150 Ns/m and ±50 deg for the magnitude and phase, respectively.

DISCUSSION

The outcome of this investigation clearly shows that the mechanical impedance of the human hand–arm system is not only dependent on the frequency but also on the conditions of the vibration exposure, at least with respect to hand–arm posture, grip force and amplitude of the vibration stimuli. In addition to the fact that the hand–arm system has resonant frequencies close to, or within the range of 100–300 Hz, the system behaves in a non-linear way.

Comparison of results obtained in this investigation with studies carried out by others is difficult if not impossible. This is due to the fact that investigators in general have used either different measuring techniques or other experimental conditions as regards excitation levels, hand–arm postures, grip forces, etc. However, Panzke and Balasus (1985), in a review summarised in Fig. 6, concluded that most studies have been made with respect to hand–arm impedance in the *z*-direction, as defined in ISO 5349. For comparison, one corresponding graph obtained in this study, shown in Fig. 3 (posture 3, grip force 50 N, vibration level 27 mm/s) was inserted in Fig. 6. As can be seen, our results agree with those presented by Reynolds (1977), both showing comparatively low values for the impedance. Moreover, it can be concluded that almost all impedance graphs have a pronounced minimum within the frequency range of 50–150 Hz. It should be noted that most inves-

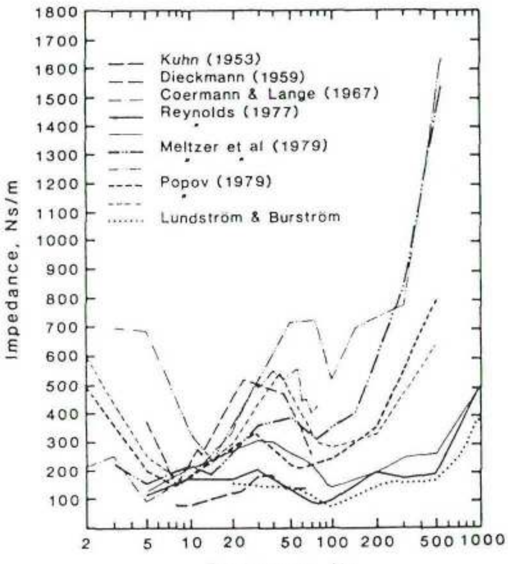

Fig. 6. Comparison of hand–arm impedance curves for the z-direction, as defined in ISO 5349, according to results found in this study and from earlier investigations (modified from Panzke and Balasus, 1985).

tigations are marred with uncertainties in the higher frequency region, i.e. above 500 Hz. There is a risk that the dynamic mass of the handle influenced the test results. This may be the result of either incorrect cancellation of the handle mass or none at all.

Again referring to Panzke and Balasus (1985), not as many investigations concerning the impedance in the x-direction, as defined in ISO 5349, have been carried out as in the z-direction. When comparing our data with those of the others, a relatively good agreement was found (Fig. 7). The closest agreement was with the results of Reynolds (1977).

As previously mentioned, various grip forces seem to have little or no influence on the impedance at lower frequencies, i.e. below 100 Hz. As the hand grip force is increased, the impedance values increase at all but the lower frequencies, where the hand–arm system seems to act as a pure and rigid mass. This finding is in agreement with results reported by Reynolds (1977) and Mishoe and Suggs (1977). In general, the hand–arm system must be considered as a highly damped system. As the frequency increases, the influence of mass-elements which are most distant from the vibration source decreases due to energy absorption in associated parts of the system. Quite naturally, this is followed by a decrease in vibration transmission up the arm. This process continues and remote elements become less active as the frequency is increased. With a progressively increased frequency, the final effect will be that the vibration tends to be more and more localized at the fingers and cutaneous tissues. In this region, large amounts of energy are consequently dissipated in small volumes of tissues which may be responsible for the cell and tissue destruction associated with the vibration syndrome.

The International Standard ISO 5349 (1986) risk assessment guidelines are based on "broad-banded frequency weighted acceleration levels". The frequency weighting is done within the range of about 5–1400 Hz with a filter, whose characteristics, expressed in terms of vibration velocity, decrease at the start by 12 dB per octave up to about 16 Hz. For higher frequencies the velocity signals should not be affected by the filter, assuming that the hand–arm system is equally sensitive within this region. The shape of this frequency weighting network is primarily based on studies regarding perception threshold and equal comfort contours for the hand resting on a vibrating table (Miwa, 1967, 1968). Ever since these guidelines were first proposed, several investigators have tried to correlate vibration measurements of tools with

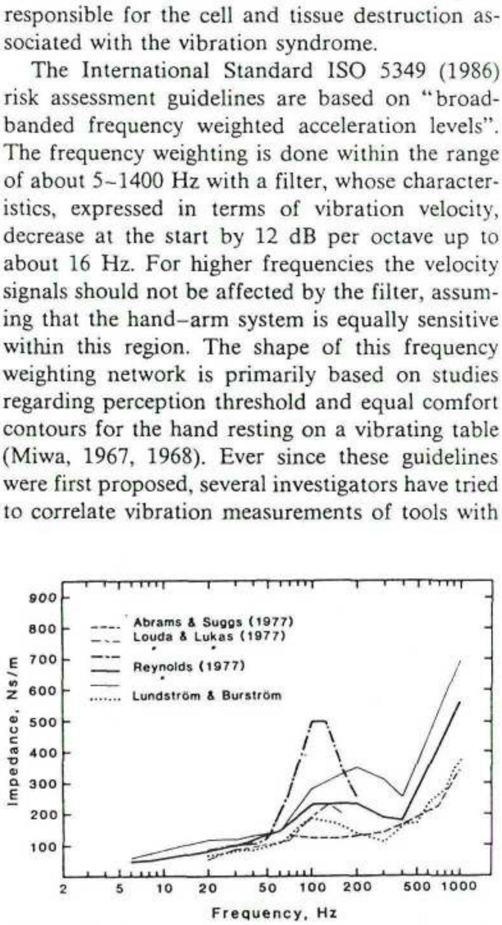

Fig. 7. Comparison of hand–arm impedance curves for the x-direction, as defined in ISO 5349, according to results found in this study and from earlier investigations (modified from Panzke and Balasus, 1985).

generated injuries. Some of these investigations have however led to contradictory results. There are of course, several possible explanations for these discrepancies. For instance, inadequate vibration measurements or incorrect determination of the exposure time. A model for a dose–effect relationship, based on a selected number of investigations, has however been constructed and shows somewhat better agreement (Brammer, 1982). This model is now added to ISO 5349 as an annex. Still, it is not possible to conclude that the guidelines given in this standard, and consequently the dose–effect model, are based on a wrong assumption, namely equal sensitivity within the frequency range of 16–1250 Hz. As has been shown in this study (Figs. 6 and 7), and in several others, the hand–arm system does not respond equally from a mechanical point of view within this frequency range. A large part of the handheld tools in use today have an operating frequency between 50 and 200 Hz. This is rather unfortunate, considering the mechanical properties of the hand–arm system. As is shown earlier, the system can be caused to vibrate easily with large mechanical loads as a consequence. Furthermore, several studies regarding vibro-tactile threshold measurements and neuronal responses from mechanoreceptive afferents have also shown an unequal sensitivity within this frequency range (For review and references, see Löfvenberg and Johansson, 1984; Lundström, 1986). Thus, there may be critical frequency ranges for the hand–arm system which should be taken into consideration when setting up future standards.

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PAPER II

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Mechanical energy absorption in human hand-arm exposed to sinusoidal vibration

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Summary. A possible basis for risk assessment of human exposure to vibration when using hand-held tools may be to determine the amount of mechanical energy that is absorbed by the hand-arm system. The aim of this investigation was to study the absorption of mechanical energy in the human hand-arm system during exposure to sinusoidal vibration within the frequency range of 20 to 1500 Hz. A handle, specially designed for this type of experiments, was used during the measurements. The influence of various experimental conditions, such as three different hand-arm postures, grip force (25–75 N) and vibration levels (27–53 mm/s_{rms}), were studied on eight subjects. The outcome clearly shows that the energy absorption properties of the human hand-arm system are more or less dependent on all of the experimental conditions studied, but mainly to the frequency of the vibration stimuli. Furthermore, the results indicate a non-linear relationship between the energy absorbed and all other variables studies.

Key words: Vibration – Hand-arm – Energy absorption

Introduction

The effects of vibrating hand tools upon human operators have been studied in many investigations and several hundreds of papers can be found in the literature (for a review, see Brammer and Taylor 1982). However, a great deal of uncertainty still surrounds the mechanisms with regard to the development of vibration injuries, such as vibration-induced white fingers (VWF).

In many studies the main emphasis has been on establishing a correlation between the vibration characteristics of the tool and the risk of injury (for references, see Brammer 1982). Several of these investigations have, however, produced conflicting results. This is probably due to the fact that human response to vibration is influenced by so many physical factors, among others frequency, intensity, duration, direction, grip force and working posture. Furthermore, the problem is accentuated by large biological variations among individuals.

In principle it is reasonable to assume that the biological effects might depend on the vibrational energy transmitted to and absorbed by the hand-arm system (see Cundiff 1976; Lidström 1976, 1977; Reynolds et al. 1982). These ideas are particularly supported by studies carried out by Lidström (1976, 1977), in which the prevalence of VWF seems to be very related to the amount of energy dissipated. However, only three categories of workers are covered by these studies, and this is not sufficient to ascertain whether or not these dose-effect relationships are generally applicable, or to elucidate its nature.

A mechanical system, such as the hand-arm system, can be broken down into a numerous number of separate elements consisting of masses, springs and viscous dampers (see Reynolds and Keith 1977). As a whole it constitutes what is usually called a mass-spring-system. Moreover, the response of the system can be divided into two components – one real and one imaginary. The real component reflects the viscous properties of the system, i.e. the energy absorbing part of the system. This is due to the transformation into heat by inner friction within the tissues. The imaginary part reflects the elastic properties of the system, i.e. this part does not consume any vibration energy (Anderson and Boughtflower 1978).

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The present paper is a description of some laboratory experiments carried out in order to study the energy absorption properties of the hand-arm system during exposure to sinusoidal vibration by measuring the force, velocity and phase between these factors. Furthermore, the aim has been to study how absorption of vibration energy dissipation is related to different hand-arm postures, grip forces and vibration levels.

Methods

The method used to measure the quantity of energy absorbed per unit time in the hand-arm system is based on the measurements of vibrational force and velocity made as closely as possible to the surface of the hand. This is obtained by using a handle specially designed for this type of experiment (Fig. 1), equipped with strain gauges and an accelerometer for force and vibration measurements, respectively.

Sinusoidal vibration were delivered by increasing frequency from 20 to 1500 Hz to the handle by means of an electrodynamic vibrator driven by a power amplifier and a signal generator. A piezoelectric accelerometer was mounted on the handle to control and record the vibration level. The output from the accelerometer was amplified and electrically integrated to a signal proportional to vibration velocity by a charge amplifier and fed to a level recorder and into a feed-back network facility on the signal generator. With this feed-back facility the velocity amplitude could be held on a constant level, independent of test frequency and static load. The force signal was amplified by a strain gauge bridge and fed to a level recorder. The phase relation between the force and velocity signals was simultaneously measured with a phasemeter and monitored on a level recorder. All signals were also monitored on an oscilloscope in order to ensure that no distorted signals appeared. During the experimental series the measurements of the force and velocity was done on both the upper and lower halves of the special handle to reduce the possibility of erroneous interaction between the strain gauges (see Fig. 1).

The study was carried out on the right hand and arm on eight healthy subjects. Each subject were tested on every experimental variable six times and each test period took about 3 min to carry out.

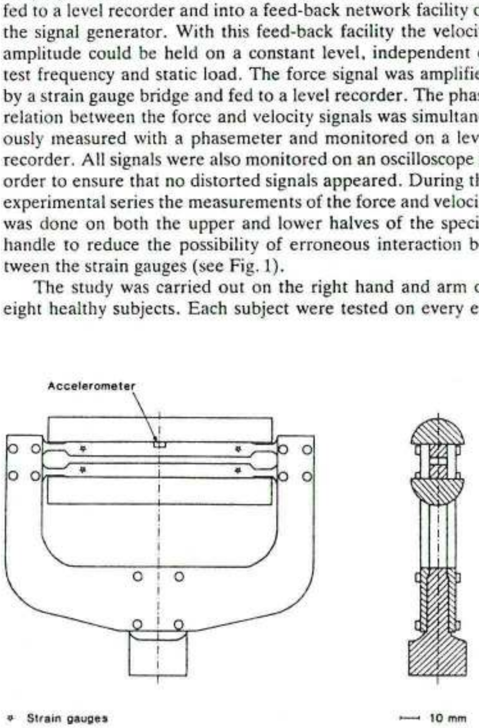

Fig. 1. The construction and design of the special handle. The handle is made of duraluminium enclosed in two beech bars

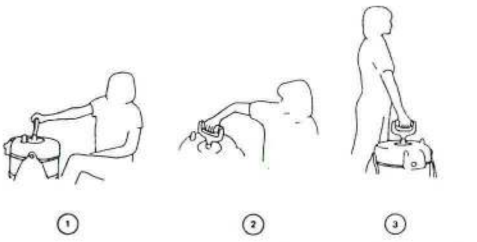

Fig. 2. Energy absorption per unit time was studied with three different hand-arm postures. The postures have a numerical code of 1 to 3 in the text according to the figure

Three different hand-arm postures were used (Fig. 2). Postures 1 and 2 represent the X-direction according to the basicentric coordinate system defined by ISO 5349. Accordingly Posture 3 represents the Z-direction.

Three quite realistic grip forces were used in the experiments (25, 50 and 75N). Furthermore, the vibration amplitude's effect on the dissipated energy was also investigated by using three different velocity levels (27, 38 and 53 mm/s_{rms}).

Twenty-three frequencies in the range of 20 to 1500 Hz were chosen for the data analysis. Directly from the chart of the level recorder, both force and phase angle values were transferred to a computer where energy absorption per unit time was calculated. These calculations also included a correction for the additional force produced by the handle itself, i.e. mass cancellation.

Results

The influence on the energy absorption per unit time by the different experimental conditions was studied by comparing results from various variable combinations. The frequency dependence on the energy dissipation was also investigated.

As can be seen in Fig. 3, the absorption of energy per unit time is dependent on the frequency. In general an increase in energy absorption with frequency could be observed. For Postures 1 and 2, however, small maxima occur in the frequency range of 50 to 150 Hz. This seems to be in agreement with the natural frequency for man's hand-arm system found in other studies (Reynolds et al. 1982; Lundström and Burström 1988). Moreover, it can be seen that there are clear differences between individuals.

On the basis of the average graphs in Fig. 4 it can be stated that the hand-arm system shows some differences with regard to energy absorption properties, depending on the hand-arm posture. The most pronounced differences are between Posture 3 and the other two, especially in the frequency range of 50 to 150 Hz. Between Postures 1 and 2 only a small differ-

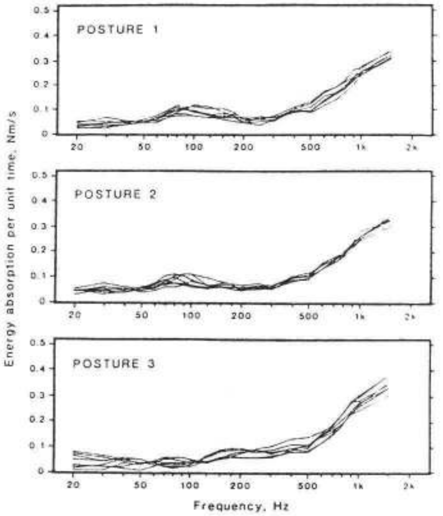

Fig. 3. Mean values of absorbed energy per unit time (Nm/s) for eight individual subjects during various hand-arm postures. Each mean-value-curve is based on data from six separate tests. During the experiment the grip force was 50 N and the vibration level 27 mm/s_{rms}

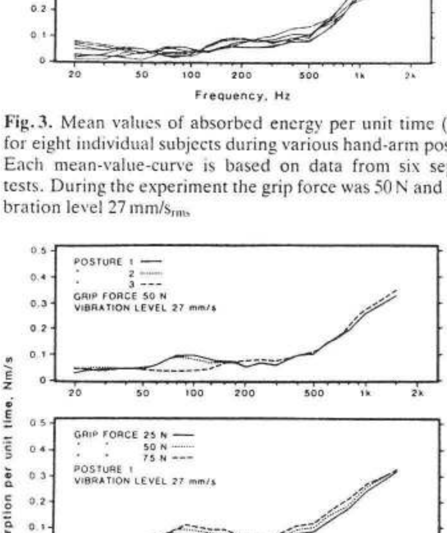

Fig. 4. Mean value of absorbed energy per unit time (Nm/s) in the hand-arm system during various experimental condition. Each curve was calculated from 48 experiments (8 subjects × 6 separate tests)

ence could be observed. As expected, firmer grip forces lead to a higher energy dissipation for frequencies above 75 Hz. At lower, however, the opposite was found.

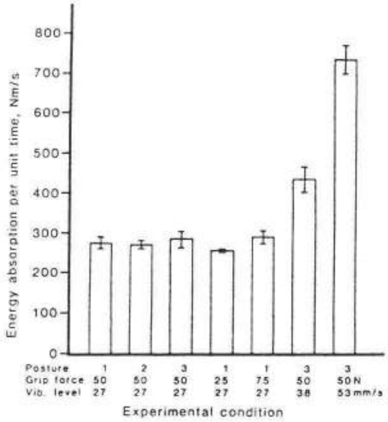

Fig. 5. Staples showing the mean value of the broad-banded energy levels for each variable combination based on 48 experiments (For more information, see text)

As can be seen in Fig. 4 the absorbed energy per unit time increases with the velocity amplitude, which in turn is most pronounced for higher frequencies.

The total amounts of energy absorption per unit time in the frequency range of 20 to 1500 Hz have been calculated by using Simpson's formula for numerical integration. The results are shown in Fig. 5 for the different variable combinations.

As can be seen, a total spread of about three times between variable combination leading to the highest and lowest energy absorption was found. Only minor influences due to different grip forces and hand-arm postures could be observed. As the power dissipation seems to increase quite rapidly with stimulus amplitude, it can be concluded that this is a very important factor in this respect. Furthermore, it can be seen that these relations are non-linear.

Discussion

With respect to the unsubstantiated premise that a higher amount of absorbed energy represents an increased risk of vibration injuries, or reduction in comfort, it can be seen that no significant differences exist between all studied postures. There are, however, some slight differences in absorbed energy within the frequency range of 50 to 150 Hz when comparing Postures 1 and 2 with Posture 3 (Fig. 4). As earlier mentioned Postures 1 and 2 represent the X-direction and Posture 3 the Z-direction according to the guidelines given in ISO 5349. This result is in agreement with earlier investigations (Mishoe and Suggs 1977; Burström and Lundström 1985). The minor differences found between Posture 1 and 2 indicate that the angle of the arm does not have a great influence on the total amount of absorbed energy.

As expected, tight handgrip forces lead to higher amounts of dissipated energy when looking over the whole frequency range studied. Somewhat surprisingly, the results indicated that the handgrip force affects energy dissipation very little, or not at all, at low frequencies. One explanation for this might be that the hand-arm system acts like a rigid body, not consuming any vibration energy.

The vibration level has a strong influence on the amount of absorbed power, particularly at higher frequencies (Fig. 4). The explanation for this is probably due to changes of the dynamic mass of the hand-arm system. When the stimulus amplitude increases, a larger part of the hand-arm system is in consequence mechanically activated. The real and energy consuming part of the dynamic mass therefore increases, leading to the possibility of more energy dissipating.

Further investigations of the mechanical properties of the human hand-arm system could provide an opportuntiy of calculating theoretically the amount of absorbed power, by using impedance data and vibration characteristics (amplitude and frequency) as tools. This could not only give further opportunities of finding a correlation between vibration data and generated injuries, but also be very useful when setting up future standards.

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PAPER III

MEASUREMENTS OF THE IMPEDANCE OF THE HAND AND ARM

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SUMMARY

The mechanical impedance of the hand and arm was studied on ten healthy subjects during exposure to sinusoidal vibration within the frequency range of 2 to 1000 Hz. A special handle for the measurements was constructed. The influence of vibration direction, handle grip, grip force, vibration level, hand-arm posture and sex as well as antropometric data were studied.The results show that the impedance of the hand-arm mainly depends on the frequency and direction of the vibration stimuli. Higher vibration levels, as well as more firm hand-grips, resulted in higher impedance. Furthermore, the outcome shows that experiments conducted with different hand-arm postures had an active influence on the mechanical impedance. Moreover, the subjects' sex and constitution of the hand and arm affected the impedance to a large extent.

Key words: Hand-arm - Measurement technique - Vibration.

INTRODUCTION

Vibration exposure of the hand and arm often produces an illness of the hands known as the vibration syndrome. It is most prevalent among workers using vibrating hand-held tools (see Brammer and Taylor 1982).

Vibrations have first of all a mechanical effect on the human hand-arm system due to the dynamic properties of the system. As a consequence of these mechanical effects, physiological effects occur depending upon several factors, such as intensity, frequency, direction and duration. Therefore, it is necessary to determine the dynamic properties of the hand-arm system in order to understand the physiological effects.

Mechanically, the hand and arm can be broken down into several separate elements consisting of masses of various structures and sizes, i.e. different bone structures, muscle groups, blood vessels etc., held together by different kinds of springs and viscous dampers (Hixon 1976, Reynolds and Keith 1977, Olesen and Randall 1979). It would be a hopeless task to give an exact description of this complex system with respect to all kinds of excitation of the whole frequency range not forgetting the fact that there is a great variation as to the individual. Nevertheless, when reviewing the literature, more or less sophisticated hand-arm models can be found (Reynolds and Soedel 1972, Mishoe and Suggs 1977). Although these models are simplified they can still provide information about how the hand and arm behave when exposed to vibrations.

Another possibility of obtaining a good insight into and describing the dynamic properties of the complex hand-arm system is to use a mechanical impedance technique (Mishoe and Suggs 1977). Similar to the measurement of a complex resistance, such as the so called impedance of an electrical circuit which consists of inductivities, capacities and resistances, it is possible to measure the mechanical impedance of the human hand-arm system. Like the electrical impedance, which is the complex ratio of the voltage to the current going through the circuit, the mechanical impedance (Z) is defined as the ratio of the transmitted force (F) to the velocity (v), i.e. $Z=F/v$ (Ns/m). This quantity can be measured for excitation by way of an experiment for each subject regardless of how complicated the system really is. Plotting the modulus of the impedance and the phase angle as the applied frequency gives two curves from which it it possible to derive, under certain limitations, the response of the subject's hand-arm system to vibration.

The modulus of the impedance can thereafter be decomposed into a large number of separate elements, consisting of masses, springs and viscous dampers. Fig. 1 shows how the separate impedance and phase characteristics vary with frequency and how they are generally represented in symbols (Coermann 1962, Hixon 1976, Lundström 1984).

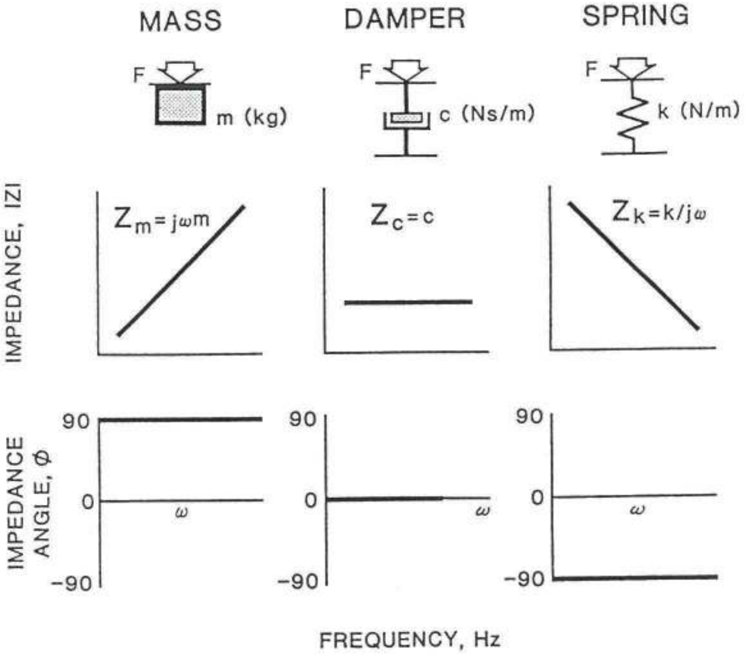

Fig. 1. The separate elements into which the mechanical impedance can be decomposed, mass, spring and damper. The upper part of the Fig. shows the symbols for separate elements in mechanical models, the lower part shows how the specific magnitude and phase of the impedance are frequency depen dent (after Lundström 1984).

In the literature the mechanical impedance of the hand-arm system have been studied in several investigations (see Panzke and Balasus 1985, Lundström and Burström 1989). However, the results from these studies do not generally show close agreement (Panzke and Balasus 1985). This is probably due to the fact that different experimental techniques and conditions were used.

The aim of this study was to investigate how the mechanical impedance of the human hand-arm system is related to different vibration directions, handle grips, grip forces, flexions of the elbow, abductions of the shoulder, hands, velocity levels and sex as well as the anthropometric data.

MATERIALS AND METHODS

Apparatus

The mechanical impedance of the hand-arm system was calculated by measuring vibration force and velocity as closely as possible to the surface of the hand (Fig. 2). The handle consists of two parallel beams between two U-shaped holders. The beams, one upper and one lower, were covered with a thick layer of polycarbonate. Between the handle and holders two force transducers (Brüel & Kjaer 8200) were mounted for dynamic force measurements. The handle was also equipped with a small piezo-electric accelerometer (Brüel & Kjaer 4374) for velocity measurements. At both ends of each beam, strain gauges were glued to measure both grip and pull/push forces applied by the subject to the handle. The weight of the handle was 225 g and the size elliptic was 31 x 42 mm.

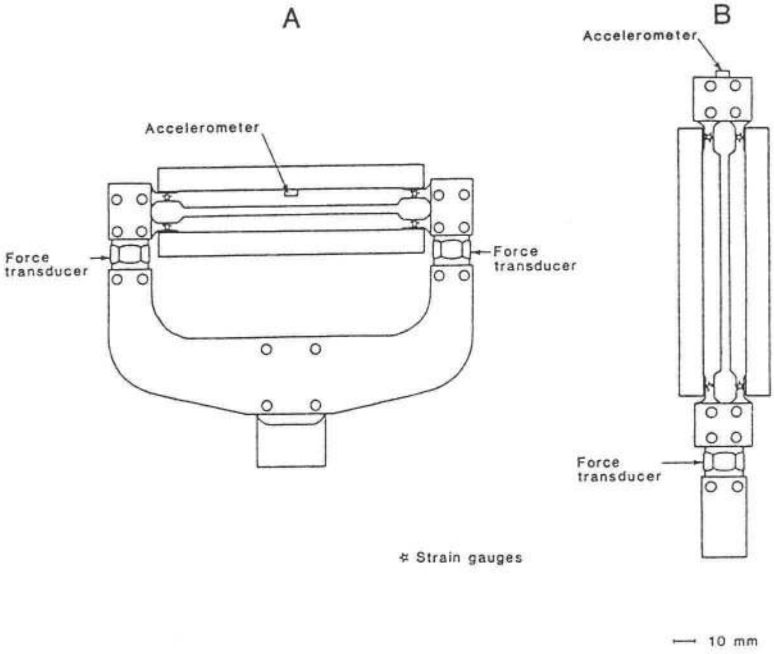

Fig. 2. Handle design and the location of the accelerometer, the force transducers and the strain gauges.

The handle was mounted on an electrodynamic shaker (Ling Altec 7/600) driven by a power amplifier (Ling Dynamic System, LDS 300) and a signal generator (Brüel & Kjaer 1027). Sinusoidal vibrations were delivered to the handle with an increasing frequency from 2 to 1000 Hz (sweep rate; 50 s/decade). The output from the accelerometer was amplified and integrated to velocity by a charge amplifier (Brüel & Kjaer 2635) before it was fed to a phase meter (Brüel & Kjaer 2971). The velocity signal was also fed to a feedback network facility on the signal generator in order to maintain the velocity amplitude at a constant level independent of test frequency and dynamic load. The varying outputs from each of the two force transducers were amplified by an charge amplifier (Brüel & Kjaer 2635) and afterwards summarized. The summarized force signal was fed into an RMS-recorder (Brüel & Kjaer 2309) and also to the phase meter. The phase between the force and velocity signals was also monitored on the RMS-recorder. The signals from the strain gauges were amplified by a strain gauges' bridge and monitored with a pointer instrument in order to give the subjects the possibility of both achieving and maintaining the grip and pull/push forces at the given level.

In order to collect data for different vibration directions of input to the hand, two different orientation of the handle were used. The one shown in Fig. 2A was used for proximal-distal and vertical direction. For the transverse direction the handle was mounted parallel to the vibration direction (Fig. 2B).

The measured dynamic force, velocity level, phase relationship and test frequency were, during each experiment, transferred to an on-line IBM AT-computer which calculated the mechanical impedance of the hand-arm system. For the entire frequency range these calculations also included a vectorial subtraction for the additional impedance produced by the handle itself, i.e. mass cancellation. The impedance of the handle itself was determined by vibrating the unloaded handle.

Subjects and studied variables

The study was carried out on ten healthy right-handed subjects, five males and five females, with no previous exposure to vibration. For the subjects some anthropometric parameters were measured, in order to study the influence of these variables on the mechanical impedance (Table 1).

During the experiments three different hand-arm postures were used in order to give a vibration exposure in the three orthogonal directions; vertical, transverse and proximal-distal. The hand-arm postures with these directions are schematically shown in Fig. 3. In accordance with ISO 5349 these directions are defined as an exposure in X_h-, Y_h- and Z_h-direction.

Table 1. Anthropometric data for the subjects right hand and arm (for definitions see Van Cott and Kinkade 1972).

	Sex	Age	Height (cm)	Weight (kg)	Hand length (cm)	Hand breadth at thumb (cm)	Hand breadth at meta-carpal (cm)	Hand thick-ness (cm)
Subj. 1	M	44	186	70	21.0	11.0	9.5	3.0
" 2	M	44	179	72	18.3	10.3	8.5	2.8
" 3	M	29	177	68	18.4	10.4	8.6	2.9
" 4	M	34	175	66	18.5	10.7	8.5	2.9
" 5	M	27	181	82	20.1	11.7	9.2	3.3
" 6	F	42	158	48	16.1	8.6	7.0	2.3
" 7	F	39	171	59	17.4	8.8	7.6	2.5
" 8	F	28	170	59	16.7	8.4	6.9	2.5
" 9	F	33	161	54	16.4	9.1	7.6	2.5
" 10	F	34	164	59	17.3	9.7	7.8	2.7
Mean		35.4	172.2	63.7	18.0	9.9	8.12	2.7
SD		6.5	9.12	9.86	1.59	1.12	0.88	0.30

	Sex	Hand volume (ml H_2O)	Shoulder-elbow length (cm)	Forearm-hand length (cm)	Forearm volume (ml H_2O)	Arm volume (ml H_2O)	Maximum gripforce (N)
Subj. 1	M	490	41.0	51.5	1695	3820	62.6
" 2	M	360	36.0	46.0	1300	3750	63.7
" 3	M	380	38.0	45.5	1345	3530	46.5
" 4	M	400	38.0	46.0	1560	3750	60.2
" 5	M	450	40.0	49.5	2050	4570	56.5
" 6	F	220	33.5	39.0	735	1910	21.8
" 7	F	290	37.0	44.0	1055	2640	27.3
" 8	F	270	36.0	43.5	1090	3075	28.8
" 9	F	260	33.5	40.5	930	2340	27.6
" 10	F	320	36.0	43.5	1095	2955	40.4
Mean		344.0	36.9	44.9	1285.5	3234.0	43.5
SD		87.33	2.46	3.75	392.76	799.76	16.47

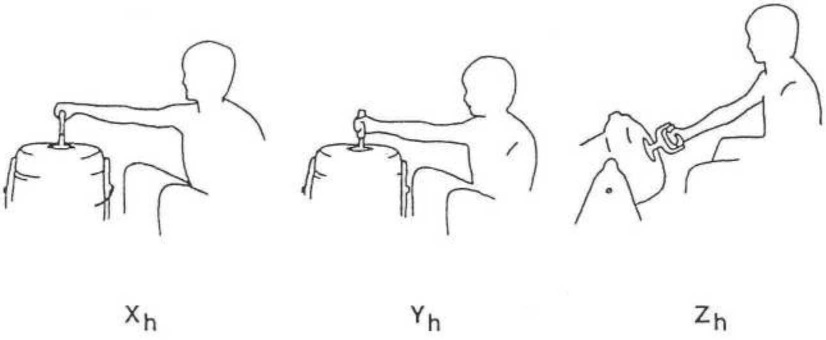

Fig. 3. Hand-arm postures used in order to get a vibration exposure in the three different directions X_h, Y_h and Z_h, as defined in ISO 5349.

Three grip forces were used in the experiment (25, 50 and 75 N) and the influence of the angle between upper arm and forearm was studied for five positions (60, 90, 120, 150, 180°). Moreover, the influence of a 90° angle between the shoulder and upper body was investigated as well as the differences between left and right hand-arm systems. Furthermore, two different handle grips were used in the study - from above and from below. The effect of the vibration amplitude on the hand-arm impedance was also investigated by using four different velocity levels (8, 14, 25 and 45 mm/s). These velocity levels represent frequency-weighted acceleration levels of 0.8, 1.4, 2.5 and 4.5 m/s^2 within the frequency range of 16 to 1000 Hz in accordance with ISO 5349.

Experimental procedure

All subjects were asked before each experiment to wear normal office clothes (without jackets) and were asked to remove rings, watches etc to minimize any possible effects of clothing. The subjects were then asked to place themselves in one of the postures, gripping the handle with a given force. After the correct posture and grip force was accomplished, the frequency sweep was started. The subjects were requested to keep the grip force on a constant level during the sweep by looking at a monitored force signal on a pointer instrument. The test was restarted if the subject for any reason failed to retain the hand-grip force or posture. Furthermore, the subjects were asked to control that no pull/push-forces were affecting the handle. Every test took about 8 min to conduct including pauses and repositioning. The total number of tests for each subject were 22 and the tests were limited to only one per day in order to eliminate any possible effects of fatigue.

RESULTS

The influence of the different experimental conditions on the mechanical impedance are presented in Fig. 4A-H and Table 2, where the average magnitudes and phases of the mechanical impedance are shown. The standard deviation for the results are also shown in Table 2.

As can be seen, the mechanical impedance is dependent on the frequency of the vibration stimuli, and a variation of about 10 to 700 Ns/m could be observed over the entire frequency range.

A comparison of the impedance average graphs in Fig. 4A shows that the mechanical impedance differs between the three vibration directions studied. For vibration exposure in the X_h-direction the impedance increases with the frequency from 2 Hz up to a maximum of about 150 Hz, followed by a decrease towards a minimum in the region of 300 Hz. Above 300 Hz the influence generally increases in quite rapidly with the frequency. The Y_h-direction is characterised by quite a low impedance which increases with frequency towards a maximum of about 40 Hz, followed by a decrease towards a minimum in the region of 200 to 300 Hz. Above 300 Hz an increase of the impedance with the frequency can be seen. For the Z_h-direction the impedance increases with frequency towards a maximum at 20 Hz followed by a decrease towards a minimum at about 100 Hz, after that it increases again similar to the X_h-direction.

When comparing the phase graphs obtained for the three vibration directions, it can be seen that the phase graphs have pronounced differences, especially in the frequency range of 10 to 500 Hz.

As can be seen in Fig. 4B, the grip direction has only a small influence on the mechanical impedance. The most pronounced differences can be found below 100 Hz, and hand grips from below give a higher impedance of the hand-arm system.

In Fig. 4C the average magnitude and phase of the impedance is presented for different grip forces and for two different velocity levels, 14 and 45 mm/s. The results show that there is a clear relation between the hand grip applied by the subject and the magnitude

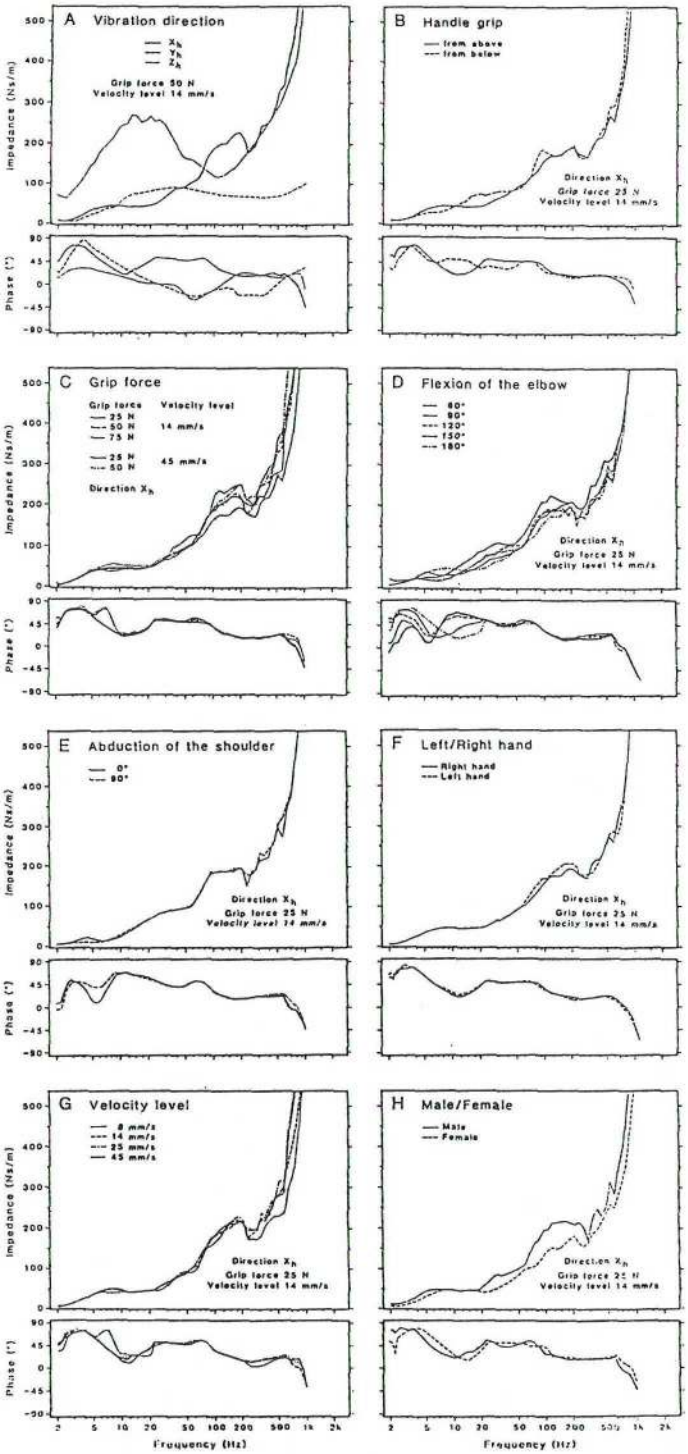

Fig. 4. Mean values for the magnitude and phase of the mechanical impedance for eight different variable combinations. The average values are based on data from ten different subjects.

of the impedance. Firmer hand grips lead to a higher impedance. The increase of the impedance magnitude also seems to be higher at the lower velocity level. There is, however, a tendency in the frequency region below 80 Hz for the impedance to be independent of the grip force. The phase of the impedance for different grip forces and velocity levels shows only small differences.

As can be seen in Fig. 4D, the angle between upper arm and forearm (the flexion of the elbow) has an influence on both the magnitude and phase of the impedance. A tendency is that an increase of the angle gives a higher impedance. For the phase of the impedance the differences is specially pronounced in the frequency region below 20 Hz.

The angle between shoulder and body (the abduction of the shoulder) has no influence on the impedance (Fig. 4E).

When comparing the impedance and phase graphs, obtained with equal postures and grip forces but with either left or right hand exposed, it can be seen (Fig. 4F) that the left hand-arm system has a slightly higher magnitude of impedance.

Fig. 4G shows the influence on the impedance and phase of different vibration levels. The magnitude of the impedance increases slightly when the vibration level increases. The phase of the impedance is, however, almost the same. It is worth noticing that the differences for the impedance magnitude are specially pronounced in the frequency region above 200 Hz.

Fig. 4H shows the average magnitude and phase of the mechanical impedance for males and females, respectively. The Fig. shows that females have a lower mechanical impedance than males and the differences are specially pronounced in the frequency region above 20 Hz. These graphs illustrate one of the studied variable combinations, but the same tendency could be found for the other variable combinations. The average difference between males and females are for all variable combination about 20%. Student's t-tests (Box et al 1978) also show that these differences are significant ($P < 0.0005$). The phase of the impedance does not show the same divergence.

From Table 2 it can be seen that the magnitude of the "between subjects" standard deviation for the results is greatest at the lowest and the highest frequencies. Furthermore, it can be observed that

Table 2. Mean values for the magnitude (Ns/m) and phase (degree) of the mechanical impedance for different variable combinations. The standard deviation are presented within the parentheses. The normal flexion of the elbow is 180° and the abduction of the shoulder 0°.

Vibration direction	Vibration level (mm/s)	Grip-force (N)	Quantity	FREQUENCY (Hz)								Comments
				2	5	10	20	50	100	200	500	
X_h	14	50	Imped. Phase	7.7 (5.5) 73 (23)	37.3 (7.6) 51 (13)	37.2 (7.9) 18 (14)	34.3 (16.3) 48 (17)	88.6 (27.0) 46 (11)	170.2 (39.0) 33 (14)	175.9 (31.1) 9 (12)	265,0 (91.9) 18 (29)	
Y_h	14	50	Imped. Phase	11.0 (6.1) 53 (23)	28.6 (13.0) 65 (9)	59.7 (30.7) 25 (10)	61.8 (22.9) -2 (12)	73.4 (24.4) -19 (20)	55.8 (13.1) -2.6 (23)	70.2 (12.2) -28 (24)	44.2 (72.2) -20 (26)	
Z_h	14	50	Imped. Phase	65.1 (31.0) 30 (15)	160.3 (45.4) 24 (7)	218.9 (62.4) 6 (10)	222.3 (44.7) -1 (19)	142. 7 (36.9) -25 (13)	101.9 (30.1) -5 (17)	170.8 (103.0) 19 (17)	276.6 (168.0) 9 (16)	
X_h	14	25	Imped. Phase	7.0 (3.3) 74 (28)	36.9 (10.3) 54 (16)	38.8 (6.9) 20 (14)	40.8 (11.3) 40 (9)	85.1 (16.5) 49 (11)	152.6 (31.7) 35 (14)	164.1 (31.5) 16 (6)	254.6 (64.0) 27 (9)	
X_h	14	25	Imped. Phase	7.9 (3.6) 71 (21)	30.8 (8.0) 28 (10)	27.0 (6.1) 33 (11)	52.3 (15.9) 54 (3)	83.7 (22.2) 48 (12)	157.9 (37.8) 32 (11)	167.0 (32.8) 12 (11)	245.8 (61.5) 23 (14)	Flexion 150°
X_h	14	25	Imped. Phase	7.8 (2.3) 63 (19)	16.5 (4.5) 23 (16)	28.0 (7.7) 63 (9)	67.0 (32.0) 58 (7)	93.3 (30.5) 48 (14)	170.1 (36.7) 29 (14)	175.6 (36.4) 17 (8)	254.5 (56.0) 25 (12)	Flexion 120°
X_h	14	25	Imped. Phase	6.8 (7.1) 40 (23)	14.0 (4.0) 11 (25)	26.9 (8.7) 69 (5)	60.0 (18.8) 57 (6)	83.9 (22.5) 44 (11)	165.5 (43.1) 30 (14)	172.0 (28.5) 16 (8)	260.1 (48.7) 23 (8)	Flexion 90°
X_h	14	25	Imped. Phase	14.9 (17.3) 22 (28)	22.1 (19.5) 12 (21)	41.9 (35.2) 69 (5)	78.6 (36.1) 58 (5)	107.0 (48.6) 54 (10)	183.0 (43.5) 33 (19)	186.4 (33.3) 20 (10)	281.7 (71.6) 28 (12)	Flexion 60°
X_h	14	25	Imped. Phase	7.7 (4.7) 54 (21)	25.6 (5.8) 47 (9)	41.1 (13.5) 51 (8)	61.6 (21.1) 37 (13)	78.6 (20.2) 42 (14)	159.8 (35.5) 7 (14)	177.7 (38.4) 10 (8)	256.4 (71.8) 16 (12)	Grip from below
X_h	14	75	Imped. Phase	8.5 (5.1) 70 (22)	42.4 (7.8) 54 (13)	45.2 (6.1) 21 (11)	48.2 (14.3) 53 (11)	108.2 (25.7) 50 (12)	203.7 (67.7) 39 (14)	219.7 (36.7) 17 (10)	315.6 (120.8) 27 (9)	
X_h	14	25	Imped. Phase	5.8 (3.3) 32 (25)	10.5 (3.3) 39 (32)	30.9 (10.9) 68 (7)	64.9 (16.0) 53 (8)	86.0 (26.0) 45 (10)	162.6 (48.0) 25 (14)	169.5 (36.2) 17 (7)	278.3 (67.8) 29 (7)	Abduct. 90°
X_h	14	25	Imped. Phase	6.8 (4.0) 78 (22)	36.2 (9.3) 52 (5)	40.8 (4.5) 24 (12)	42.2 (14.0) 48 (13)	87.0 (26.3) 51 (7)	149.7 (51.7) 30 (18)	184.4 (28.5) 13 (9)	246.5 (37.7) 20 (6)	Left hand
X_h	8	25	Imped. Phase	7.0 (3.6) 66 (21)	38.8 (10.5) 50 (12)	37.0 (6.9) 10 (14)	37.3 (9.1) 37 (12)	81.6 (18.5) 48 (9)	150.2 (57.9) 30 (18)	185.2 (25.7) 13 (13)	211.8 (36.5) 8 (25)	
X_h	25	25	Imped. Phase	6.3 (4.0) 74 (22)	38.1 (7.5) 57 (12)	36.3 (7.3) 21 (12)	43.5 (11.3) 43 (9)	85.6 (18.4) 52 (10)	165.3 (35.6) 35 (13)	191.4 (17.9) 14 (6)	290.6 (62.8) 27 (9)	
X_h	45	25	Imped. Phase	6.1 (3.3) 68 (33)	35.6 (7.5) 65 (11)	37.3 (6.9) 27 (11)	43.9 (11.6) 51 (8)	83.8 (17.7) 53 (8)	162.0 (29.3) 34 (12)	186.8 (23.8) 12 (5)	253.9 (68.0) 21 (17)	
X_h	45	25	Imped. Phase	7.1 (2.9) 69 (23)	38.8 (8.7) 69 (21)	41.9 (11.0) 25 (8)	46.2 (13.9) 49 (8)	89.0 (16.4) 52 (8)	174.1 (44.6) 38 (12)	222.0 (35.9) 16 (8)	309.9 (68.6) 27 (13)	
X_h	14	25	Imped. Phase	10.9 (2.9) 83 (17)	42.7 (7.9) 42 (18)	38.9 (2.4) 22 (7)	53.6 (8.3) 57 (5)	95.0 (11.8) 52 (8)	180.6 (23.7) 25 (6)	182.0 (32.2) 18 (8)	313.0 (56.7) 30 (9)	Male
X_h	14	25	Imped. Phase	5.0 (1.6) 64 (35)	34.1 (10.8) 63 (8)	40.5 (9.9) 21 (20)	36.2 (5.1) 39 (7)	81.7 (18.4) 50 (12)	135.6 (19.7) 39 (17)	161.6 (13.8) 18 (4)	232.2 (31.5) 23 (9)	Female

one tendency is that a firmer handgrip gives a larger standard deviation. Moreover, in the data analysis, it was found that the magnitudes of the "within-subjects" standard deviations were in the range of 15 Ns/m and corresponding deviations for the phase angle were 10 degrees. The magnitude of the "between-subjects" standard deviations was about 150 Ns/m for the magnitude and 35 degrees for the phase.

In Fig. 5 the results from performed correlation analyses (Box et al 1978) between anthropometric data (Table 1) and calculated mechanical impedance for the subjects' hand-arm system are presented. The Fig. shows which anthropometric factor has the highest correlation to the individual mechanical impedance within different frequency regions. The correlations are calculated for all studied variables in the X_h-direction.

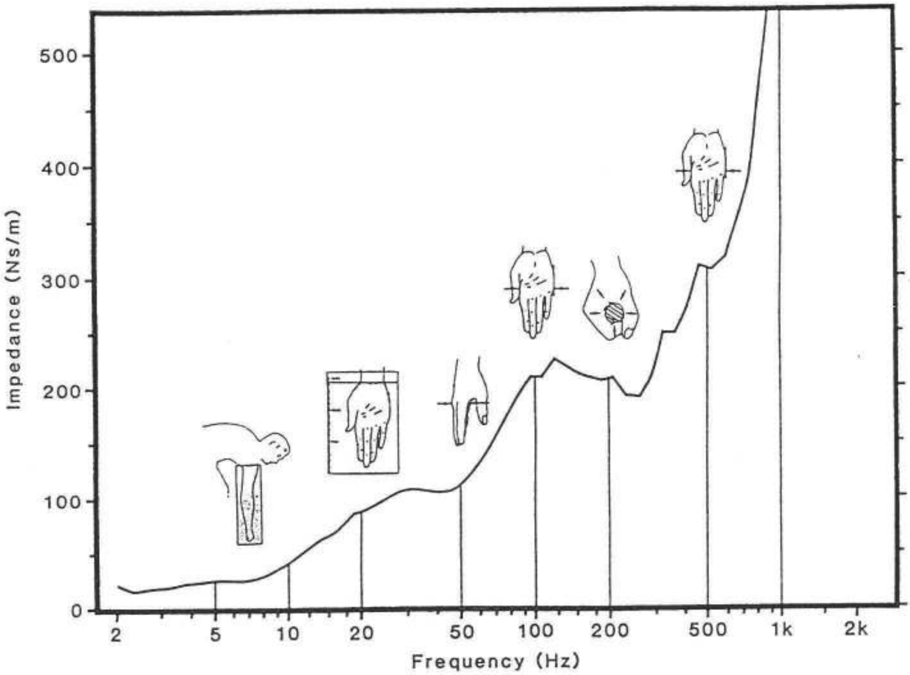

Fig. 5. Correlation between different biological factors of the subjects' hand-arm systems and the mechanical impedance as a function of the frequency (Vibration direction X_h).

As can be seen, the mechanical impedance has the highest correlation to the volume of the whole hand-arm system in the low frequency region. Above 15 Hz, however, factors describing the hand have the highest correlation against the impedance. Furthermore, in the frequency range of about 200 to 300 Hz, where the impedance has a low point, the highest correlation was found for the grip force applied by the subject.

DISCUSSION

This investigation shows that the mechanical impedance depends more or less on all studied variables, but especially on vibration direction and the amplitude of the vibration stimuli. In addition to the fact that the hand-arm system has resonant frequency areas, the system behaves in a non-linear way. Furthermore, the results show that hand-arm postures, vibration directions and grip forces have an active influence on the magnitude and phase of the mechanical impedance.

The mechanical impedance of the human hand-arm system has earlier been studied in many investigations, but only a few of these studies have presented both the magnitudes and the phases of the impedance. It is complicated to make a comparison between the present data and these earlier studies because of the very different experimental conditions, such as measuring techniques, subjects, grip forces, postures etc. Therefore, the following comparison is rather informal. However, the earlier investigations (Abrams and Suggs 1977, Mishoe and Suggs 1977, Reynolds 1977, Hempstock and O'Connor 1986) have been transformed to mechanical impedance in SI-units and are summarized in Fig. 6, as a function of the frequency. For comparison a corresponding graph obtained in this study, shown in Fig. 4A (grip force 50 N, vibration level 14 mm/s), has been inserted in Fig. 6, one for each direction. It should also be noted that the most investigations are marred with uncertainties in the lower frequency region, i.e. below 10 Hz and for frequencies above 500 Hz.

The most frequent studies of the hand-arm impedance have been made in the X_h-direction, for which four investigations have been found (Abrams and Suggs 1977, Mishoe and Suggs 1977, Reynolds 1977, Hempstock and O'Connor 1986). As can be seen, the results from the present study show close agreement with those presented by Mishoe and Suggs (1977). Characteristic for all graphs is that the magnitude has a pronounced maximum within the frequency range of 90 to 200 Hz. Furthermore, there is a tendency for two minima, one in the frequency range of 40 to 60 Hz and one in the range of 200 to 400 Hz. The phase relationships of the impedance have a large variation and the results from the present investigation are most closest to those presented by Reynolds (1977). Typical for all graphs is that the phase of the impedance is about 45 degrees within the frequency range of 20 to 80 Hz, followed by a decrease against a minimum within the frequency range of 100 to 300 Hz. Above 300 Hz the phase increases again.

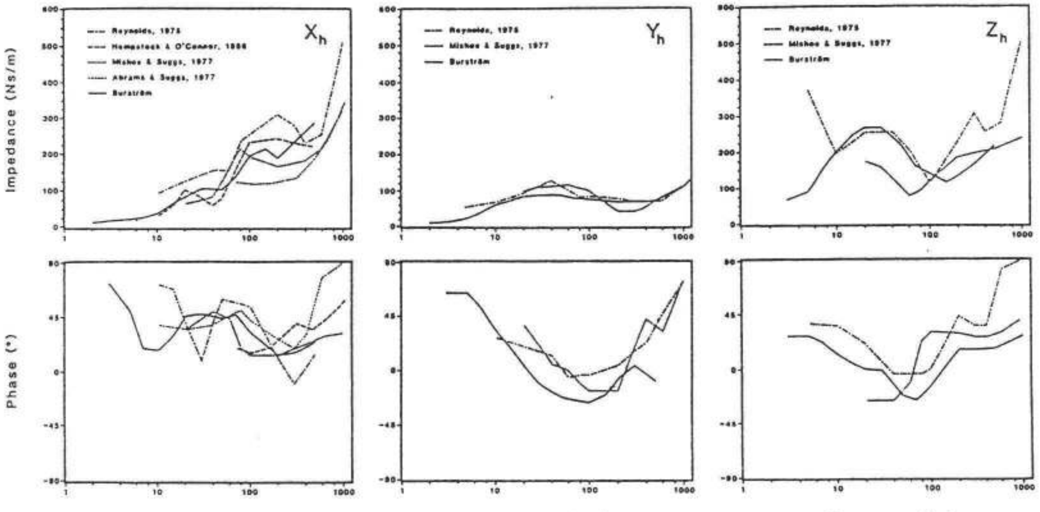

Fig. 6. Comparison of hand-arm impedance curves for the three different vibration directions, as defined in ISO 5349, according to results found in the present study and from earlier investigations.

For the Y_h- and Z_h-directions, Fig. 6 show that a relatively good agreement exists between the present data and earlier investigations (Mishoe and Suggs 1977, Reynolds 1977). For the Y_h-direction the magnitude of the impedance is characterised by a maximum within the frequency range of 2 to 40 Hz and a minimum within 300 to 500 Hz. The phase of the impedance is about 60 degrees in the low frequency area followed by a minimum between 80 to 100 Hz of about -20 degrees. Above 100 Hz the phase increases again. For the Z_h-direction the magnitude of the impedance has a maximum within the frequency range of 40 to 60 Hz and a minimum of about 100 to 200 Hz. The largest variation between the investigations is found in the low frequency area where the present investigation shows that the impedance decreases, but the investigation carried out by Reynolds (1977) shows the opposite. The phase of the impedance is characterized by a decrease against a negative value within a the frequency range of 30 to 100 Hz followed by an increase.

The hand-arm system normally has a high damping which increases with frequency. In the low frequency range the hand-arm system reacts more or less like a pure mass. When the frequency increases the influence of mass elements which are most distant from the vibration source decreases, followed by a decrease in vibration transmission up the arm (Lundström and Burström 1989). This process continues and when the frequency reaches 1000 Hz only small volumes of tissues are exposed to vibration.

The results show the importance of keeping factors depending on the posture of the whole body under control when measuring the mechanical impedance. For instance, a slightly bent arm, i.e. with different angles between upper arm and forearm, affects the magnitude of the impedance. No significant differences seem to exist between the subjects' left and right hand-arm systems, which is in agreement with earlier investigations (Mishoe and Suggs 1977).

An increased handgrip force leads to an increased magnitude of impedance at higher frequencies. Tentatively, this is preliminarily due to the mass-like behaviour of the hand-arm system in this region. Furthermore, it is worth noting that the relation between increased gripforce and increased impedance are not linear. One reason could be that the impedance depends on the amount of viscous elements in the hand-arm system. This amount of viscous elements is influenced by the tension of the muscles and a higher tension enables the vibrations to put a larger part of the hand-arm system in motion, which causes the apparent mass and the impedance of the system to increase. The reason for the non-linear behaviour could be that the amount of viscous elements is limited in the hand and arm. With an increased gripforce the muscles do not strain a corresponding amount of viscous elements. This could explain the comparatively smaller increase of the mechanical impedance.

The vibration level has a rather strong influence on the magnitude of the impedance, particularly at higher frequencies. The explanation for this could be that when the stimulus amplitude increases, a larger part of the hand-arm system is mechanically activated, and the dynamic mass of the system increases, leading to higher impedance.

The influence of the biological factors (anthropometric data) on the impedance presumably depends on differences in the construction of the subjects' hands and arms. A tendency in the data is that larger biological size gives a higher mechanical impedance. This could explain why females have a lower impedance than males.

A high mechanical impedance must not necessarily be detrimental. In principle it is reasonable to assume that the biological effects might depend on the vibration energy transmitted to and absorbed by the hand-arm system (Cundiff 1976, Lidström 1977, Reynolds et al. 1982). The variation of the mechanical impedance only affects the transmission of vibration into the hand-arm and therefore gives no information about the risk of injury. According to the guidelines given in the International Standard ISO 5349 (1986) risk assessments are based on "broad-banded frequency weighted acceleration levels" within the frequency range of 5 to 1500 Hz. The frequency weighting should be done with a filter whose attenuation, expressed in terms of vibration velocity, decreases from the start by 6 dB per octave up to 16 Hz. For higher frequencies of up to 1500 Hz the velocity signals should not be affected by the filter. From a mechanical point of view this filter describes a pure mass below 16 Hz and a viscous damper above. The results from this study and from others (Fig. 6) shows, however, that the response of the hand-arm system is not equal for frequencies within the range of 16 to 1400 Hz.

Further investigations of the mechanical properties of the human hand-arm system are needed and could provide an opportunity of calculating theoretically the amount of absorbed energy, by using impedance data and vibration characteristics (amplitude and frequency) for a hand-held tool. This not only gives an opportunity of determining the individual risk of vibration exposure, but could also be very useful when setting up future standards.

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PAPER IV

ABSORPTION OF VIBRATION ENERGY IN THE HUMAN HAND AND ARM

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Abstract

A possible basis for risk assessment for hand-transmitted vibration may be to determine the amount of energy absorbed in the human hand and arm. In the present study the mechanical energy absorption in the hand-arm system has been measured within the frequency range of 4 to 1000 Hz. The study was carried out on ten healthy subjects during exposure to sinusoidal vibration. The influence of various experimental conditions, such as vibration direction, grip force, vibration level and hand-arm posture were studied. The outcome shows that the energy absorption in the human hand and arm mainly depends on the frequency and direction of the vibration stimulus. Higher vibration levels, as well as more firm handgrips, resulted in higher absorption of energy. Furthermore, the results show that varying hand-arm postures had only a small influence on the amount of absorbed energy. On the contrary, the constitution of the hand and arm affected the energy absorption to a larger extent.

Key words: Vibration, Hand-transmitted, Energy absorption

Resume

Une base possible d'évaluation de risque de vibration transmise à la main peut être de déterminer la somme d'énergie absorbée par la main et le bras humain. Au cours de la présente étude, l'absorption énergitique mécanique de l'ensemble main-bras a été mesurée dans une plage de fréquence de 4 à 1000 Hz. L'étude a été menée sur dix sujets sains pendant exposition à vibration sinusoidale et on y a relevé l'influence de différentes conditions expérimentales telles que direction de la vibration, force de préhension, niveau vibratoire et position main-bras. Le résultat montre que l'ábsorption énergitique de la main et du bras de l'homme dépend principalement de la fréquence et de la direction des stimuli vibratoires. De hauts niveaux de vibrations tout autant que des saisies plus plus fermes, ont pour résultat une plus grande absorption d'énergie. En outre, les résultats indiquent que les expériences faites avec différentes positions main-bras n'ont qu'une faible influence sur la quantité de l'énergie absorbée. Par contre, la constitution de la main et du bras affecte grandement l'absorption d'énergie.

Zusammenfassung

Eine mögliche Basis für die Risikobeurteilung der auf die Hand übertragenen Vibrationen könnte die Festlegung der Energiemenge sein, die von der menschlichen Hand/ dem menschlichen Arm absorbiert wird. In der vorliegenden Untersuchung erfolgte die Messung der mechanischen Energieabsorption im Hand-/Armsystem innerhalb des Frequenzbereiches 4-1000 Hz. Die Untersuchungen wurden an zehn gesunden Versuchspersonen vorgenommen, indem sie sinusförmigen Vibrationen ausgesetzt wurden. Der Einfluβ verschiedener Versuchsbedingungen, wie Vibrationsrichtung, Greifkraft, Vibrationsniveau und Hand-/Armstellung wurde untersucht. Das Ergebnis zeigt, daβ die Energieabsorption in der menschlichen Hand/ dem menschlichen Arm hauptsächlich von der Frequenz und der Richtung des Vibrationsreizes abhängig ist. Sowohl hohe Vibrationsniveaus als auch kräftigeres Greifen führten zu einer höheren Energieabsorption. Weiter zeigen die Ergebniβe, daβ Verusche, die mit unterschiedlichen Hand-/Armstellungen durchgeführt wurden, die absorbierte Energiemenge nur geringfügig beeinfluβen. Dagegen wird die Energieabsorption im gröβeren Ausmaβ von der Konstitution der Hand/des Armes beeinfluβt.

1. Introduction

The vibration in many hand-held tools or workpieces may cause an occupational disease known as the vibration syndrome (for references see Brammer and Taylor 1982). In many studies the main emphasis has been on establishing a connection between the characteristics of the vibration stimulus and generated disturbances. Several of these investigations have, however, produced conflicting results. One reason may be that the assessments are based on measurements conducted directly on the vibrating handle, which in fact may give a false reflection of the actual vibration dose attributed to the exposure. In principle, it is reasonable to assume that the detrimental effects might depend on the vibration energy transmitted to and absorbed by the hand-arm system. Therefore, measurements of the energy absorbed in the hand and arm may be a better and more objective method for risk assessment. These assumptions are also supported by studies carried out by Lidström (1977) in which the prevalence of vibration injuries was shown to be related to the amount of energy absorbed by the operators.

The human hand and arm are elastic systems capable of storing both potential and kinetic energy. Potential energy is stored as a result of the relative compression or extension of tissues. Kinetic energy results from the motion of the tissues in the hand and arm (Reynolds 1975). In an ideal system, i.e. without damping, the vibration results in the transfer of energy between the hand-arm system and the tool handle and the average transfer of energy is zero. However, several investigators have found that the hand and arm in fact is a highly damped system (for references see Reynolds 1975). Damping has the effect that part of the energy is absorbed. In principle it is therefore reasonable to assume that the occupational diseases might be related to the absorption of vibration energy (Cundiff 1976, Lidström 1977).

The amount of energy per unit time (power) the hand and arm system are exposed to can be expressed in terms of the transmitted force (F) and the velocity (v), i.e. $P = F \cdot v$ (Nm/s). Moreover, the total amount of power can be divided into two components - one real and one imaginary. The real component reflects the energy absorbing part of the system, due to the transformation into heat by inner friction within the tissues. The imaginary component reflects the energy storing part of the system which does not consume any vibration energy (Anderson and Boughtflower, 1978). This indicates that if the phase angle between the force and velocity signals is close to zero, most of the energy transferred to the hand is absorbed by the system. On the other hand, if the angle is close to 90° most of the energy is stored in form of kinetic and potential energy.

According to the guidelines given in the International Standard, ISO 5349 (1986), risk assessments should be based on the broad-banded frequency weighted acceleration levels. The frequency weighting could for instance be done with a filter whose attenuation, expressed in terms of vibration velocity, decreases with 6 dB per octave from about 6 Hz up to 16 Hz. For higher frequencies, up to 1400 Hz, the velocity signals should not be affected by the filter.

Against this background, one purpose of the present study has been to investigate the human hand-arm system's capacity of absorbing vibration energy. This has been done by measuring how the absorption is related to different vibration directions and velocity levels, different handle grips, grip forces, flexion of the elbows, abduction of the shoulders and hands, as well as male/female and anthropometric differences. Another purpose of this study has been to determine if any clear relation exists between the energy absorbing properties of the hand-arm system and the dose-effect model for risk assessment specified in ISO 5349.

2. Methods

2.1. *Apparatus*

The technique used to determine the amount of absorbed energy in the hand-arm system is based on measurements of vibration force and velocity as well as the phase between these parameters, made as closely as possible to the surface of the hand. This is obtained by using a specially designed handle (Figure 1). The handle consists of two parallel beams mounted between two U-shaped holders. Both beams and holder are made of duraluminium. The beams, one upper and one lower, are furthermore covered with polycarbonate. The handle is a rigid and stiff construction, and distortion and artifacts due to resonances within the frequency range of interest can therefore be avoided. Between the handle and holders, two force transducers (Brüel & Kjaer 8200) are mounted for dynamic force measurements. The handle is also equipped with a small piezo-electric accelerometer (Brüel & Kjaer 4374) for velocity measurements. At both ends of each beam strain gauges are glued for the measurements of both grip and pull/push forces applied by the subject to the handle. The weight of the handle, above the force transducers, is 225 g. The handle has an elliptic size with the dimension of 31 x 42 mm.

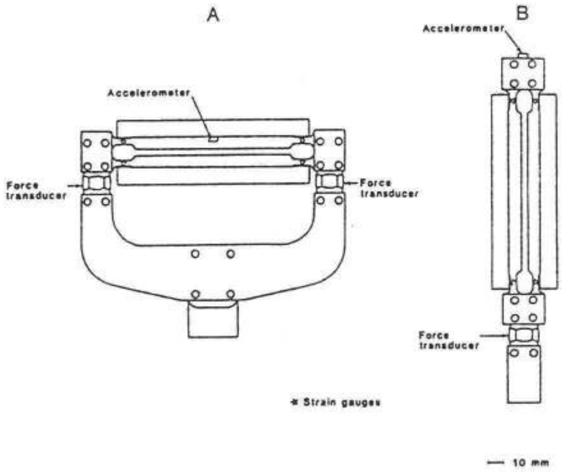

Figure 1. Handle design and the location of the accelerometer, the force transducers and the strain gauges.

The handle was mounted on an electrodynamic shaker (Ling Altec 7/600) driven by a power amplifier (Ling Dynamic System, LDS 300) and a signal generator (Brüel & Kjaer 1027). Sinusoidal vibrations were delivered to the handle with an increasing frequency from 4 to 1000 Hz (sweep rate; 50 s/decade). The output from the accelerometer was amplified and integrated to velocity by a charge amplifier (Brüel & Kjaer 2635) before it was fed to a phase meter (Brüel & Kjaer 2971). The velocity signal was also fed to a feed-back network facility on the signal generator in order to maintain the velocity amplitude at a constant level independent of test frequency and dynamic load. The varying outputs from each of the two force transducers were amplified by an charge amplifier (Brüel & Kjaer 2635) and afterwards summarized. The summarized force signal was fed to a level recorder (Brüel & Kjaer 2309) and also to the phase meter. The phase between the force and velocity signals was also monitored on the level recorder. The signals from the strain gauges was amplified by strain gauge bridges and monitored with pointer instruments in order to give the subjects possibility of both achieving and maintaining the grip and pull/push forces at the given level. In order to collect data for different vibration directions of input to the hand, two different orientation of the handle were used (Figure 1).

The measured dynamic force, velocity level, phase relationship and test frequency were during each experiment transferred to an on-line personal computer which calculated the amount of absorbed energy per unit time in the hand-arm system. For the entire frequency range these calculations also included a vectorial subtraction for the additional dynamic force produced by the handle itself, i.e. mass cancellation. The dynamic force of the handle itself was determined by vibrating the unloaded handle. These measurements revealed that the handle behaved as a rigid mass with the force remaining in 90 degrees out of phase with the velocity in the frequency range investigated. The handle data were also used to compare instrument calibration and to serve as a permanent indication of possible errors in gain settings.

2.2. *Subjects and studied variables*

The study was carried out on ten healthy right-handed subjects, five males and five females, with no previous exposure to vibration. For all subjects some anthropometric parameters were measured, in order to study the influence of these variables on the amount of absorbed energy (Table 1).

Table 1. Anthropometric data for the subjects' right hand and arm (for definitions see Van Cott and Kinkade 1972).

Subject	Sex	Age (year)	Height (cm)	Weight (kg)	Hand length (cm) 	Hand breadth at thumb (cm) 	Hand breadth at meta-carpal (cm) 	Hand thick-ness (cm) 
1	M	44	186	70	21.0	11.0	9.5	3.0
2	M	44	179	72	18.3	10.3	8.5	2.8
3	M	29	177	68	18.4	10.4	8.6	2.9
4	M	34	175	66	18.5	10.7	8.5	2.9
5	M	27	181	82	20.1	11.7	9.2	3.3
6	F	42	158	48	16.1	8.6	7.0	2.3
7	F	39	171	59	17.4	8.8	7.6	2.5
8	F	28	170	59	16.7	8.4	6.9	2.5
9	F	33	161	54	16.4	9.1	7.6	2.5
10	F	34	164	59	17.3	9.7	7.8	2.7
Mean		35.4	172.2	63.7	18.0	9.9	8.12	2.7
SD		6.5	9.12	9.86	1.59	1.12	0.88	0.30

Subject	Sex	Hand volume (cm^3) 	Shoulder-elbow length (cm) 	Forearm-hand length (cm) 	Forearm volume (cm^3) 	Arm volume (cm^3) 	Maximum gripforce (N) 
1	M	490	41.0	51.5	1695	3820	62.6
2	M	360	36.0	46.0	1300	3750	63.7
3	M	380	38.0	45.5	1345	3530	46.5
4	M	400	38.0	46.0	1560	3750	60.2
5	M	450	40.0	49.5	2050	4570	56.5
6	F	220	33.5	39.0	735	1910	21.8
7	F	290	37.0	44.0	1055	2640	27.3
8	F	270	36.0	43.5	1090	3075	28.8
9	F	260	33.5	40.5	930	2340	27.6
10	F	320	36.0	43.5	1095	2955	40.4
Mean		344.0	36.9	44.9	1285.5	3234.0	43.5
SD		87.33	2.46	3.75	392.76	799.76	16.47

Three different hand-arm postures were used in order to give a vibration exposure in the three orthogonal directions; vertical, transverse and proximal-distal. Hand-arm postures related to these directions are schematically shown in Figure 2. In accordance with ISO 5349 these directions refer to an excitation of the hand and arm in X_h-, Y_h- and Z_h-directions.

Figure 2. Hand-arm postures used in order to get a vibration exposure in the three different directions X_h, Y_h and Z_h, as defined in ISO 5349.

Three grip forces were used in the experiment (25, 50 and 75 N) and the influence of the angle between upper arm and forearm (the flexion of the elbow) was studied for five positions (60°, 90°, 120°, 150°, 180°). Moreover, the influence of a 90-degree angle between the shoulder and upper body (the abduction of the shoulder) was investigated as well as the differences between left and right hand-arm systems. Furthermore, two different handle grips were used in the study; from above and from below. The effect of the vibration amplitude on the energy absorption was also investigated by using four different velocity levels, 8, 14, 25 and 45 mm/s. These velocity levels represent frequency-weighted acceleration levels of 0.8, 1.4, 2.5 and 4.5 m/s^2 within the frequency range of 16-1000 Hz in accordance with ISO 5349.

2.3. *Experimental procedure*

All subjects were asked before each experiment to wear normal office clothes, without jackets, and were also asked to remove rings, watches etc to minimize any possible effects of clothing. The subjects were then placed in one of the postures, gripping the handle with a given force. After the correct posture and grip force was accomplished the frequency sweep was started. The subjects were requested to keep the grip force on a constant level during the sweep by looking at a monitored force signal on a pointer instrument as previously mentioned. The test was restarted if the subject for any reason failed to retain the hand-grip force or posture. Furthermore, the subjects were asked to control that no pull/push-forces were affecting the handle. Every test took about eight minutes to conduct including pauses and repositioning. The total number of tests for each subject were 22 and the tests were limited to only one per day in order to eliminate any possible effects of fatiguing.

3. Results

The influence of the different experimental conditions on the energy absorption per unit time are presented in Figure 3, where the average magnitudes of the absorbed energy are shown.

As can be seen, the absorption of vibration energy is, first of all, dependent on the frequency of the mechanical stimulus. A variation of about 0.0001 to 0.5 Nm/s could be observed over the entire frequency range.

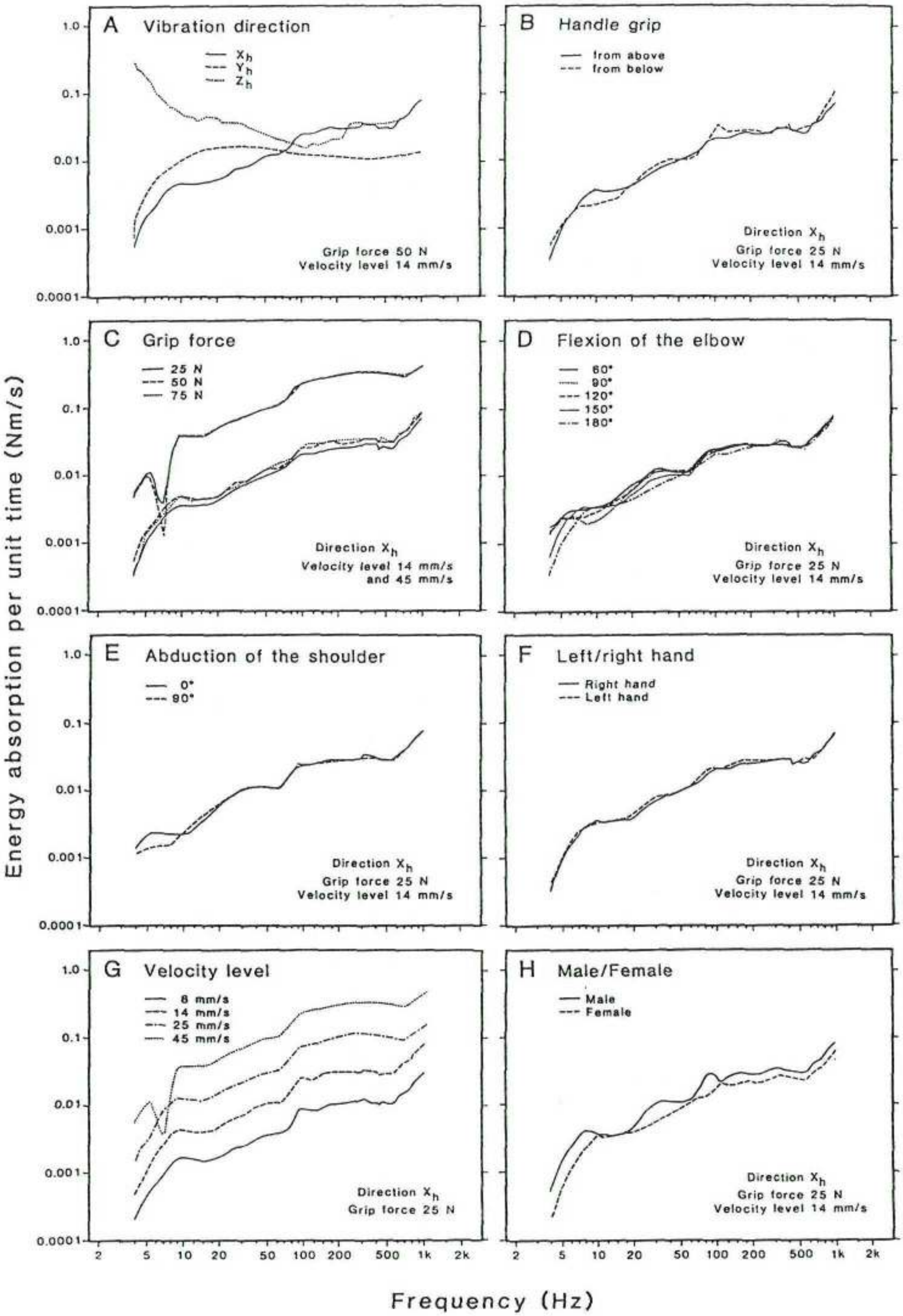

Figure 3. Mean values for the magnitude of the energy absorption per unit time for eight different variable combinations. The average values are based on data from ten different subjects.

A comparison of the average graphs in Figure 3A shows that the energy absorption differs between the three studied vibration directions. For vibration exposure in the X_h-direction the absorption, roughly increases with the frequency. The Y_h-direction is characterised by an energy absorption which increases with the frequency towards a maximum at about 20-30 Hz, followed by an almost flat response for the rest of the frequency range. For the Z_h-direction the absorption decreases with the frequency towards a minimum at about 100 Hz followed by an increase with the frequency similar to the X_h-direction.

The grip direction has only a small influence on the energy absorption (Figure 3B). Hand grips from below tend to give a higher amount of absorbed energy per unit time.

In Figure 3C the average magnitude of the energy dissipation is presented for different grip forces and for two different velocity levels, 14 and 45 mm/s. (The upper curves represent the velocity level of 45 mm/s.) First of all, the results show that a higher velocity level gives a higher absorption of energy per unit time in the hand-arm system. Moreover, it can also be concluded that firmer hand grips lead to a higher absorption of energy. The increase of absorption also seems to be relatively higher at the lower velocity level. The amount of absorbed energy increases with a factor 1.3 when the grip force increases from 25 N to 50 N. The corresponding factor is 1.1 when the grip force increases from 50 N to 75 N. The pronounced minimum at 8 Hz for the velocity level of 45 mm/s is probably due to incorrect measurement of the phase angle between force and velocity.

As can be seen in Figure 3D the angle between upper arm and forearm (the flexion of the elbow) has an influence on the average amount of absorbed energy and it is specially noticeable in the frequency region of 4 to 50 Hz. A clear tendency is that an increase of the angle gives a higher energy absorption.

The angle between shoulder and body (the abduction of the shoulder) has no influence on the energy dissipation, except in the low frequency region (Figure 3E).

When comparing the energy dissipation graphs, obtained with equal postures and grip forces but with either left or right hand exposed, it can be noticed, as shown in Figure 3F, that the differences are small or non-existing.

Figure 3G shows the influence on the energy absorption of different vibration levels. The amount of energy absorption increases quite rapidly when the vibration level increases. It is worth noticing that the graphs have similar frequency appearance. If the velocity level is changed from 8 mm/s to 14 mm/s the amount of absorbed energy increases with a factor 3.0. From 14 mm/s to 25 mm/s or from 25 mm/s to 45 mm/s the corresponding factors are 3.3 and 3.0 respectively.

Figure 3H shows the average magnitude of the energy dissipation for male and female, respectively. The figure shows that females overall have a lower absorption of energy than males. These graphs illustrate one of the studied variable combinations, but the same tendency could be found for the other combinations. The average difference between males and females are for all variable combinations about 30%. Conducted T-tests (Box et al. 1978) also show that these differences are significant ($p>0.0005$).

Furthermore, it can be noticed that in the data analysis it was found that the magnitudes of the "within subjects" standard deviations were in the range of 5% and the magnitudes of the "between-subjects" were about 25%.

In Figure 4 the results from performed correlation analyses (Box et al. 1978) between individual anthropometric data (Table 1) and calculated energy absorption in the hand-arm system are presented. The figure shows which anthropometric factor has the highest correlation to the individual energy absorption within different frequency regions. The correlation is calculated for all studied variable combinations in the X_h-direction.

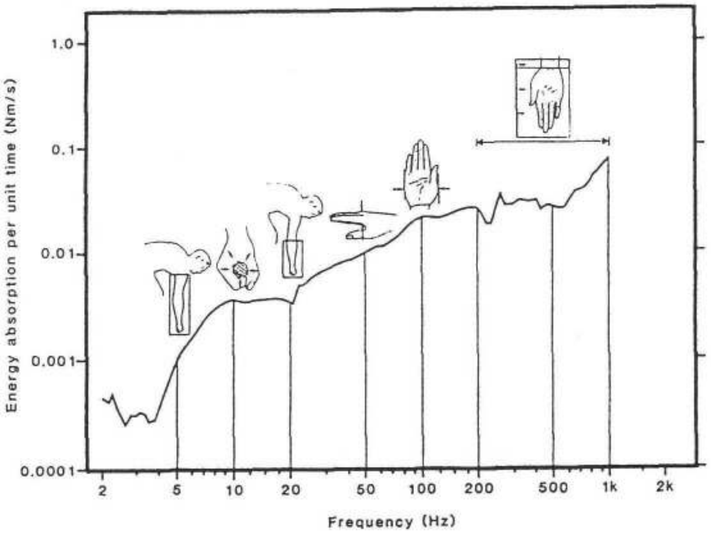

Figure 4. Correlation between different anthropometric data for the subjects' hand-arm systems and the energy dissipated in the hand-arm system as a function of the frequency (vibration direction X_h).

As can be seen, the energy absorption is highest correlated to the volume of the whole hand and arm in the low frequency region. Above 50 Hz however, factors describing the hand have the highest correlation against the absorption.

4. Discussion

The outcome of this investigation clearly shows that the energy absorption in the human hand-arm system is not only dependent on the frequency and level of the vibration stimuli, but also on the conditions surrounding the vibration exposure, at least with respect to vibration direction, grip force and the flexion of the elbow. As concerns the unsubstantiated premise that a higher amount of absorbed energy per unit time represents an increased risk of vibration injuries or reduction in comfort, it can be concluded that all studied variables have a more or less significant influence on the risk assessment.

The absorption of vibration energy per unit time in the human hand-arm system has earlier been studied in only a few investigations. It is, however, complicated to make a comparison between the present data and these earlier studies because of the very different experimental conditions. Therefore, only one comparable investigation has been found, one made by Mishoe and Suggs (1977). They have used a velocity level of 5.3 mm/s compared to 14 mm/s in this investigation. However, this only affects the relative level of the graphs not their shape, as shown in Figure 3G. The results obtained in this study (Figure 3A) have thus been recalculated to the same velocity level as Mishoe and Suggs used and are together with their results summarized in Figure 5.

These graphs almost coincide as regards both the levels and the shapes of the average curves. Furthermore, it can be noticed that to minimize the energy absorption in the hand and arm the vibration input should be in the X_h-direction for frequencies below 70 Hz, and in the Y_h-direction for frequencies above 70 Hz.

The hand-arm system has normally a high damping which increases with the frequency. In the low frequency range the hand-arm system reacts more or less like a pure mass for the X_h- and Y_h-directions. For the Z_h-direction the system acts more like a spring, probably because a larger part of the body is involved in absorbing the vibration. When the frequency increases the influence of mass elements which are most distant from the vibration source decreases due to energy absorption in associated parts of the system. This is followed by a decrease in vibration transmission up the arm (Lundström and Burström 1989). This process continues and when the frequency reaches 1000 Hz only small volumes of tissues are brought into vibration and will therefore absorb a high amount of energy. In the Z_h-direction the body's "spring behaviour" will decrease and the hand-arm system will have a more mass-like behaviour. It is worth noticing that above 200 Hz the energy absorption graph has a lot in common with the corresponding graph for the X_h-direction.

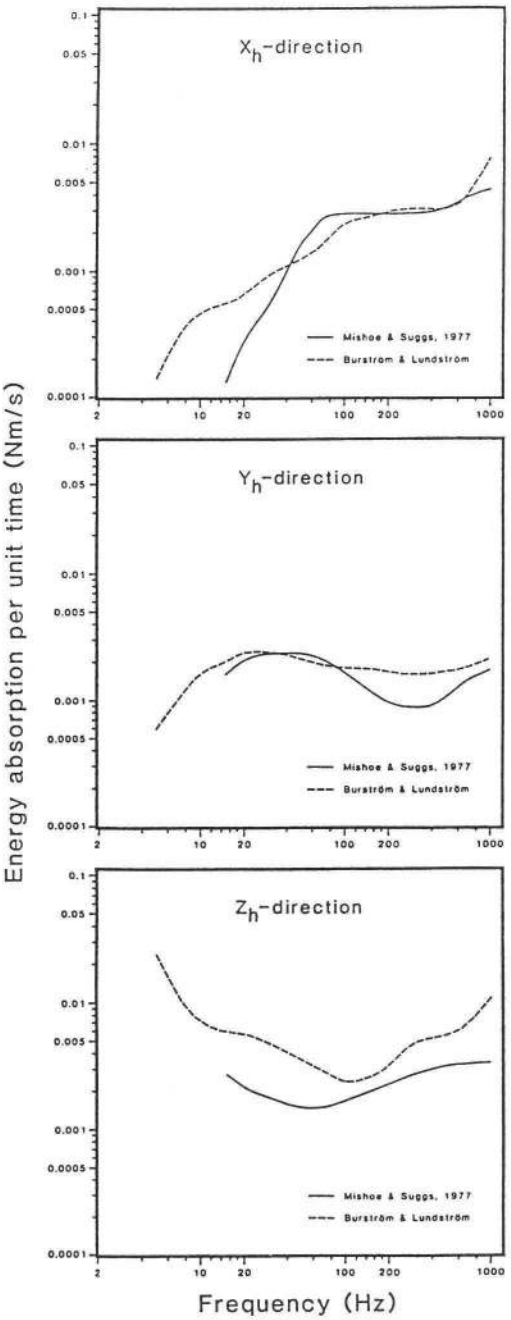

Figure 5. Comparison of energy absorption in the hand-arm for the three different vibration directions, as defined in ISO 5349, according to results found in the present study and from one earlier investigation (Mishoe and Suggs 1977).

The results show the importance of keeping factors depending on the posture of the whole body under control during the measurement of the energy absorption per unit time. For instance, a slightly bent arm, i.e. with different angles between upper arm and forearm, will affect the magnitude of the absorption.

An increased handgrip force leads to an increased magnitude of absorbed energy. It is worth noticing that this relation between grip-force and absorption does not seem to be linear. One reason could be that the energy absorption depends on the amount of viscous elements in the hand-arm system. This amount of viscous elements is influenced by the tension of the muscles and a higher tension enables the vibrations to put a larger part of the hand-arm system in motion, which causes the apparent mass of the system to increase. The reason for the non-linear behaviour could also be that the amount of viscous elements is limited in the hand and arm. With an increased grip force the muscles do not strain a corresponding amount of viscous elements. This might explain the comparatively smaller increase.

The vibration level has a rather strong influence on the magnitude of the amount of absorbed energy, particularly at higher frequencies. The explanation for this could be that when the stimulus amplitude increases, a larger part of the hand-arm system is mechanically activated, and the dynamic mass and the volume of the energy absorptions part of the system increases which makes the system able to absorb more energy (Reynolds 1977).

As concerns the influence of the biological factors (anthropometric data), findings in this study suggest that larger biological size gives a higher energy dissipation. This could explain why females have a lower absorption of energy than males.

According to the frequency weighting routine described in ISO 5349 the hand-arm system is considered to be equally sensitive to a constant vibration velocity level for all frequencies above 16 Hz. For lower frequencies higher velocity levels are accepted.

It is reasonable to assume that a certain amount of energy absorbed by the hand-arm system at different frequencies reflects an equal risk for getting vibration injuries. On the basis of the hand-arm system mechanical response to a vibration stimulus, it is possible, at least theoretically, to establish a new ISO weighting curve expressed in terms of absorbed energy rather than of vibration magnitude as described in the current standard.

Absorbed energy is related to the real component of the mechanical impedance of the system multiplied by the velocity level squared. By using the results achieved in this investigation for all three directions (see Figure 3A) an average value for this component of the impedance at 16 Hz has been calculated. This average value has then been used for determination of the relative position of a new energy absorption curve at this particular frequency. For reasons of simplicity, the damping features of the hand-arm system are held constant over the entire frequency range. The new ISO weighting curve as well as results obtained for the three different exposure directions in the present study are illustrated in Figure 6 for a frequency weighted velocity level of 14 mm/s.

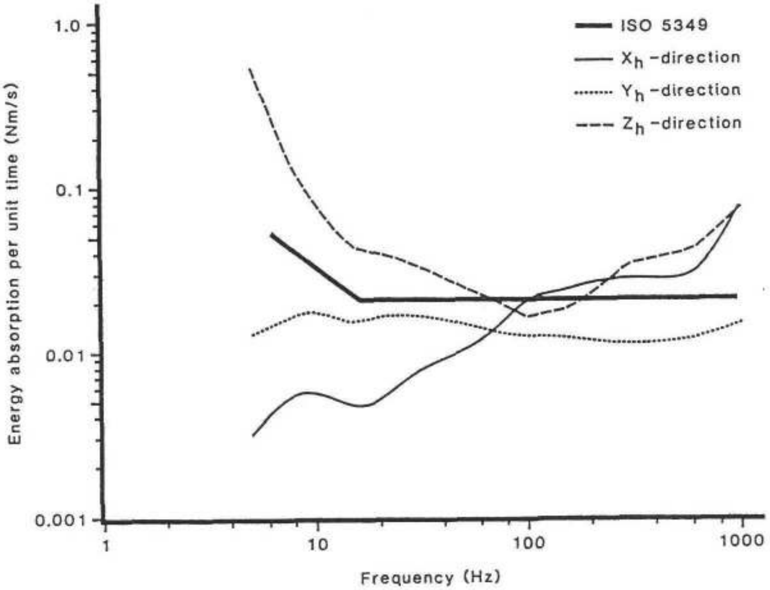

Figure 6. Comparison of hand-arm energy absorption curves for the three different vibration directions and a corresponding ISO weighting curve expressed in terms of absorbed energy.

As can be seen in the figure, the shape of the calculated ISO risk assessment curve is about the same as the energy absorption in the Y_h-direction for frequencies above 16 Hz. For the other two directions the weighting curve does not seem adequate. One conclusion is therefore that the international standard underestimates the risk for the development of vibration injuries, such as vibration-induced white fingers (VWF), especially for exposure in the Z_h-direction as well as for frequencies above 100 Hz in the X_h-direction. On the contrary for frequencies below 100 Hz and 16 Hz the standard overestimates the risk for vibration exposure in the X_h- and Y_h-direction, respectively.

To our knowledge, only one study can be found in the literature in which the relation between generated disturbance (VWF) and absorbed energy has been investigated, on three categories of workers (Lidström 1977). This is not sufficient to ascertain whether or not these dose-effect relationships are generally applicable. Further investigation of the energy absorption of the human hand-arm system is therefore needed. Before setting up future standards the energy absorbing properties of the human hand-arm system should, however, be taken into careful consideration.

Acknowledgements

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PAPER V

MEASUREMENT OF THE MECHANICAL ENERGY ABSORPTION IN THE HAND AND ARM WHILST USING VIBRATING TOOLS

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ABSTRACT

The mechanical energy absorption in the human hand and arm during exposure to simulated vibration from five common types of hand-held tools within the frequency range of 5 to 1500 Hz, has been directly measured and indirectly determined.

The study was carried out on ten healthy subjects, five males and five females. A special handle was used during the measurements. The influence of various experimental conditions, such as vibration level, vibration direction and grip force were also studied.

The results show that the energy absorption depends upon the frequency spectra of the tools. The differences between the amount of absorbed energy for the hand-held tools correspond to a factor 3.1 although the frequency weighted acceleration is equal. Furthermore, the results show that experiments conducted with different exposure directions have a significant influence on the amount of absorbed energy. On the other hand, the grip force has only a minor influence. The results also show that it is possible to theoretically calculate the amount of absorbed energy by using the vibration characteristics for the hand-held tool and the mechanical characteristics of the hand and arm.

Key words: Energy absorption, Hand-transmitted, Mechanical
impedance,Vibration.

1. Introduction

The term "vibration syndrome" is often used collectively for the symptoms associated with prolonged and repeated exposure to vibration from hand-held tools or industrial processes in which vibration enters the hands. These symptoms, which include vascular disorders, bone alterations and joint deformations, neurological disturbances, and muscle disorders, have also been recognized as an important occupational disease (for a review see 43).

Today the risk assessment for hand-transmitted vibrations is based upon measurements of the vibration, expressed in terms of frequency weighted acceleration, on the surface in contact with the hand (21). By using the frequency-weighted energy equivalent acceleration for a period of four hours per day it is possible to develop a dose-effect relationship between the vibration exposure and the early stages of the vibration syndromes (5). Some investigations have, however, produced conflicting results of this dose-effect relationship (7, 13, 14, 31, 38, 39, 40). Furthermore, various components of the vibration syndrome may develop independently and at different rates (4, 6, 15, 18, 32, 34, 41).

It is, however, reasonable to assume that the biological effects might depend to a large extent on the vibration energy transmitted from the vibration source to the hand and arm where it is absorbed (12, 27, 33). These assumptions have also been supported by an investigation (26) in which the prevalence of vibration injuries is shown to be related to the amount of energy absorbed by the operators. Therefore, measurements of the energy absorption in the hand and arm could be a better method for risk assessment than the currently used frequency weighting procedure.

The amount of energy per unit time (power) which is absorbed in the human hand and arm could, in principle, be determined by two different techniques, directly or indirectly.

The direct technique is based on measurements of the vibration force (F) and the velocity (v) as well as the phase angle (φ) between these parameters, made as closely as possible to the surface of the hand. The power involved in such a dynamic situation is equal to the product of the force and velocity, but it is only the real component that reflects the energy absorbing part of the system (1). This could be expressed as; $P(t) = F(t) \cdot v(t) \cdot \cos(\varphi)$. The average transferred power could also be expressed in the frequency domain with a cross-spectrum. Since the cross-spectrum is complex the coincidens spectrum describe the energy absorbing part.

The direct method is applicable to sinusoidal as well as random vibration and has no demands as concerns a linear mechanical behaviour of the hand and arm (24).

The indirect technique is based on the presumption that the mechanical behaviour of the hand and arm is known and has been described using the complex ratio of force and motion, for instance the mechanical impedance.

The mechanical impedance (Z) is defined as the complex ratio of the force vector (F) to the velocity vector (v) (2, 20, 22, 25), i.e. Z=F/v. Mechanical impedance is therefore a complex quantity with magnitude and phase, but it is not a phasor since it does not symbolize a quantity that varies sinusoidally with time. It is instead a function of the parameters of the mechanical system and the angular frequency (ω) of the force input (11). The mechanical impedance is also deterministic of the mechanical power transferred from the environment to the hand and arm, and the impedance is essentially a description of the energy flow. The real and imaginary parts of Z have significant meaning with regard to power dissipation in the physical system. The real part of Z, i.e. $Z \cdot \cos(\varphi)$, which is related to the damping coefficient, is proportional to the amount of power which is actually dissipated by the system in the form of heat. The imaginary part of Z, i.e. $Z \cdot \sin(\varphi)$, is due to components of the system which dissipate no power but simply store and release energy either in the potential or kinetic form (42).

From the definition of absorbed power and the mechanical impedance the total amount of absorbed energy per unit time can be expressed as; $P(t) = \{\mathrm{Re}(Z(t))\} \cdot |v(t)|^2$ and only velocity level measurements are necessary. This equation could also be expressed in the frequency domain as a function of the real part of the impedance and the auto-spectrum of the velocity.

The indirect technique is applicable on condition that the hand and arm act almost like a mechanical linear system for every frequency, in the meaning that the impedance would be independent of the vibration level or, in other words, the force would increase linearly with the vibration level (42, 46).

Studies using one or the other of the techniques are found in the literature. For the direct technique fewer studies have been found (1, 10, 27, 28) than for the indirect technique (17, 19, 23, 30, 36, 37, 44, 45). It is difficult if not impossible, to make a comparison of the results in these studies. This is due to the fact that the investigators in general have used different excitation and measuring techniques or other experimental conditions as regards vibration levels, vibration directions, hand-arm postures, grip force etc. Furthermore, differences in the impedance angle, especially for the indirect technique, could give large divergences of the results. However, five of these studies have investigated the influence on the power absorption from two types of hand-held tools, namely the chipping hammer and the grinder. The results from these studies are presented in Table I. From the investigations the total average amount of absorbed power has been summarized within the one-third octave band, having centre frequencies from 6.3 Hz to 1250 Hz.

Table I. Comparison of the total average amount of absorbed power for two different types of hand held tools according to results of earlier investigations. Used technique is also indicated in the table.

Absorbed power (W)		Measurement technique	Reference number
Grinder	Chipping hammer		
0,089		Direct	1
0,07	2,7	Direct	27
0,29	0,52	Direct	10
0,017	362,9	Indirect	37
2,5	4,1	Indirect	17

As can be seen the results for the two types of hand-held tools vary a lot between the investigations. For the grinder a variation between 0.017 and 2.5 W could be observed and for the chipping hammer between 0.52 and 362.9 W. There is a tendency in the results is that the variation is greater for the indirect technique than for the direct technique.

The direct technique is normally technically very complicated and therefore mostly suitable for laboratory experiments. For many applications the indirect technique would be to prefer, partly because of its simplicity and partly because measurements of the acceleration (or velocity) are commonly used today. However, in the literature no comparison of the two techniques could be found.

Against this background the purpose of the present experiments have been threefold. Firstly, to study the absorption of vibration energy in the hand and arm while the subjects are exposed to simulated vibration of five common types of hand-held tools. Secondly, to measure how the absorption is related to different vibration directions and frequency weighted acceleration levels as well as different grip forces. Thirdly, to compare the results obtained with the two different techniques, by direct measurements and by indirect determinations.

2. Methods

2.1 Apparatus

Vibration acceleration signals were measured and recorded on five different hand-held tools (vibration sander, gig saw, impact drill, angle grinder, chipping hammer) under practical working conditions. The recorded signals were delivered to a specially designed handle mounted on an electrodynamic shaker (Figure 1). For the Y_h-direction the handle was mounted parallel to the vibration direction. By feeding the signals through a spectrum sharper (Brüel & Kjaer 5612) it was possible to achieve an almost identical frequency spectrum (1/3-octave bands) from the vibrator compared to the original recordings.

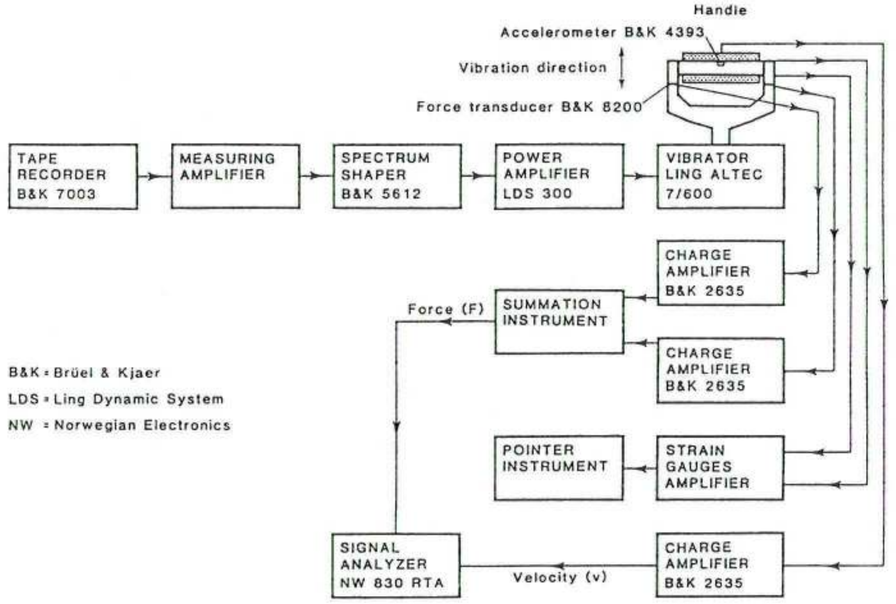

Figure 1. Block diagram of the instrumentation used in the study of absorbed power. Arrows indicate the signal direction.

The handle was equipped with two force transducers and one small piezo-electric accelerometer for force and velocity measurements, respectively. The handle was also equipped with strain gauges for measurements of both grip and pull/push forces applied by the subject to the handle. The output from the accelerometer was amplified and integrated to velocity by a charge amplifier (Brüel & Kjaer 2635) before it was fed to a dual channel real time analyser (Norwegian Electronics NW 830 RTA). The varying outputs from each of the two force transducers were amplified by a charge amplifier (Brüel & Kjaer 2635) and afterwards summarized. The summarized force signal was then fed to the dual channel analyser. For the indirect determination of the amount of absorbed energy in the hand and arm only the velocity signal was fed to the analyser.

The signals from the strain gauges were amplified by a strain gauges' bridge and monitored with a pointer instrument in order to give the subjects possibility of both achieving and maintaining the grip and pull/push forces at the given level.

For the direct measurements the measured cross-spectrum and phase relationship between the force and velocity signal were after each experiment transferred to a Personal Computer for calculations. These calculations also included a subtraction of the additional dynamic force produced by the handle itself. For the indirect determination the measured auto-spectra for the velocity signal were transferred to the computer for later analysis.

2.2 Studied variables, subjects and experimental conditions

In the study, simulated vibrations from five common types of hand-held tools were used (vibration sander, gig saw, impact drill, angle grinder, chipping hammer). Their frequency spectra expressed in 1/3-octave band are shown in Figure 2. In the experiments two different frequency weighted acceleration levels were used for all tools, 3.1 m/s^2 (SD 0.2) and 9.3 m/s^2 (SD 0.7). The levels were determined in accordance to the guidelines given in the International Standard ISO 5349 (21).

Three different hand-arm postures were used during the experiments in order to give a vibration exposure in the three orthogonal directions; vertical, transverse and proximal-distal. In accordance with ISO 5349 these directions are defined as exposures in X_h-, Y_h- and Z_h-directions. Furthermore, the influence of two different grip forces was investigated, 25 and 50 N.

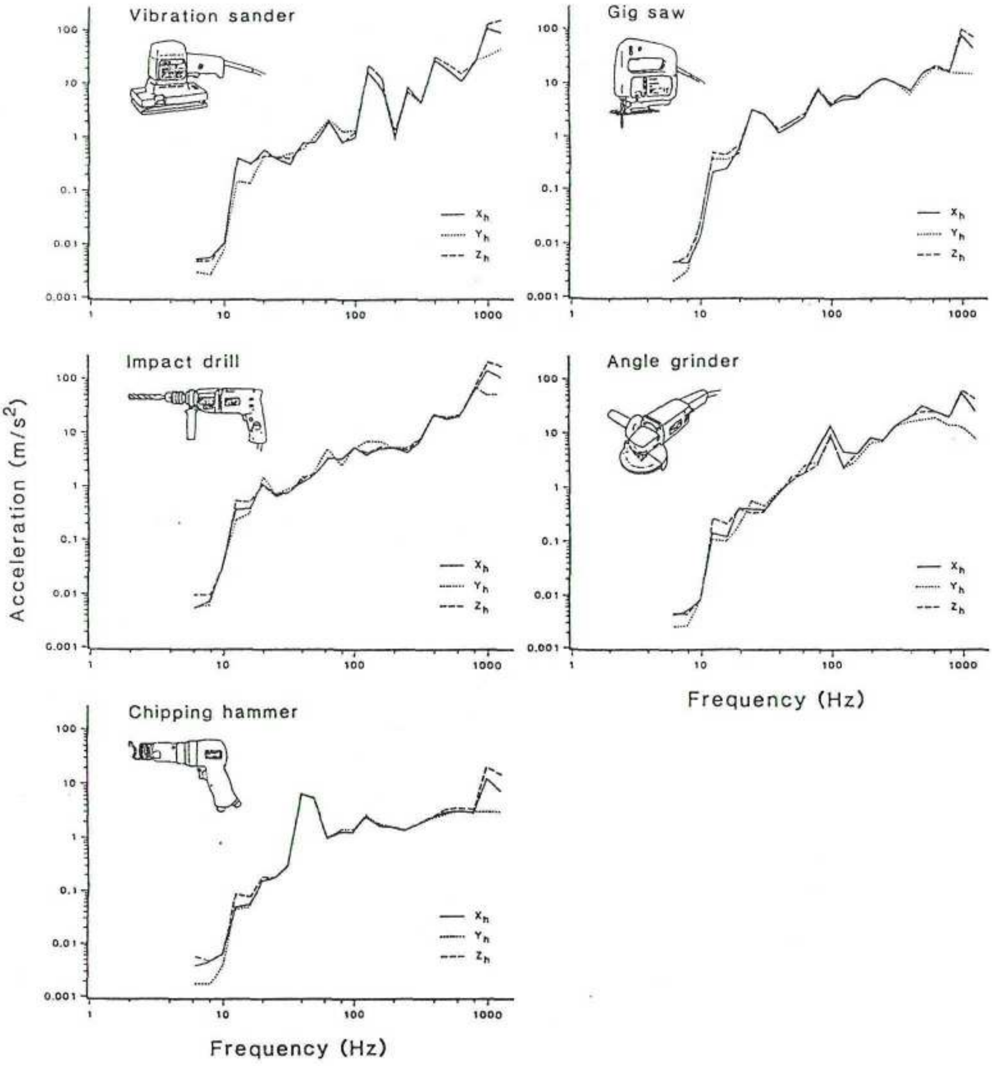

Figure 2. Average acceleration in 1/3-octave bands for the five tools and for the three orthogonal vibration directions. The curves correspond to a frequency weighted acceleration of 3 m/s^2.

The study was carried out in a laboratory (air temperature 22.5 °C ± 1.5 °C) on ten healthy right-handed subjects (age 28-45 years, height 158-188 cm, weight 47-82 kg), five males and five females, with no previous work-exposure to vibration. The subjects were asked to place themselves in one of the three postures, gripping the handle with the right hand and with a given force. After the correct posture and grip force was accomplished the vibration exposure was started. The subjects were requested to keep the grip force on a constant level during the exposure by looking at the monitored force signal on the pointer instrument. Furthermore, the subjects were asked to control that the pull/pushforce was 20 N. The test was restarted if the subject for any reason failed to retain the posture or forces. Every test period included exposure to simulated vibrations from five tools and took about 15 minutes to conduct including pauses and repositioning. The number of test periods for each subject were limited to 1-2 per day (rest period 4-6 hours) in order to eliminate any possible effects of fatiguing. The total number of test periods for each subject were 24.

In calculations of differences between the experimental conditions, all comparisons were made on the assumption that each subject was used as his own reference. Test on paired observations were performed with both parametric and non-parametric methods. The performed tests showed that the results were either statistically significant or not. Therefore, paired T-tests have been used throughout the whole study. For calculations of correlations between parameters, linear regression analysis was used (3). A p-value of <.001 was considered significant.

2.3 Mechanical impedance

To determine the amount of the absorbed power in the hand and arm for the indirect technique, knowledge of the mechanical behaviour expressed in terms of mechanical impedance are necessary. For this purpose earlier presented impedance data have been used (8, 9; Figure 3). These data were determined for the three orthogonal directions (X_h, Y_h, Z_h) during both sinusoidal and random vibration exposure.

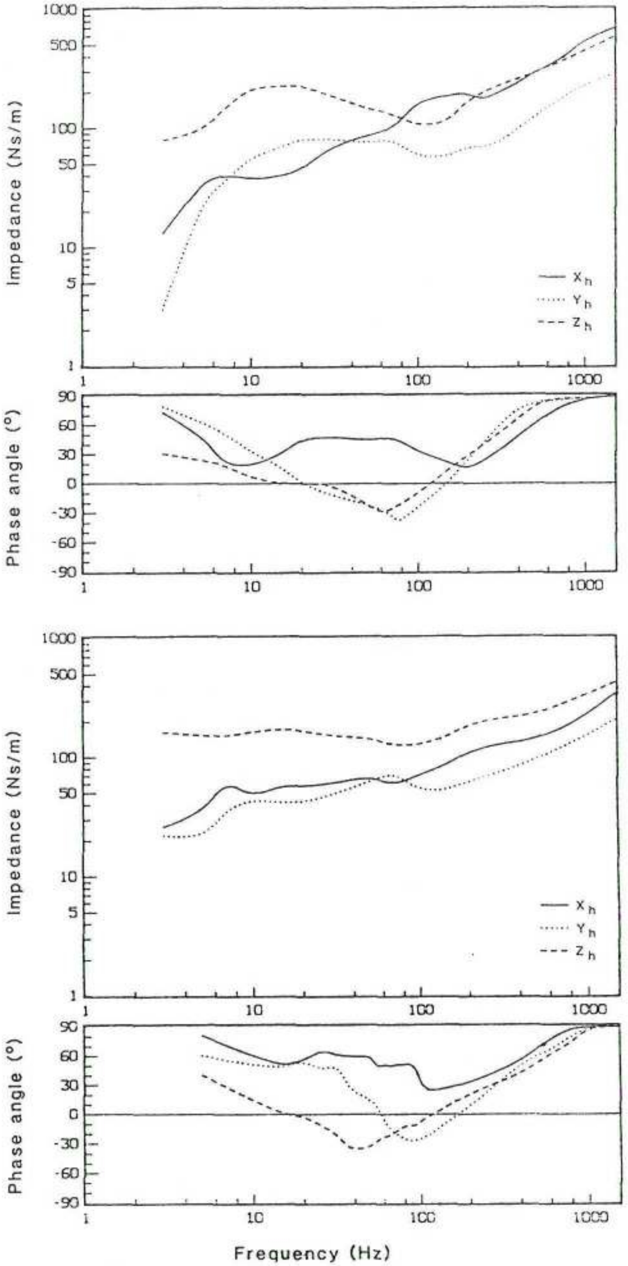

Figure 3. Mean values for the magnitude and phase of the mechanical impedance determined with sinusoidal and random vibration, respectively, for different vibration directions. The average data are based on data from ten different subjects (modified from 8, 9).

For the sinusoidal vibration exposure the impedance and phase angle correspond to a constant velocity level of 14 mm/s and to a grip force of 25 N. For the random vibration the impedance and phase angle were determined for a frequency weighted acceleration level of 3 m/s^2 and for a grip force of 25 N. The average values, presented in the figure, are based on data from ten different subjects.

3. Results

The influence on the absorption of vibration energy per unit time was studied by comparing results from various variable combinations and from the two techniques.

The results from different types of tools and different exposure direction are shown in Figure 4 for a grip force of 50 N and a frequency weighted acceleration of 3 m/s^2. In the figure the phase relationship for the cross-spectra is also given.

As can be seen when comparing the results from each tool, an exposure in the Z_h-direction gives the highest absorption of energy. Furthermore, the frequency appearances for the absorption spectra are almost the same for all three exposure directions. Moreover, most of the energy transferred to the hand and arm is correlated to the fundamental operational frequency for each tool. For the different tools these frequencies caused between 51 and 97% of the total amount of absorbed energy. There is a tendency in the data that the phase relationship is dependent upon the vibration spectra of the tools.

The total amount of absorbed power within the actual frequency range has been calculated by summation of the energy value for each of the one-third octave bands, having centre frequencies from 6.3 Hz to 1250 Hz. The results are shown in Figure 5 for different variable combinations and for the three vibration directions.

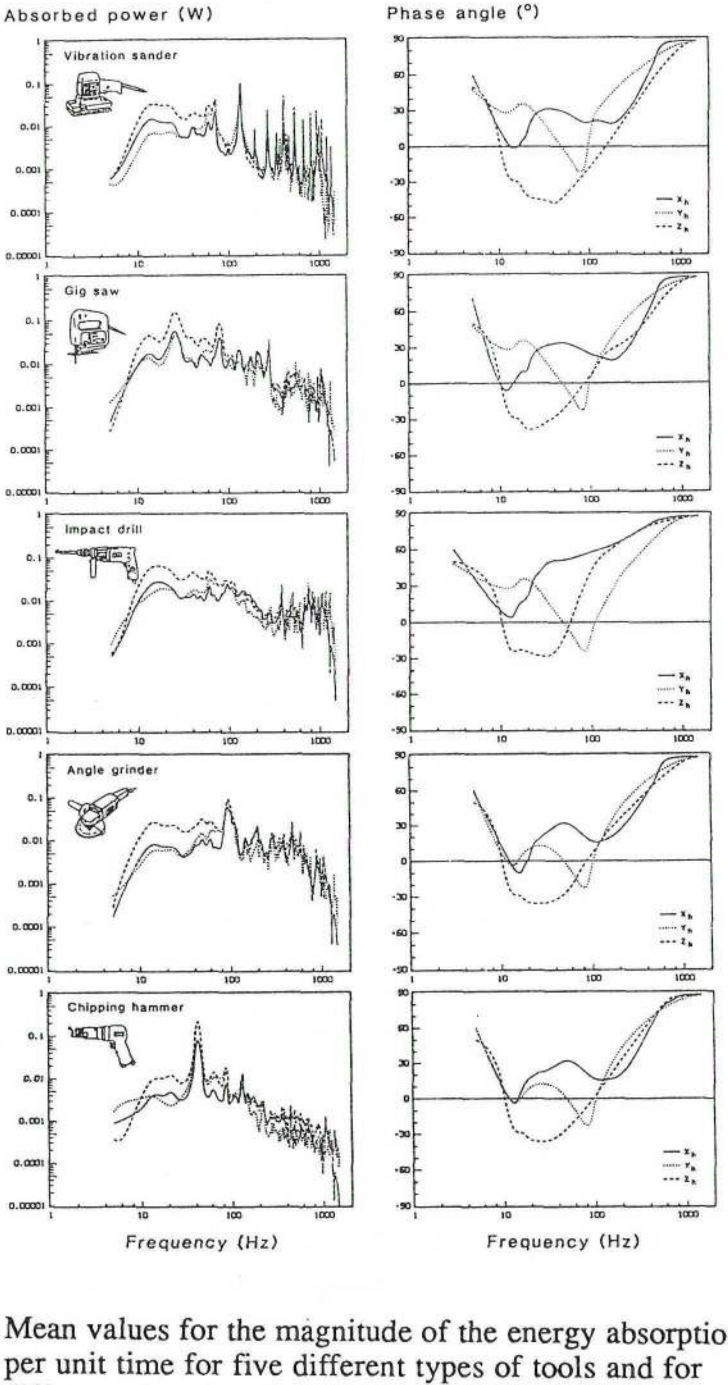

Figure 4. Mean values for the magnitude of the energy absorption per unit time for five different types of tools and for different vibration directions determined with the direct technique. The average values are based on data from ten different subjects during a vibration exposure that correspond to a frequency weighted acceleration of 3 m/s^2.

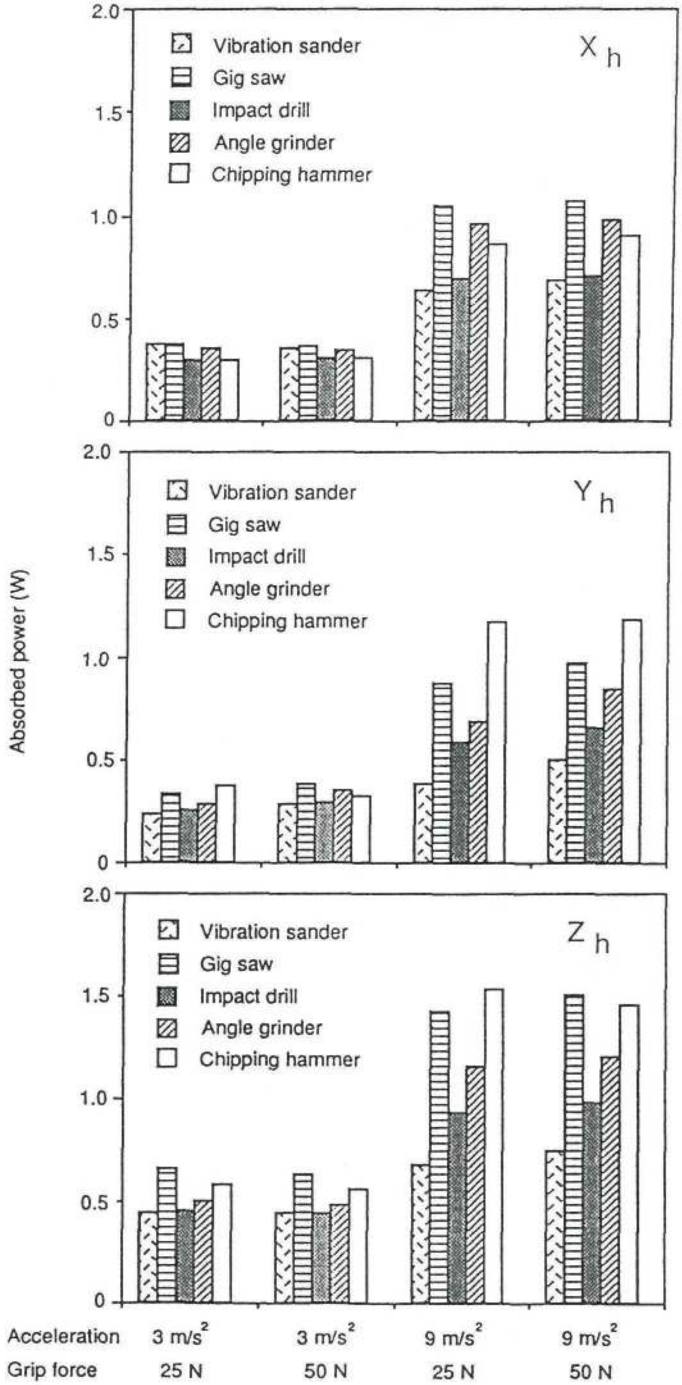

Figure 5. Staples showing the mean value of the summarized 1/3-octave band energy level for each tool and variable combination within the frequency range of 6.3 to 1250 Hz.

As can be seen, a total spread in absorbed energy from 0.2 to 1.5 W was found. The gig saw caused the highest amount of absorbed energy of all the tools and the vibration sander the lowest. The difference is about three times and conducted paired T-tests also show that there are significant differences between the absorption of energy for all tools, except between the saw and the chipping hammer. It can also be observed that the vibration direction has a great influence on the amount of absorbed energy. The highest absorption could be found in the Z_h-direction and the lowest in the Y_h-direction. The differences between different tools and directions correspond to a factor of 1.2 to 2.0. A comparison of the results shows, furthermore, that these differences between all three directions are significant.

The figure also shows that firmer hand grips lead to a higher absorption of energy. The amount of absorbed energy increases with a factor 1.1-1.3 when the grip force increases from 25 N to 50 N. The greatest differences were found for the Y_h-direction and the smallest for the Z_h-direction. Conducted paired T-tests show that the influence of the grip force on the total amount of energy was only significant for the Y_h-direction.

The amount of energy absorption increases quite rapidly when the vibration level increases.The absorption increases with a factor of 1.5 to 3.2 when the frequency-weighted acceleration increases from 3 to 9 m/s^2. The increase is, as can be seen in Figure 5, dependent on type of tool and vibration direction, and it is specially pronounced for the chipping hammer. As expected, the increase of the total amount of energy was significant for all types of tools when the frequency weighted acceleration was increased.

Figure 6 shows the results from conducted measurements of the velocity level and later multiplication with the impedance data obtained from both sinusoidal exposure and random. The data in the figure correspond to a frequency weighted acceleration of 3 m/s^2.

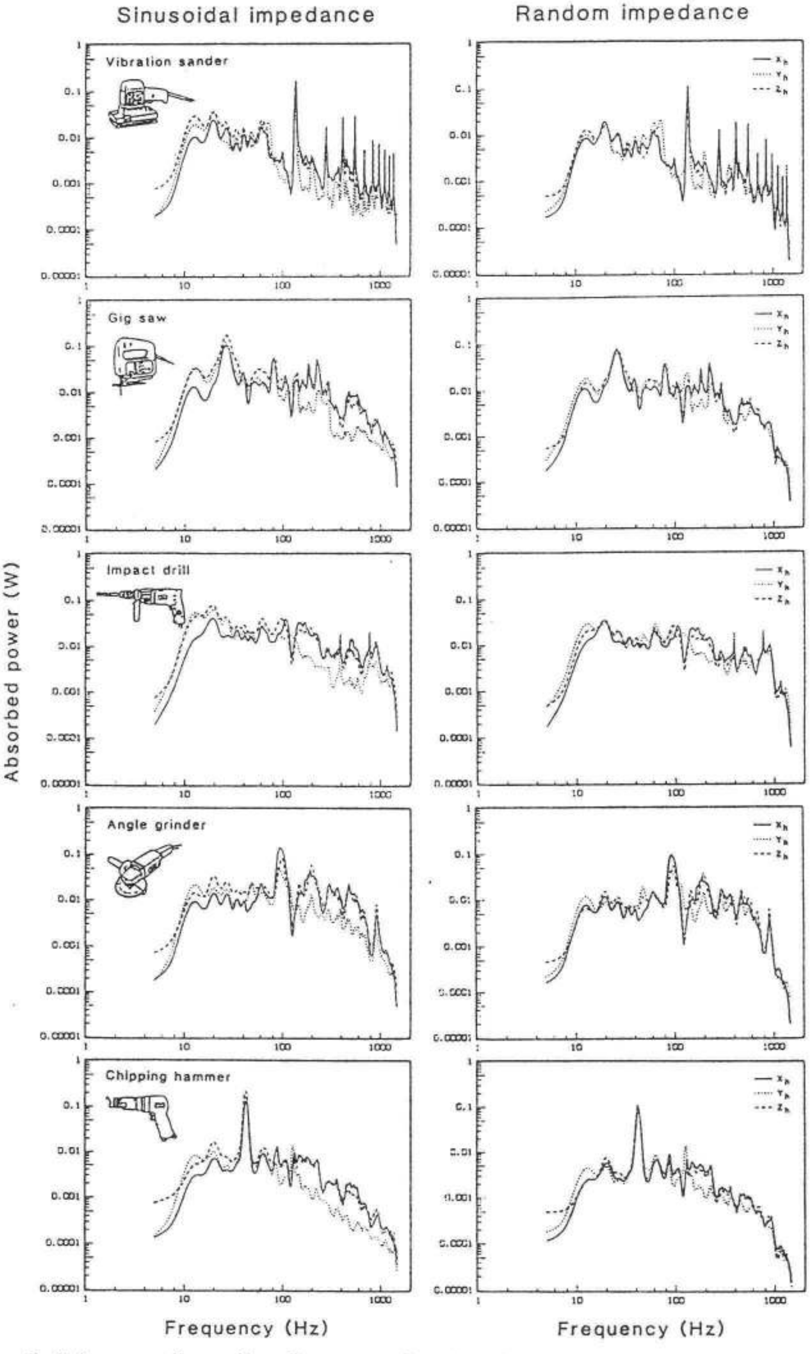

Figure 6. Mean values for the magnitude of the energy absorption per unit time for five different types of tools and for different vibration directions determined with the indirect technique for both sinusoidal impedance as well as random impedance. The average values are based on data from ten different subjects during a vibration exposure that correspond to a frequency weighted acceleration of 3 m/s^2.

The figure shows that the frequency appearance for the absorption is highly dependent on the operational frequency for the tool. A comparison of the frequency spectra for the two techniques shows that a fairly good agreement seems to exist between the techniques. The noticeable differences are for frequencies above 200 Hz where the sinusoidal impedance data give a higher absorption than the random impedance data.

A comparison of results obtained with the two techniques are illustrated in Figure 7 and 8. For the indirect technique, the impedance determined during exposure of sinusoidal vibration has been used in Figure 7 and the impedance determined during exposure to random vibration has been used in Figure 8. In the Figures the absorption within the one-third octave band, having centre frequencies from 6.3 Hz to 1250 Hz, is summarized.

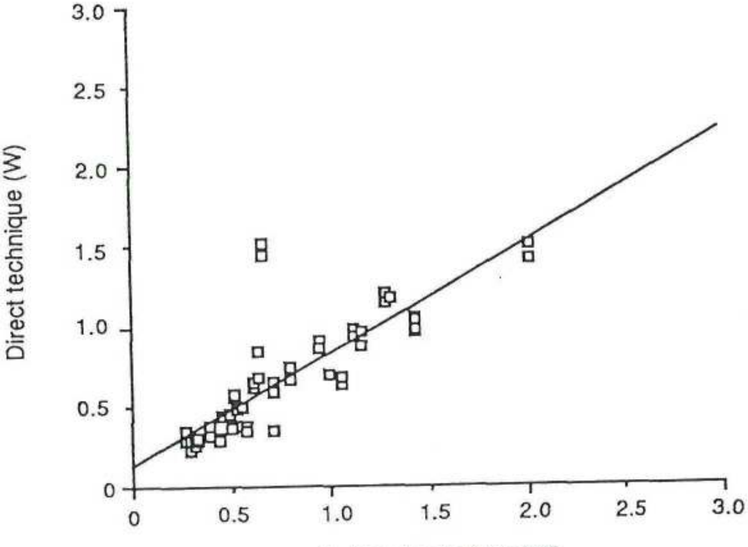

Figure 7. Comparison of energy absorption in the hand-arm for the direct and indirect technique, respectively. For the indirect technique impedance data obtained with sinusoidal exposure have been used.

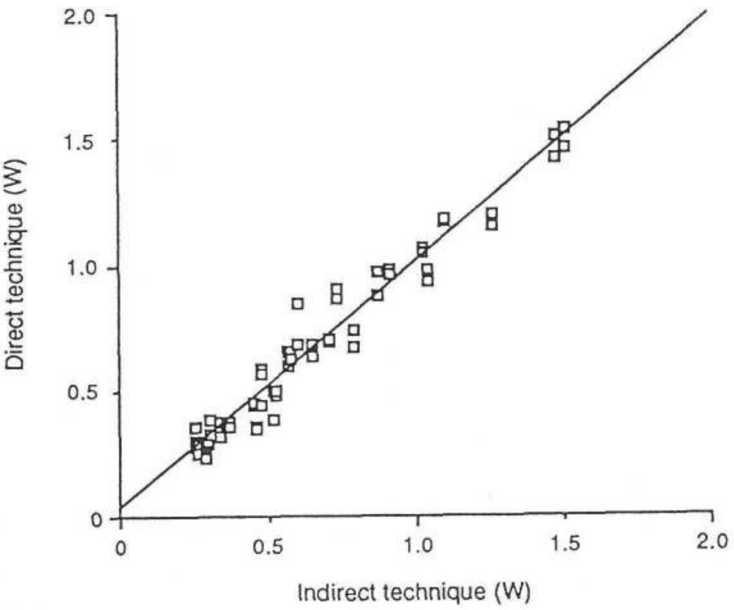

Figure 8. Comparison of energy absorption in the hand-arm for the direct and indirect technique, respectively. For the indirect technique impedance data obtained with random exposure have been used.

As can be seen from Figure 7 the indirect technique in general gives higher absorption values then the direct technique. The correlation between the two techniques is rather small with a correlation coefficient of 0.67. The greatest differences could be observed for the X_h-direction and the smallest for the Y_h-direction.

On the contrary, from Figure 8 a rather good agreement could be observed between the direct technique and the indirect technique. The correlation coefficient was found to be 0.96.

4. Discussion

The present study clearly shows that measurements of the energy absorption in the human hand and arm are not only dependent upon the magnitude and the frequency of the vibration stimuli but also upon the conditions surrounding the vibration exposure, at least with respect to the vibration directions and the grip forces.

Since the experimental conditions were controlled, in the sense that the frequency weighted acceleration was the same for the simulated vibration for each of the five tools, it can be concluded that the total amount of absorbed mechanical energy in the human hand and arm depend upon the frequency spectra of each tool. The explanation for this could be that the frequency spectra are not continuous, and that some frequencies dominate, mainly the operational frequency. If these dominating frequencies for a tool are in a frequency area which causes a high absorption of energy an increase of the acceleration level will then have a great influence on the total amount of absorbed energy. The opposite could also occur if the operational frequency for the tool is in an area where the hand and arm have a lower absorption. This could also explain the tendency in the material that the higher operational frequency correspond to a lower influence on the energy absorption as the frequency weighted acceleration increases. These findings indicate that the frequency weighting routine purposed by ISO 5349 does not correspond to the frequency dependence of the absorbed power. Furthermore it can be concluded that it is the fundamental operational frequency of the tool that leads to the highest energy levels, and also causes the main part of the total amount of absorbed energy. A tendency in the results is also that lower operational frequency corresponds to a greater part of the total amount of absorbed power.

ISO 5349 specifies that the risk assessment should be based upon the vibration direction which causes the largest vibration acceleration. However, the results in the present study have shown that the energy absorption to a large extend is dependent upon the vibration direction and that the hand-arm system does not respond equally from a mechanical point of view to these different exposure directions. It could therefore be questioned whether the assessment of vibration rather should be based upon the sum of vibrations in all three vibration directions instead. Furthermore, in order to minimize the energy absorption in the hand and arm, the vibration input in no cases should be in the Z_h-direction.

The influence of the grip force on the power absorption is known from other investigations (10, 17, 29). However, the results from this study have demonstrated that the influence is less than previously have been shown. One explanation for this might be that the influence of the grip force is mostly pronounced for frequencies below 15 Hz. However, these frequencies have not been found in the tools investigated here, which is also quite normal (29). From this study it can furthermore be noticed that the effect of the grip force on the total amount of absorbed energy differs between different vibration directions. One reason could be that the amount of viscous elements, which can absorb energy, are unequal for the hand and arm depending on the exposure direction. Moreover, it could be concluded that the higher the operational frequency the lower the influence of the grip force on the amount of absorbed energy.

The effects of the time history of vibration has been studied only in a few investigations and very little is known about human response in such situations (16). Evidence has also been presented which indicates that in some cases the vibration response characteristics of the hand and arm differ, depending upon whether the signal is a discrete frequency signal or a signal consisting of several frequencies (35). From the comparison of the two techniques presented in this study it is obvious that a correct description of the hand-arm system's mechanical response to vibration is necessary. By use of the impedance data from the random excitation, a far better correlation between the direct and indirect technique could be obtained than with impedance data based on sinusoidal excitation. One conclusion is therefore that the indirect and more simple technique can be used for determination of the amount of absorbed energy in the human hand and arm. However, the indirect technique does not take into consideration to intrinsic variables like grip force, hand-posture, individual factors etc. These factors have, on the other hand, been examined in earlier investigations and a correction for their influence is possible. For more exact measurements of the amount of absorbed energy the direct technique is still to prefer.

In the literature only one study (27) could be found concerning the relation between absorbed energy and generated disturbance, so more epidemiological investigations are desirable. This might clarify the dose-response relationship between vibration injuries and the amount of absorbed power. Finally, according to the results presented in this study and earlier determined relationships between generated disturbance and absorbed energy, it could be questioned if future standards should not take into careful consideration the energy absorbing properties of the human hand and arm.

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