THE INFLUENCE OF BIODYNAMIC FACTORS ON THE 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 quantity 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 on 10 healthy subjects during exposure to random vibration with constant velocity spectrum. In the study, the influence of various conditions, such as vibration direction (X_h, Y_h, Z_h), grip force (25—75 N), feed force (20—60 N), frequency weighted acceleration level (3, 6, 9, 12 m/s^2) and hand and arm posture (5 flexions, 2 abductions) were studied. The outcome showed that the energy absorption in the human hand and arm depended mainly on the frequency and direction of the vibration stimuli. Higher vibration levels, as well as firmer hand grips and higher feed forces, resulted in a significantly higher absorption. As concerns the hand and arm posture the results show that the flexion had a significant contribution to the vibration absorption but the abduction had no influence on the quantity of absorbed energy. Furthermore, the influence of some of the studied variables had a non-linear effect on the absorption but also differed between different exposure directions. Moreover, it was concluded that the frequency-weighting routine in the international standard ISO 5349 do not reflect the energy absorbing properties of the human hand and arm.

Key Words: Energy absorption, Hand-transmitted, Biodynamic factors, Vibration.

INTRODUCTION

The risk assessment of vibration transmitted to the hand and arm is in several countries based on the international standard ISO 5349[1] and the exposure-response relationship presented in its annex. Since several investigations have produced results that disagree with the risk predicted by the exposure-response relationship in the Annex of ISO 5349, the validity of this model has been questioned[2]. It is, however, reasonable to assume that any detrimental effects might be related to the quantity of vibration absorbed by the hand and arm. If so, measurements of the mechanical energy absorbed in the human hand and arm may be a better and more objective method of risk assessment.

The quantity of energy per unit time (power) to which the hand and arm system are exposed can be expressed in terms of the transmitted force (F) and the velocity (v), i.e., P = F · v (Nm/s). Moreover, the total quantity 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 of friction within the tissues. The imaginary component reflects the energy-storing part of the system which does not consume any vibration energy[3]. The phase angle between the force and velocity signals plays therefore an important part in the energy flow and

if the angle 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 $\pi/2$ most of the energy is stored in the form of kinetic and potential energy. The average transferred energy could also be expressed in the frequency domain within the cross-spectrum. Since the cross-spectrum is complex the coincident spectrum describes the energy-absorbing part[4].

Against this background, the purpose of this study was to investigate the hand and arm system's capacity to absorb vibration energy under various experimental conditions. Furthermore, the aim was also to compare results obtained with the frequency-weighted routine specified in ISO 5349, which is the basis of the exposure-response model.

METHODS

Apparatus

The technique used to determine the quantity of absorbed energy in the hand-arm system was based on measurements made as close as possible to the surface of the hand, of vibration force, velocity, and phase between these parameters. These were obtained using a specially-designed handle (figure 1), mounted on an electrodynamic shaker (Ling Dynamic System, LDS PA 300). For the Y_h-directions the handle was mounted parallel to the direction of vibration. By feeding the signals from a signal generator (Brüel & Kjær 1027) through a spectrum shaper (Brüel & Kjær 5612) it was possible to achieve a constant velocity spectrum (1/3-octave band) independent of frequency and dynamic load. This represents an acceleration spectrum which increases with frequency (6 dB/octave) and after frequency-weighting, according to ISO 5349, gives a constant spectrum within the frequency range of 16 to 1250 Hz.

The handle was equipped with two force transducers (Brüel & Kjær 8200) and one small piezo-electric accelerometer (Brüel & Kjær 4393) for force and velocity measurements, respectively. The handle was also equipped with strain gauges for measurements of both grip and feed forces applied by the subject to the handle. The output from the accelerometer was amplified and integrated to velocity by a charge amplifier (Brüel & Kjær 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 & Kjær 2635) and afterwards added together. The total force signal was then fed to the dual channel analyser.

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

The measured cross-spectrum between the force and velocity signal were, after each experiment, transferred to a P.C. for calculations. These calculations also included subtraction of the additional dynamic force produced by the handle itself[4].

Subjects and Studied Variables

The study was carried out in a laboratory (air temperature 22.5°C $\pm$ 1.5°C) on ten healthy right-handed subjects (age 28–48, mean 37.3 years; height 162–188, mean 171.4 cm; weight 54–74, mean 63.6 kg), five males and five females, with no previous work-exposure to vibration.

Three different hand-arm postures were used to achieve 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.
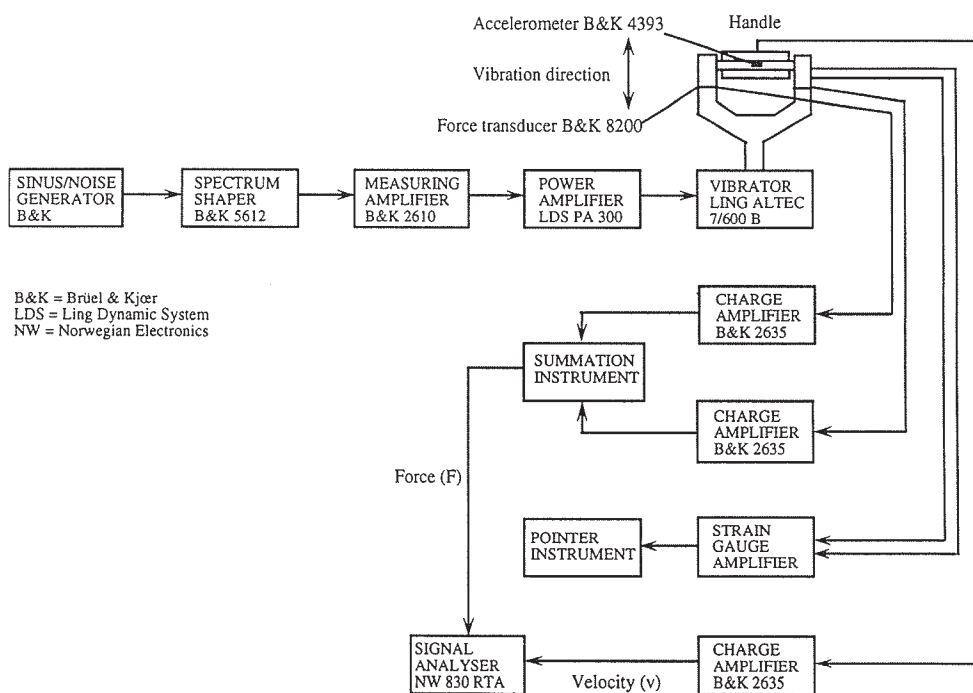
Fig. 1. Block diagram of the instrumentation used in the study of absorbed energy per unit time. Arrows indicate the signal direction.

Three grip and feed forces were used (25, 50, 75 N and 20, 40, 60 N respectively) and the angle between upper arm and forearm (the flexion of the elbow) was varied ($\pi/3$, $\pi/2$, $5\pi/6$, $4\pi/3$, π). The influence of a $\pi/2$ angle between shoulder and upper body (the abduction of the shoulder) as well as the effect of vibration amplitude on energy absorption was investigated by using four different velocities (6.5, 13, 19.5 and 26 mm/s). These velocity levels represent frequency-weighted acceleration levels of 3, 6, 9 and 12 m/s^2 in accordance with ISO 5349.

Experimental Procedure

All subjects were asked to wear normal office clothes, without jackets, and 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 the appropriate force. After the correct posture and grip/feed force were established the vibration exposure was started. The subjects were requested to keep the grip and feed forces at a constant level during the exposure by looking at the displayed force signals. The test was restarted if the subject failed to maintain grip/feed force or posture. Every test took about 20 seconds to conduct and during each experiment 6 to 8 different conditions were investigated. The total number of experiments for each subject was 198 and only one experiment was performed each day to avoid the effects of fatigue.

Statistics

In order to investigate the influence of different variables on the absorption of vibration

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energy and to study their frequency dependency (1/3-octave band), regression analysis has been carried out. With absorption as the dependent variable a model has been specified where all the other experimental variables have been used as explanation variables. Also included in the model are a number of terms for interaction (the product of two explanation variables) together with an indicator variable for each subject. The number of observations used is 47520 (10 subjects, 198 experimental conditions, 24 1/3-octave bands).

The experimental variables have been excluded one at a time from the regression model, and the parameters of the model have been estimated by the weighted-least-square method, where vibration level has been used as a weighting variable[5]. From this smaller model the residuals have been calculated. The residuals include the error-term of the model and the effects of the excluded variable, but the effects of all other variables have been eliminated.

The residuals have been separated for each of the three orthogonal directions (X_h, Y_h, Z_h) and for each frequency (1/3-octave band) the mean value for the residuals has been calculated for each level of the excluded variable. The hypothesis that the mean values are the same has been tested by a two-sided t-test or by analyses of variances[5]. The multiple significant level of $\alpha=0.05$ has been used for these tests.

The total quantity 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 with centre frequencies from 6.3 Hz to 1250 Hz in accordance with IEC 225[6]. The total quantity of absorbed power has then been used as the dependent variable to specify a regression model to study the effect of other variables on the absorption. Terms for interaction between two variables together with indicator variables has been used in this model also. The total number of observations used is 1980 (10 subjects, 198 experimental conditions). The parameters of the model have been calculated by the weighted-least-square-method and the probability level accepted for statistical significance was $\alpha=0.05$.

RESULTS

Biodynamic Factors

Direction
The mean magnitudes of the absorbed energy for the three different directions of vibration are illustrated in Figure 2.

As can be seen the absorption of energy was dependent on the frequency of the mechanical stimulus. The absorption increases with frequency toward a maximum of, depending on the exposure direction, about 8 to 80 Hz, followed by decreased absorption with frequency. The statistical analyses show that an exposure in the X_h-direction gives an higher absorption compared with an exposure in the Y_h-direction for all frequencies except within the frequency range of 50 to 100 Hz. A comparison of the X_h- and Z_h-directions shows that the X_h-direction exposure gives a lower absorption for frequencies below 125 Hz and a higher absorption for frequencies above 150 Hz. Furthermore, the Z_h-direction gives a higher absorption than the Y_h-direction for all frequencies except for those at about 80 Hz.

Grip force
Firmer handgrips produced a higher absorption of energy for the X_h-direction at about 10 Hz and within the frequency range of 200 to 400 Hz. For the Y_h-direction a higher grip force gives a higher absorption for frequencies below 30 Hz and in the range of 80 to 150 Hz. An increased
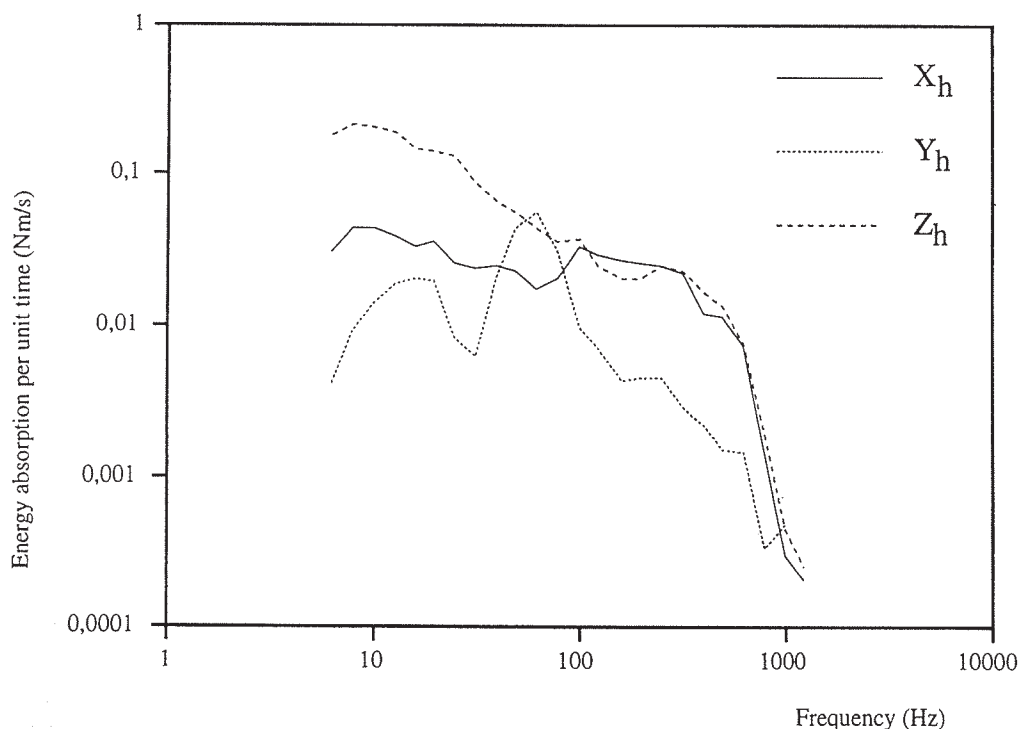
Fig. 2. Mean values for the magnitude of the energy absorption per unit time (Nm/s) as a function of the frequency (1/3-octave band) for the three different directions, X_h, Y_h and Z_h, as defined in ISO 5349 (Grip force 25 N, Feed force 20 N, Flexion π, Abduction 0, Velocity 26 mm/s).

grip force leads for the Z_h-direction to a higher absorption of vibration energy for frequencies below 50 Hz and in the frequencies between 300 to 500 Hz.

Feed force

In the X_h-direction absorption increased with the feed force for frequencies below 20 Hz and decreased in the frequency range of 100 to 150 Hz. For the Y_h- and Z_h-direction higher feed forces also caused a higher absorption for frequencies below 40 Hz and in the range of 80 to 100 Hz.

Flexion

The angle between upper arm and forearm (the flexion of the elbow) has an influence on the average quantity of absorbed energy for frequencies below 50 Hz. The highest absorption was found for the π-flexion (extended arm) and the lowest for $5\pi/6$-flexion. Compared with π-flexion all the other flexions have in the X_h-direction an influence on the absorption for frequencies below 100 Hz, in the Y_h-direction for frequencies below 20 Hz and in the Z_h-direction for frequencies below 125 Hz.

Abduction

The angle between shoulder and body (the abduction of the shoulder) has for all vibration directions an influence on the energy dissipation for frequencies below 20 Hz, where an abduction

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of $\pi/2$ gives the highest absorption.

Velocity

Energy absorption increases with the velocity level for the whole frequency range investigated and for all three different vibration directions.

Relation between Absorption and Investigated Variables

Table 1 shows the parameter estimates in the multiple regression model between the total quantity of absorbed energy, within the one-third octave bands having centre frequencies from 6.3 Hz to 1250 Hz, and the other investigated variables. Also presented in the table is the interaction between different variable combinations, but the regression coefficients for the subjects are omitted. Only variables and variable combinations that have a significant influence on the absorption are to be found in the model.

The flexion, abduction, grip and feed force as well as the velocity level have a significant influence on the absorption. Abduction has, on the contrary, no influence on the absorption. Furthermore, the absorption is different for an exposure in the Z_h-direction compared with the other two directions. Between the X_h- and Y_h-directions no differences could be found. The

Table 1. Regression coefficients in the regression model between the total quantity of absorbed energy and investigated variables. Standard deviation for the regression coefficients as well as the significant level are also presented. The adjusted multiple coefficient of determination of the whole model was 0.900.

Variable	Regression coefficient	Standard deviation for the regression coefficient	Significant level
Flexion	−0.001031	0,0001936	0,0000
Grip force	−0,000739	0,0001673	0,0000
Feed force	−0,003134	0,0004116	0,0000
Velocity	0,008443	0,0008367	0,0000
Direction X_h/Z_h	0,206382	0,0082150	0,0000
Direction Y_h/Z_h	0,124047	0,0082300	0,0000
Squared velocity	0,000094	0,0000218	0,0000
Squared flexion	0,000005	0,0000007	0,0000
Direction X_h/Z_h and Velocity	−0,015436	0,0003143	0,0000
Direction Y_h/Z_h and Velocity	−0,013528	0,0003148	0,0000
Direction X_h/Z_h and Flexion	−0,000717	0,0000536	0,0000
Direction Y_h/Z_h and Flexion	−0,000783	0,0000536	0,0000
Direction X_h/Z_h and Grip force	−0,000339	0,0001160	0,0036
Direction Y_h/Z_h and Grip force	0,000184	0,0001160	0,1122
Direction X_h/Z_h and Feed force	−0,000386	0,0001486	0,0095
Direction Y_h/Z_h and Feed force	0,001615	0,0001486	0,0000
Velocity and Grip force	0,000064	0,0000075	0,0000
Velocity and Feed force	0,000113	0,0000093	0,0000
Velocity and Flexion	0,000025	0,0000040	0,0000
Feed force and Flexion	0,000009	0,0000022	0,0001
Feed force and Grip force	0,000012	0,0000029	0,0001
Intercept	−0,043763	0,0156470	0,0017

correlation between the absorption and the squared velocity or flexions suggests that these relations are non-linear.

The interaction between the vibration direction and the velocity, flexion, grip and feed forces shows that changes in these variables give an effect on the absorption that is different for the Z_h-direction compared with the other directions. The only relation that deviates from this general statement is the grip force, where it there was no difference between the Y_h- and Z_h-directions. Moreover, a difference in the interaction for the grip and feed forces can be observed between X_h- and Y_h-direction.

The table also shows that there is a significant interaction between velocity and the variables flexion, grip and feed forces. Their effects on the absorption are therefore dependent on the velocity level. Feed force interacts also with the grip force and flexion.

DISCUSSION

The severity of the effects from hand-transmitted vibration is influenced by physical, biodynamic and individual factors. Monitoring all these variables for each worker has been considered impractical. 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 the most important variables for 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[7]. The outcome of the present study clearly shows that measurement of the energy absorption in the human hand and arm is not only dependent on the magnitude and frequency of the vibration stimuli but also on other factors which influence the severity of vibration, at least with respect to vibration direction, grip and feed forces as well as flexion of the elbow. Therefore, measurements of the energy absorption as presented here may be a complementary method for risk assessment. With regard to the unsubstantiated premise that a higher quantity 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.

In ISO 5349 it is specified that risk assessment should be based upon the vibration direction which has the highest acceleration value. The results of the present study have shown, however, that the hand and arm do not respond equally from a mechanical point of view to these different exposure directions. These differences imply that it can be questioned whether assessment should not be based upon the total sum of vibrations in all three vibration directions instead.

Biodynamic factors, as shown, influence the quantity of absorbed energy. Relatively small changes in position and posture can appreciably affect the transmission of vibration as well as vibration energy to the hand and arm. For instance, bending the arm at different angles significantly affects the magnitude of the energy absorption and should consequently influence the risk assessment. Furthermore, it has been shown that the influence of these factors on the absorption are different for different vibration directions. Moreover, it has been discovered that an interaction exists between many of the biodynamic factors studied.

The vibration level has, as expected, a strong influence on the magnitude of the quantity of absorbed energy. The reason for this is probably changes in 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 therefore increases, leading to the possibility of more energy dissipation. The increase in energy absorption seems, furthermore, to be non-linear, i.e. the risk for vibration injuries will

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increase more rapidly at high vibration exposure than at low. This emphasises the need of further exposure reduction of hand-held tools. Moreover, it has been demonstrated that the influence of the vibration level on the absorption of vibration energy is dependent on the exposure direction, grip and feed forces as well as the flexion.

The investigated variables explain 90% of the quantity of absorbed energy. This implies that other factors influence the absorption of energy in the hand and arm. Earlier studies[8,9] have shown that one of these factors could be individual differences.

If the assumption is correct that energy absorption will reflect the hand-arm system's response to vibration, then it is possible to establish a relation between the exposure-response model given by ISO 5349 and the results found in this investigation. This relation has been illustrated in Figure 3. In the figure the attenuation for the frequency-weighting specified by ISO 5349 as well as the attenuation for the transferred energy obtained for the three different exposure directions are given. The attenuation for the transferred energy has been established by dividing the transferred energy by the absorbed energy.

As can be seen in the figure, the shape of the ISO-model is about the same as the energy absorption in the Z_h-direction. For the other two directions the model does not seem adequate. One conclusion is therefore that the international standard may underestimate the risk for the development of vibration injuries, such as vibration-induced white fingers (VWF), especially for frequencies above 80 Hz. For frequencies below 80 Hz the standard overestimates the risk for vibration exposure in the X_h- and Y_h-direction.

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 exposure-response relationship. Furthermore, it has been shown in the present study 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 reasonable 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. Finally, the present findings support the
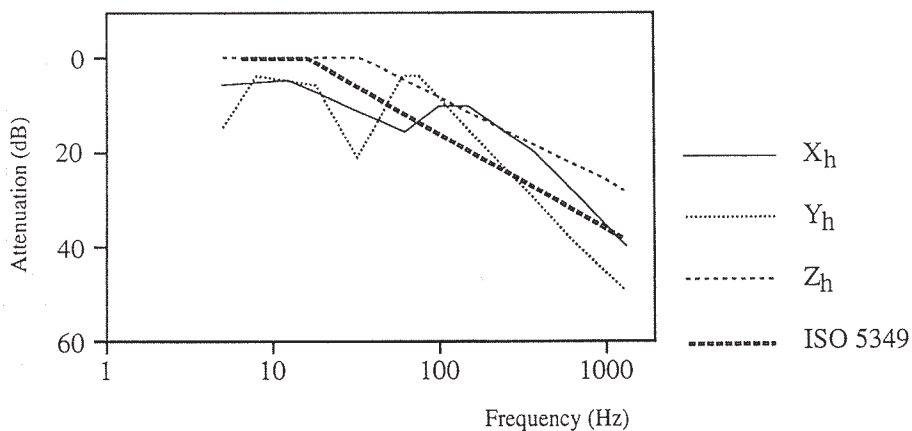

Fig. 3.   Comparison of the attenuation of transferred energy to the hand and arm system for the three different vibration directions and a corresponding frequency-weighting curve specified by ISO 5349.

idea that future standards for risk assessment of vibrations could instead be based on the energy absorption concept.

ACKNOWLEDGEMENTS

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