Int Arch Occup Environ Health (1997) 69:437–446

ORIGINAL ARTICLE

Lage Burström

The influence of biodynamic factors on the mechanical impedance of the hand and arm

Received: 2 August 1996/Accepted: 20 September 1996

Abstract The purpose of this study was to investigate the mechanical impedance of the human hand-arm system during exposure to random vibration under various experimental conditions and to evaluate statistically whether these experimental conditions have any influence on magnitude and phase of the mechanical impedance. A further aim was to compare the obtained results with other investigations where sinusoidal excitation has been used. The mechanical impedance was estimated in ten healthy subjects during exposure to random vibration, with a constant velocity spectrum within the frequency range 4–2000 Hz, by use of a specially designed laboratory handle. 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 (five flexions, two abductions) were studied. The outcome showed that the vibration direction and the frequency of the vibration stimuli have a strong significant influence on the impedance of the hand. An increased vibration level resulted in a significantly lower impedance for frequencies over 100 Hz. Increased grip and feed forces led on the other hand to an increased impedance for all frequencies. With regard to hand and arm posture, the results show that the flexion and abduction had a significant contribution for frequencies below 30 Hz. Furthermore, the influence of some of the studied variables had a non-linear effect on the impedance but also differed between different exposure directions. It was concluded, moreover, that 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.

L. Burström (✉)
National Institute for Working Life, P.O. Box 7654, S-907 13 Umeå, Sweden.
Fax: +46-90-165027; e-mail: lage.burstrom@niwl.se

Introduction

It is known that occupational usage of vibrating hand-held tools can cause different symptoms including vascular disorders, bone alterations and joint deformations, neurological disturbances and muscle disorders. 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 will occur depending upon several factors such as intensity, frequency, direction and duration. Therefore, determining the dynamic behaviour of the hand-arm system can provide knowledge for understanding the mechanisms behind the development of vibration injuries.

As an approach, the human hand and arm may be considered a complex system of masses, springs and dampers. These elements are interconnected and influence each other and cannot of course be measured on the human hand and arm directly. Instead, to measure the properties of the hand and arm, the transfer function could be used. The use of transfer functions comes from electrical engineering. Similar to the measurement of a complex electrical resistance, the mechanical impedance of the hand and arm can be measured. It is defined as the complex ratio of transmitted force (F) and vibration velocity (v) at the point of excitation, i.e. $Z = F/v$ (Ns/m). The magnitude of the impedance and the phase relationship between the two parameters and frequency-dependent. With impedance measurements, the magnitude and phase can indicate whether the hand and arm have a mass-like, damper-like or spring-like response. The impedance can thereby provide the information necessary to calculate the effective masses, spring constants and damping factors. Mathematical and mechanical models are widely used to explain the impedance results [for example; 12, 15, 28, 30, 37, 38, 42]. Although these models are simplified they can still give a lot of information about how the hand and arm behave when exposed to vibrations. Some authors have also used these models for the construction of physical models [7, 17, 22]. For the hand and arm, no international standard has been presented, but such a standard is in preparation in the working-group ISO/TC 108/SC 4/WG 5: "Biodynamic modelling". Moreover, impedance measurements can also be used to determine the energy absorbed by the hand and arm [4].

The effects of the time history of vibration have been studied in only a few investigations. Very little is known about the human response where this is concerned [13]. Evidence has been presented where 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 [5, 35]. In the international literature, a great number of reports can be found where the mechanical impedance of the hand-arm system has been studied [2, 5, 7, 8, 10, 11, 16, 18, 19, 23, 24, 25, 27, 29, 30, 31, 33, 34, 37, 38, 39]. However, these studies do not generally show close agreement. This is probably due to the fact that different experimental techniques and conditions have been used. Furthermore, most of these studies are made during sinusoidal vibration exposure and only two investigations could be found where random vibration exposure has been used [8, 16].

The measured impedance could also reflect the differences that occur both between and within subjects. The "within subjects" deviation has proved to be quite small but the magnitude of the "between subject" standard deviation could be rather greater [5, 16, 33]. Unfortunately, in the studies presented there is a lack of statistical evaluation of the influence of different experimental conditions on the mechanical impedance where these effects have been taken into account. Normally only descriptive statistics have been used.

Against this background, the purpose of this study was threefold: (i) to investigate the mechanical impedance of the human hand-arm system during exposure to random vibration under various experimental conditions; (ii) to evaluate statistically whether investigated experimental conditions have only influence on magnitude and phase of the mechanical impedance; (iii) to compare the results obtained with other investigations where sinusoidal excitation has been used.

Materials and methods

Apparatus

The mechanical impedance of the hand-arm system was calculated by measuring vibration force, velocity and phase between these parameters as closely as possible to the surface of the hand. These were obtained using a specially designed handle, used in earlier studies [6], mounted on an electrodynamic shaker, equipped with two force transducers and one accelerometer for force and velocity measurements, respectively. The handle was also equipped with strain gauges for measurement of both grip and feed forces applied by the subject to the handle. By feeding the signals from a signal generator, random vibration within the frequency range 4–2000 Hz, through a spectrum shaper it was possible to achieve a constant velocity spectrum (1/3-octave band) on the handle independent of frequency and dynamic laod. The varying outputs from the transducers were amplified by separate charge amplifiers and were fed to a dual-channel real-time 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 dual-channel real-time analyser was used for measurement of the auto spectra of the force and the velocity signal. Furthermore the cross-spectrum between the two signals was used for determining the phase. The measured spectra were, after each experiment, transferred to a computer for calculations of the mechanical impedance. These calculations also included subtraction of the additional dynamic force produced by the handle itself.

Subjects and studied variables

The study was carried out in a laboratory (air temperature 22.5 °C ± 1.5 °C) on ten healthy right-handed subjects (age 28–48 years, mean 37.3 years; height 162–188 cm, mean 171.4 cm; weight 54–74 kg, mean 63.6 kg), five males and five females, with no previous work-exposure to vibration. All subjects gave their informed consent to participation in the study, and the project was approved by the Ethics Committee of Umeå University.

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 [21] these directions refer to an excitation of the hand and arm X_h-, Y_h- and Z_h-directions.

Three grip and feed forces were used (25, 50, 75 N and 20, 40, 60 N respectively) and the angle between upper and forearm (the flexion of the elblow) was varied (60°, 90°, 120°, 150°, 180°). The influence of a 90° angle between shoulder and upper body (the abduction of the shoulder) as well as the effect of vibration amplitude on impedance 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. All studied variables were considered to be within the normal range during regular use of vibrating tools [30].

Experimental procedure

All subjects were asked to wear normal office clothes, without jackets, and to remove rings, watches, etc., to minimise 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 and feed forces 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 and feed forces or posture. Every test took about 20 s to conduct and during each experiment five to eight different conditions were investigated. The total number of experiments for each subject was 33 (198 conditions) 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 magnitude and phase of the impedance and to study their frequency dependency (1/3-octave band), regression analysis was carried out.

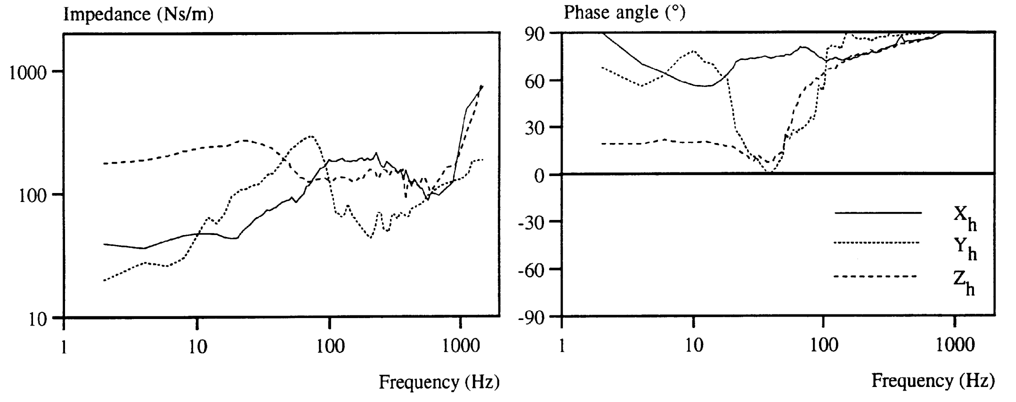


Fig. 1 Mean values for the magnitude and phase of the mechanical impedance as a function of the frequency for different directions (grip force 25 N, feed force 20 N, flexion 180°, abduction 0°, Velocity 6.5 mm/s)

With the logarithmic impedance 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 indicator variables for the subjects. The number of observations used is 47520 (10 subjects, 198 experimental conditions, 24 1/3-octave bands).

The experimental variables were excluded one at a time from the regression model, and the parameters of the model estimated by the weighted least-square method, where velocity was used as a weighting variable [32]. From this smaller model, the residuals were calculated. The residuals include the error-term of the model and the effect of the excluded variable, but the effects of all other variables have been eliminated.

The residuals were 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 was calculated for each level of the excluded variable. The hypothesis that the mean values are the same was tested by a two-sided *t*-test or by analyses of variance [32]. Since a great number of analyses have been conducted, the control for mass significance was done by use of the Holm method [20]. The multiple significance level of $\alpha = 0.05$ was used for these tests.

Results

The influences of the different experimental conditions on the magnitude and phase of the mechanical impedance as a function of the frequency (4–2000 Hz) are presented in Figs. 1–6. However, only representative sets of measured data are shown to highlight the overall pattern and the influence of each experimental variable.

Direction

The mean magnitudes and phases of the impedance for the three different directions of vibration are illustrated in Fig. 1.

As can be seen, the mechanical impedance was dependent on the frequency of the mechanical stimulus. The impedance increases with frequency toward a maximum of about 20–200 Hz, depending on the exposure direction, followed by decreased impedance with frequency. At higher frequencies the impedance increases again. The statistical analyses show that an exposure in the X_h-direction gives a higher impedance compared with an exposure in the Y_h-direction for frequencies below 10 Hz and above 80 Hz. For frequencies between 20 and 80 Hz the opposite was found. A comparison of the X_h - and Z_h-directions shows that an exposure in the X_h-direction gives a lower impedance for frequencies below 60 Hz. Furthermore, the Z_h-direction gives a higher impedance than the Y_h-direction for all frequencies except for those at about 80–100 Hz. When comparing the phase graphs obtained for the three vibration directions, it can be noted that the phase graphs have pronounced differences, especially in the frequency range 10–500 Hz.

Grip force

Firmer handgrips produced in general a higher impedance for all frequencies and for the three exposure directions (Fig. 2). For the X_h-direction an increased grip force leads to a significantly higher impedance for all frequencies, except at about 80 Hz. For the Y_h-direction, a higher grip force gives a higher impedance for frequencies above 10 Hz. Moreover, it could be seen that the frequency for the maximum impedance is shifted upwards when the grip force increases. For the Z_h-direction an increased grip force leads to a higher impedance for all frequencies and is especially pronounced for frequencies around 30 Hz. The phase of the impedance is not statistically influenced by the grip force.

Feed force

Figure 3 shows the average magnitude and phase of the impedance of different feed forces. In the X_h-direction, the impedance increased statistically with the feed force for frequencies below 25 Hz and above 125 Hz. For the Y_h- and Z_h-directions, higher feed forces caused a higher impedance for all frequencies. The influence of the feed force on the phase is not significant.

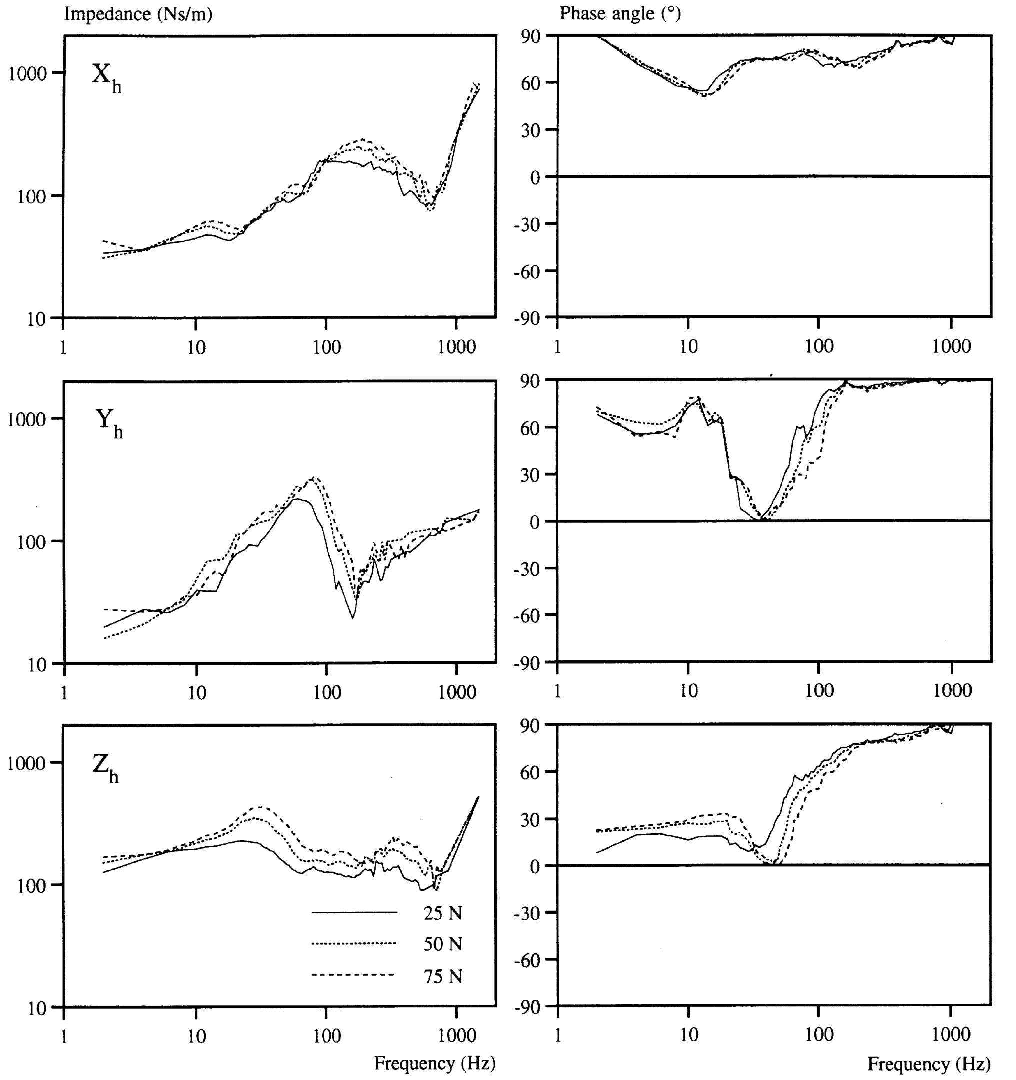


Fig. 2 Mean values for the magnitude and phase of the mechanical impedance as a function of the frequency for different grip forces (feed force 20 N, flexion 180°, abduction 0°, velocity 13 mm/s)

Flexion

The angle between upper arm and forearm (the flexion of the elbow) has an influence on the average magnitude of the impedance which is especially pronounced for frequencies below 50 Hz (Fig. 4). In general, the highest impedance was found for the 180° flexion (extended arm) and the lowest for 120° flexion. When the angle between upper arm and forearm decreases, the impedance in the X_h-direction is decreased for frequencies below 15 Hz and increased for frequencies between 20 and 40 Hz. In the Y_h-direction the impedance increases for frequencies below 20 Hz. In the Z_h-direction the impedance is decreased for frequencies below 40 Hz and increased for frequencies between 40 and 100 Hz. The influence of the flexion of the elbow on the phase is significant for frequencies below 50 Hz for all three directions of exposure.

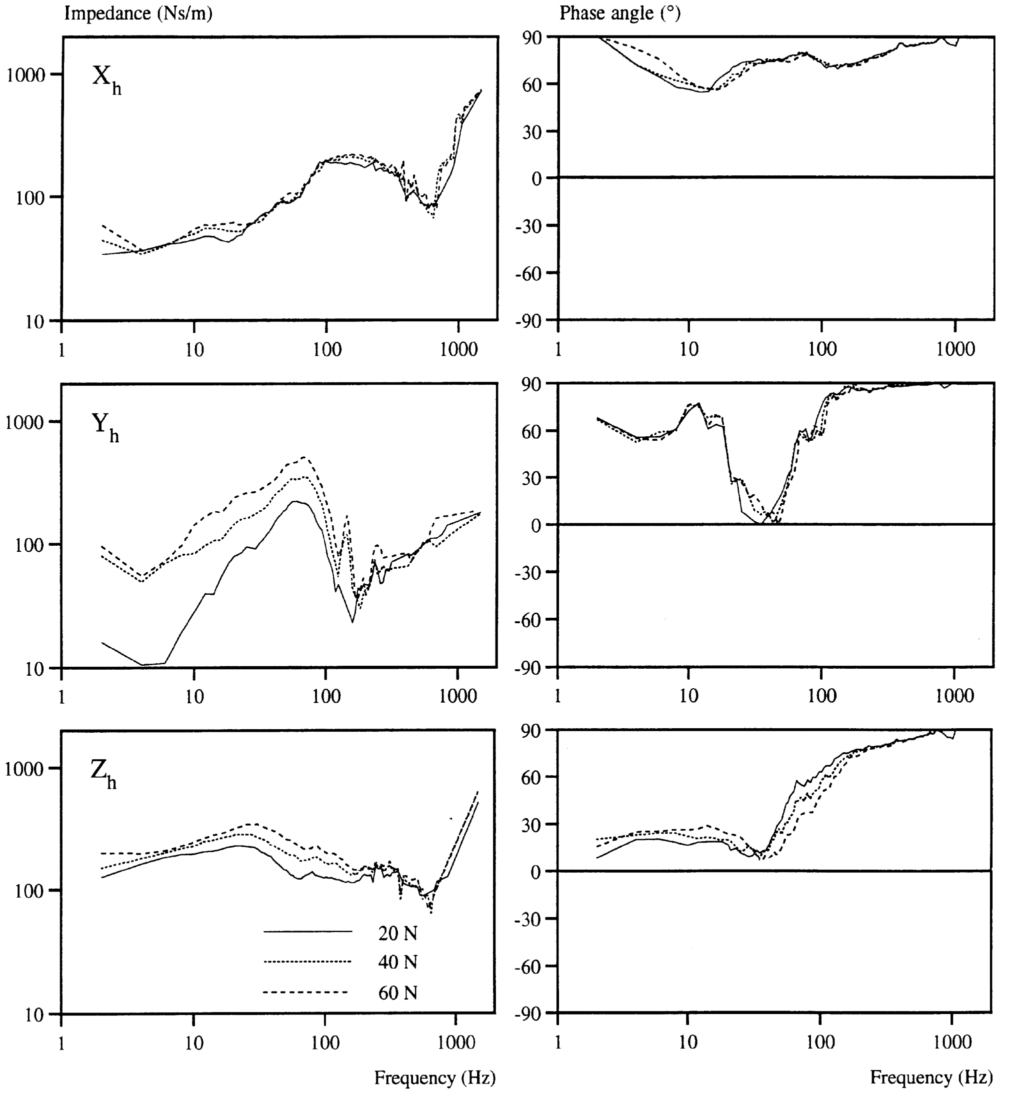
Abduction

The angle between shoulder and body (the abduction of the shoulder) has for all vibration directions an influence on the impedance for frequencies below 20 Hz, where an abduction of 90° gives the highest impedance (Fig. 5). The phase of the impedance is not statistically influenced by the abduction.

Velocity

The magnitude of the impedance decreases slightly when the velocity level increases, Fig. 6. In the X_h-direction this tendency is significant for frequencies above 150 Hz. For frequencies between 60 and 80 Hz a significant increase of the impedance was found. In the Y_h-direction a decreased impedance was observed

Fig. 3 Mean values for the magnitude and phase of the mechanical impedance as a function of the frequency for different feed forces (grip force 25 N, flexion 180°, abduction 0°, velocity 13 mm/s)



for frequencies below 10 and above 40 Hz. In the Z_h-direction the mechanical impedance decreases with the velocity level for all frequencies above 10 Hz. The influence of different velocity levels on the phase of the impedance is not statistically significant for any of the directions.

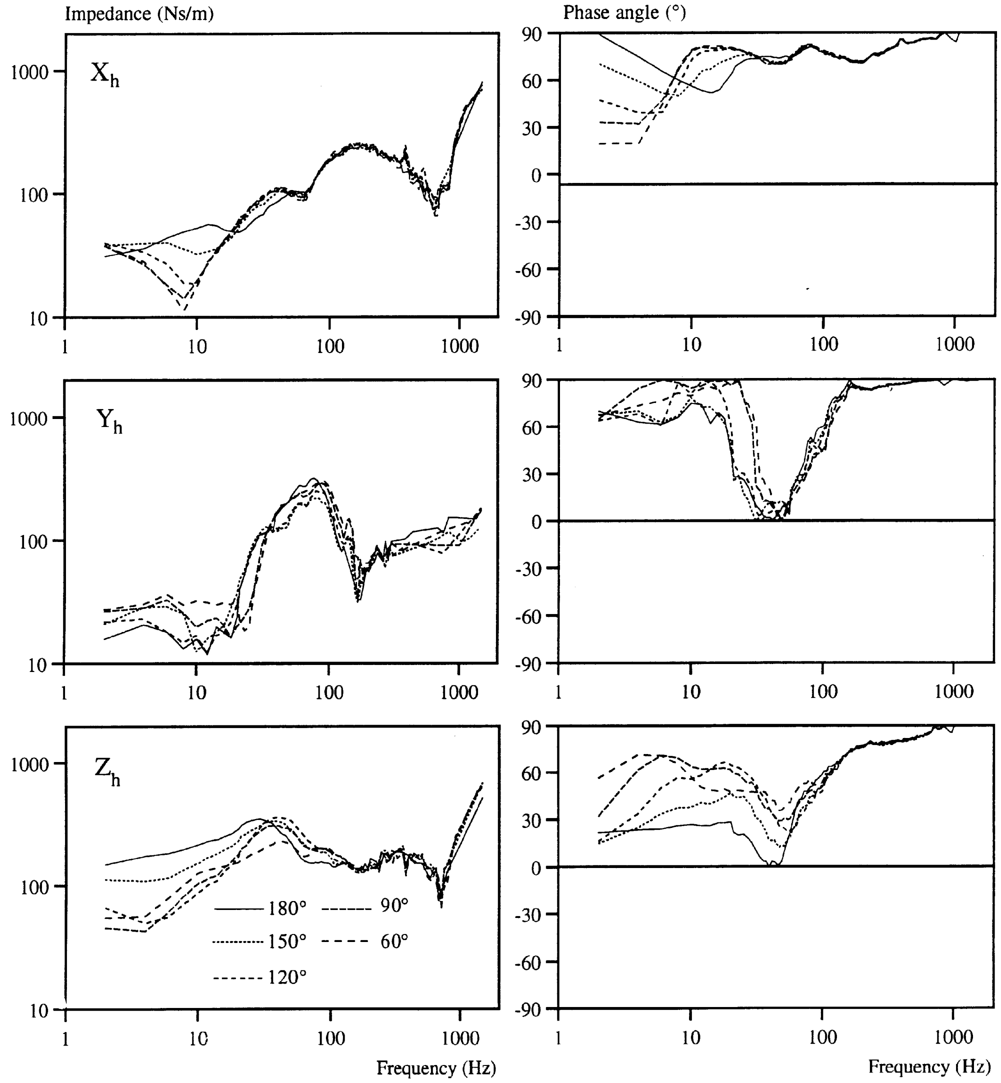
Discussion

The results show that the mechanical impedance depends more or less on all studied biodynamic variables, but especially on vibration direction. The reason for the influence of the direction could be differences in the amount of viscous elements in the hand and arm as well as the coupling of the hand and arm to the upper body. With an increased flexion of the elbow this coupling becomes less significant, and is especially pronounced for an exposure in the Z_h-direction.

An increased handgrip force leads to an increased magnitude of impedance at higher frequencies. This could be due to the dependency of the impedance on the amount of viscous elements in the hand-arm system. The 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. This stiffer system also leads to a frequency shift towards higher frequencies. The influence on the biodynamic response of grip force is also evident from the literature [1, 16, 36].

An increased feed force also gives a higher impedance due to the system becoming stiffer and more mass-like. The greatest influence was found in the Y_h-direction and the smallest in the Z_h-direction. The influence of the feed force on the dynamic characteristics of the hand-arm system have in other investigations only been seen at low frequency excitations [3,

Fig. 4 Mean values for the magnitude and phase of the mechanical impedance as a function of the frequency for different flexions of the elbow (grip force 25 N, feed force 20 N, abduction 0°, velocity 13 mm/s)



14]. The discrepancy is presumbaly due to the deviation between and within subjects.

The abduction of the shoulder has only a minor influence and could be seen for frequencies below 20 Hz. For the flexion of the arm the highest impedance was found with a straight arm and the impedance decreased for frequencies below 25 Hz when the arm was bent. Presumably, this is due to the fact that the coupling against the upper body decreases when the arm is bent.

The impedance of the hand and arm decreases when the vibration level increases. This is in agreement with other studies [4, 16], but is somewhat surprising since the impedance of a linear system should be independent of the vibration level. One reason could be nonlinear behaviour of the hand-arm system.

Except for the vibration direction, only the flexion has a significant influence on the phase of the impedance, and only for frequencies below 50 Hz.

The general conclusion from this study is that biodynamic variables that are dependent on the body constitution, i.e. flexion and abduction, have a significant influence on the impedance that is concentrated at frequencies below about 30 Hz. The biodynamic variables that are related to the hand constitution, i.e. grip and feed forces, have an influence that is significant within the whole investigated frequency range. The reason for this could be that 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 [27]. This process continues and when the frequency reaches 1000 Hz only small volumes of tissue in the hand are exposed to vibration.

The mechanical impedance of the human hand-arm system has, as mentioned earlier, been studied in many investigations but only a few of these studies have presented both the magnitudes and the phases of the

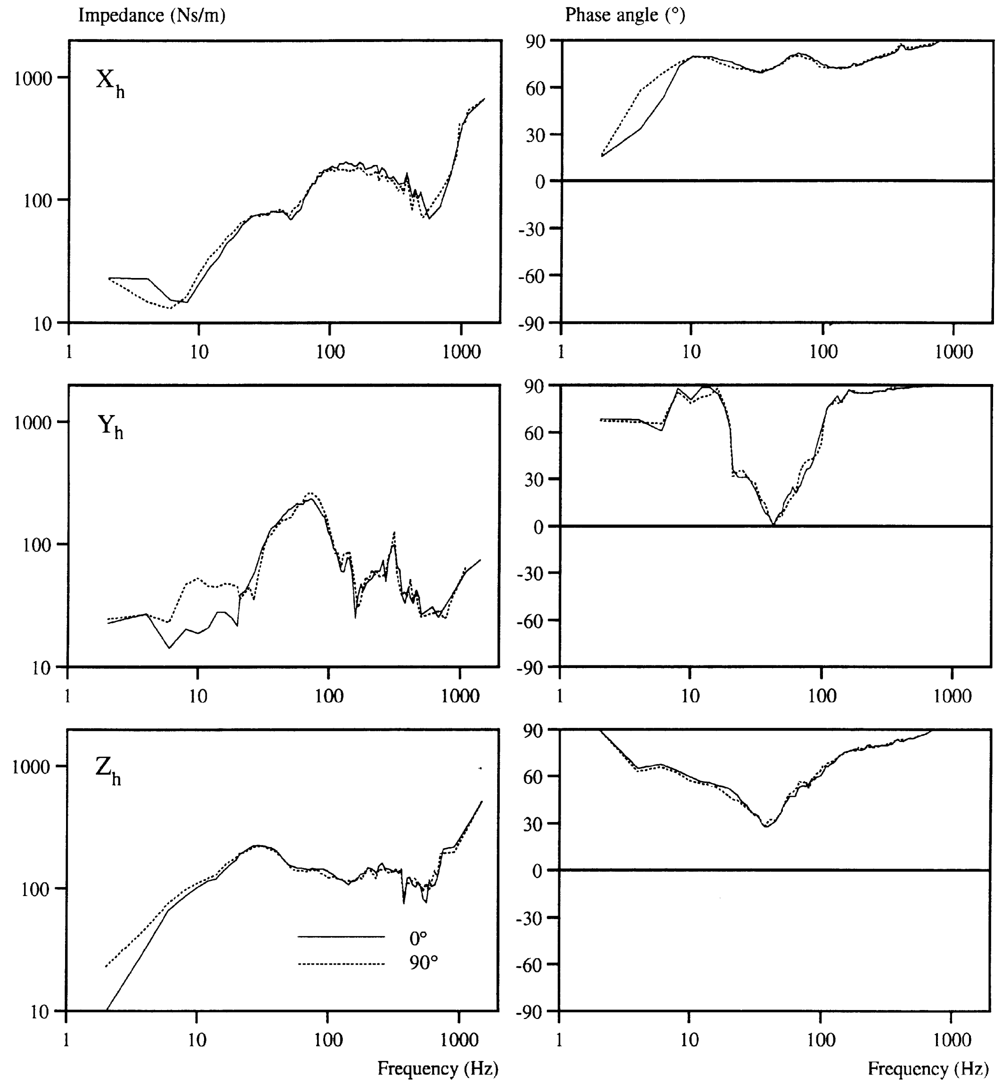


Fig. 5 Mean values for the magnitude and phase of the mechanical impedance as a function of the frequency for different abductions of the shoulder (grip force 25 N, feed force 20 N, flexion 90°, velocity 19.5 mm/s)

impedance for all three directions of vibration [5, 16, 30, 35]. From these investigations, sets of measured data during comparable conditions, i.e. sinusoidal excitation, grip force, vibration level and posture, have been used for calculation of the overall mean value and standard deviation for the magnitude and phase of the impedance. These values are summarised in Fig. 7, as a function of the frequency for each vibration direction. For comparison, a corresponding graph obtained in this study has been inserted in the figure, one for each direction.

As can be seen, the magnitude of the impedance tends to be somewhat lower than that measured using sinusoidal excitation above 400 Hz. This is also in agreement with Gurram et al. [16]. For the phase of the impedance, a relatively large variation in the results could be noticed, especially at higher frequencies. The main reason for these divergencies between random and sinusoidal exaction on the magnitude and phase of the impedance may be the different nature of excitations. The vibration response characteristics of the hand and arm seem to differ, depending upon whether the signal is a discrete frequency signal or a signal consisting of several frequencies [16, 35].

A low mechanical impedance is not necessarily 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 [9, 26, 40]. 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. Variation of the mechanical impedance will only affect the transmission of vibration into the hand and arm and will therefore give no information about the risk of injury. However, the real and imaginary parts of impedance have significance with regard to power dissipation in the physical system. The real part of impedance, i.e.

Fig. 6 Mean values for the magnitude and phase of the mechanical impedance as a function of the frequency for different velocity levels (grip force 25 N, feed force 20 N, flexion 180°, abduction 0°)

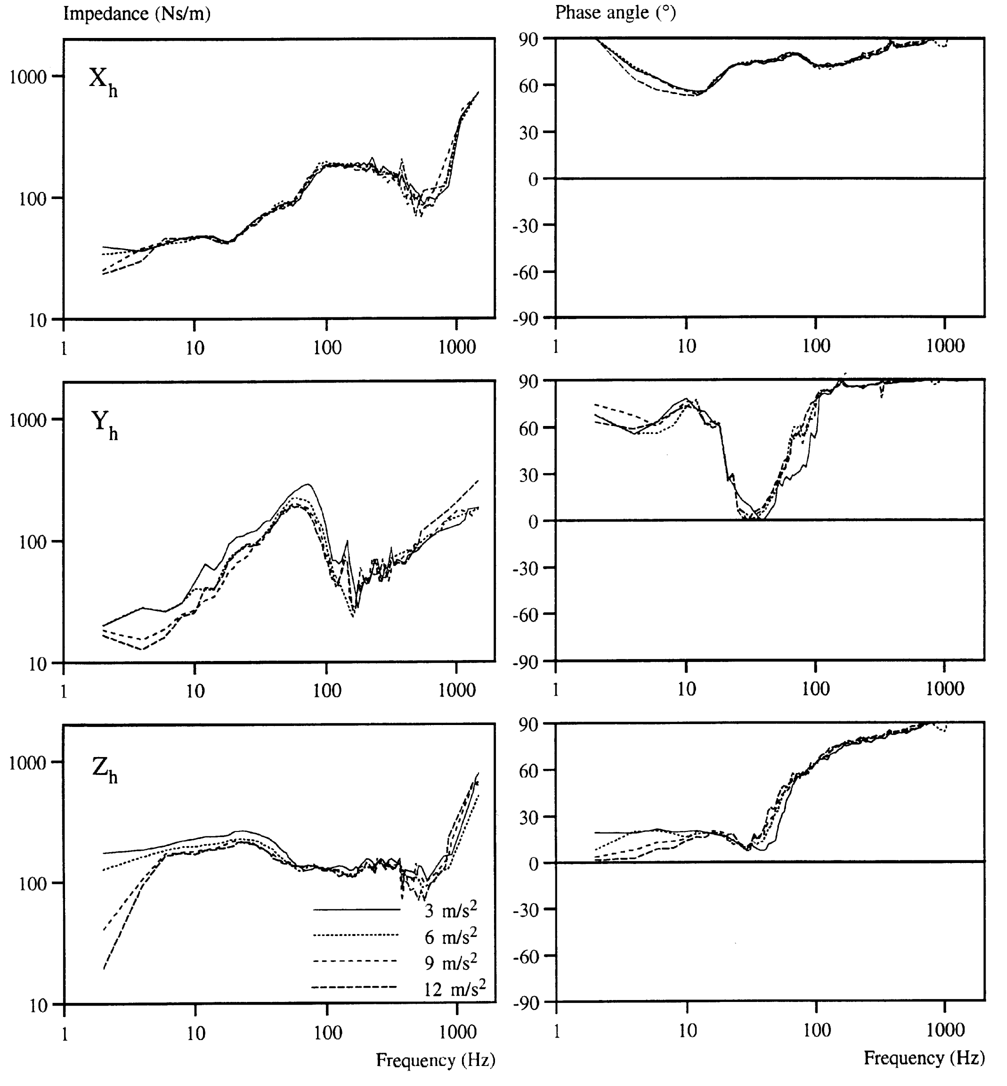
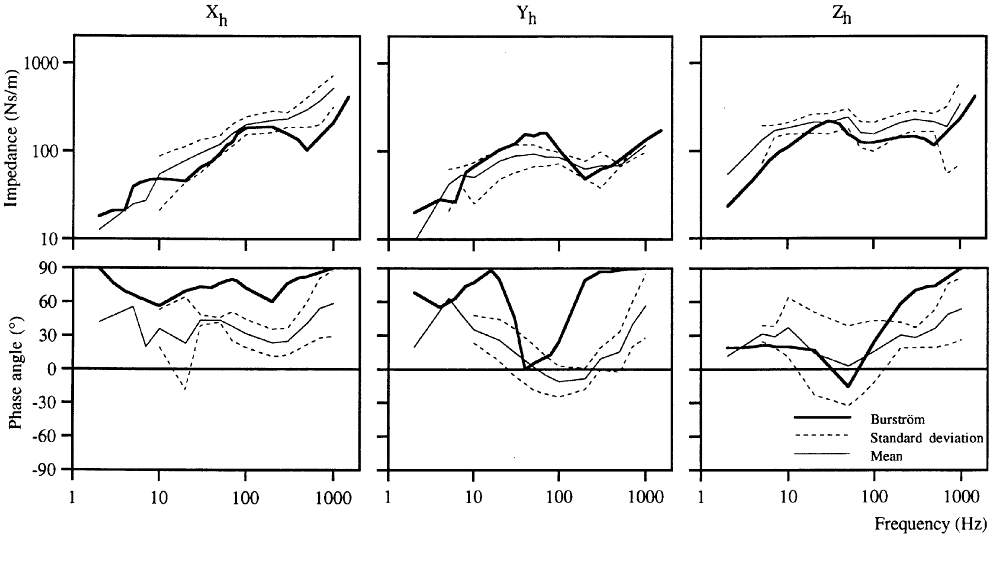


Fig. 7 Comparison of hand-arm impedance curves for the three different vibration directions, as defined in ISO 5349 [21], according to results found in the present study and from earlier investigations (mean and standard deviation)



$Z \cdot \cos(\varphi)$, 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 impedance, 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 [4, 41]. 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 measurements of the velocity level are necessary. However, this equation demands a correct description of the hand-arm system's mechanical response to vibration. The observed differences between impedance data and the random and sinusoidal excitation imply that more studies in this area are necessary. This will not only give an opportunity for obtaining more knowledge about the human hand-arm system, but could also be very useful in setting future standards.

Acknowledgements The financial support of the Swedish Work Environmental Fund is gratefully acknowledged. Special thanks are due to Sonya Hörnqwist Bylund and Markku Peltonen for their technical assistance.

References

1. Aatola S (1989) Transmission of vibration to the wrist and comparison of frequency response function estimators. J Sound Vib 131:497–507
2. Abrams CF, Suggs CW (1977) Development of a simulator for use in the measurement of chain saw vibration. Appl Ergon 8:130–134
3. Bernard D (1990) Etude de la masse apparente du système main-bras et de l'activité musculaire correspondante lors d'une simulation de brise-breton. Institut National de Recherche et de sécurité, report MAV-DT-140/DB
4. Burström L (1990) Measurement of the mechanical energy absorption in the hand and arm whilst using vibrating tools. J Low Freq Noise Vib 9:1–14
5. Burström L (1990) Measurements of the impedance of the hand and arm. Int Arch Occup Environ Health 62:431–439.
6. Burström L (1994) The influence of biodynamic factors on the absorption of vibration energy in the human hand and arm. Nagoya J Med 57:159–167
7. Byström B-O, Nilsson A, Olsson E (1982) Development of artificial hands for use in chain saw vibration measurement. J Sound Vib 82:111–117
8. Cronjäger L, Hesse M (1990) Hand-arm system's response to stochastic excitation. In: Okada A, Taylor W, Dupuis H (eds) Fifth Int Conf Hand-Arm Vibration, Kanazawa. Kyoei Press, Kanazawa, 39–42
9. Cundiff JS (1976) Energy dissipation in human hand-arm exposed to random vibration. J Acoust Soc Am 59:212–214
10. Daikoku M, Ishikawa F (1990) Mechanical impedance and vibration model of hand-arm system. In: Okada A, Taylor W, Dupuis H (eds) Fifth Int Conf Hand-Arm Vibration, Kanazawa. Kyoei Press, Kanazawa, pp 167–171
11. Dieckmann D (1959) Ein schwingungsmechanisches Modell für das schwingungserregte Hand-Arm-System des Menschen. VDI-Z 101:23–26
12. Fritz M (1991) An improved biomechanical model for simulating the strain of the hand-arm system under vibration stress. Biomechanics 24:1165–1171
13. Griffin MJ (1974) Some problems associated with the formulation of human response to vibration. In: Taylor W (ed) The vibration syndrome. Academic Press, London, pp 13–23
14. Griffin MJ, Macfarlane CR, Norman CD (1982) The transmission of vibration to the hand and the influence of gloves. In: Brammer AJ, Taylor W (eds) Vibration effects on the hand and arm in industry. Wiley, New York, pp 103–116
15. Gurram R, Rakheja S, Gouw GJ (1993) Parameter identification of hand-arm vibration (HAV) models using nonlinear optimization techniques. In: Dupuis H, Christ E, Sandover DJ, Taylor W, Okada A (eds) Sixth Int Conf Hand-Arm Vibration, Bonn 1992. Sankt Augustin, BIA, pp 713–726
16. Gurram R, Rakheja S, Gouw GJ (1995) Mechanical impedance of the human hand-arm system subject to sinusoidal and stochastic excitations. Int J Ind Ergon 16:135–145
17. Hansson J-E, Kihlberg S (1982) A test rig for measurement of vibration in hand-held power tools. Arbetarskyddsverket. (in Swedish with an English summary) Arbete och Hälsa 1982:15
18. Hempstock TI, O'Connor DE (1986) Accuracy of measuring impedance in the hand-arm system. Scand J Work Environ Health 12:355–358
19. Hesse M (1989) Über die Hand-Arm-Impedanz und ihre Bedeutung für den Schwingungsschutz. In: Dompke M, Kopp I (eds) Mechanische Schwingungen als Belastungen in der Arbeitswelt, 1989, Werkstattberichte 3. Wirtschaftsverlag NW, Bremerhaven, pp 79–87
20. Holm S (1979) A simple sequentially rejective multiple test procedure. Scand J Stat 6:65–70.
21. International Organisation for Standardization (1986) Mechanical vibration: Guidelines for the measurement and the assessment of human exposure to hand-transmitted vibration (ISO 5349). International Organization for Standardization, Geneva
22. Jahn R, Hesse M (1986) Applications of hand-arm models in the investigation of the interaction beween man and machine. Scand J Work Environ Health 12:343–346
23. Jandák Z (1990) Energy transfer to the hand-arm system at exposure to vibration. In: Okada A, Taylor W, Dupuis H (eds) Fifth Int Conf Hand-Arm Vibration, Kanazawa. Kyoei Press, Kanazawa, pp 49–52
24. Kihlberg S (1994) Vibration transmission and hand-arm impedance. In: Gemne G, Brammer A, Hagberg M, Lundström R, Nilsson T (eds) Proceedings of Stockholm Workshop 94. Arbete och Hälsa 5:73–78
25. Kuhn F (1953) Über die mechanische Impedanz des Menschen bei der Arbeit mit dem Presslufthammer. Arbeitsphysiologie 15:79–84
26. Lidström I-M (1977) Vibration injury in rock drillers, chiselers, and grinders. Some views on the relationship between the quantity of energy absorbed and the risk of occurence of vibration injury. In: Wasserman DE, Taylor W, Curry MG (eds) Int Occup Hand-Arm Vib Conf, Cincinnati. NIOSH publ 77–170, Cincinnati, pp 77–83
27. Lundström R, Burström L (1989) Mechanical impedance of the human hand-arm system. Int J Ind Ergon 3:235–242
28. Meltzer G (1981) A vibration model for the human hand-arm system. In: Bianchi G, Frolov KV, Oledzki A (eds) Man under vibration: suffering and protection. Elsevier, Amsterdam, pp 210–221
29. Meltzer G, Melzig-Thiel R, Schatte M (1980) Ein mathematisches Schwingungsmodell für das menschliche Hand-Arm System. Maschinenbautechnik 29:54–58
30. Mishoe JW, Suggs CW (1977) Hand-arm vibration. Part II. Vibrational responses of the human hand. J Sound Vib 53: 545–558
31. Miwa T (1975) Mechanical impedance of the human body in various postures. Jpn J Ind Health 13:1–22
32. Norusis M (1993) SPSS for Windows. Release 6.0 SPSS Inc., Chicago

33. Panzke K-J, Balasus W (1985) Time-dependence and non-linearity of the impedance of the human hand-arm system while exposed to intense vibration. Int Arch Occup Environ Health 57:35–45
34. Popov K (1979) Untersuchung der Ausbreitung Mechanischer Schwingungen im menschlichen Gewebe als Beitrag zur Messmethodik, zur arbeitshygienischen Standardisierung und als Optimierungshilfe für die Schwingungsminderung an Arbeitsplätzen mit Schwingungsexposition, Doctoral – Eng thesis. Technischen Universität Dresden
35. Reynolds D (1977) Hand-arm vibration: a review of 3 years research. In: Wasserman DE, Taylor W, Curry MG (eds) Int Occup Hand-Arm Vib Conf Cincinnati. NIOSH publ 77-170, Cincinnati, pp 99–128
36. Reynolds DD, Angevine EN (1977) Hand-arm vibration. Part II. Vibration transmission characteristics of the hand and arm. J Sound Vib 51:255–265
37. Reynolds DD, Falkenberg RJ (1982) Three- and four-degrees-of freedom models of the vibration response of the human hand. In: Brammer AJ, Taylor W (eds) Vibration effects on the hand and arm in industry. Wiley, New York, pp 117–132
38. Reynolds DD, Keith RH (1977) Hand-arm vibration. Part I. Analytical model of the vibration response characteristics of the hand. J Sound Vib 51:237–253
39. Reynolds DD, Soedel W (1972) Dynamic response of the hand-arm system to a sinusoidal input. J Sound Vib 21:339–353
40. Reynolds DD, Wasserman DE, Basel R, Taylor W (1982) Energy entering the hands of operators of pneumatic tools used in chipping and grinding operations. In: Brammer AJ, Taylor W (eds) Vibration effects on the hand and arm in industry. Wiley, New York, pp 133–146
41. Suggs CW (1974) Modelling of the dynamic characteristic of the hand-arm system. In: Taylor W (eds) The vibration syndrome. Academic Press, London, pp 169–186
42. Wood LA, Suggs CW, Abrams CF (1978) Hand-arm vibration. Part III. A distributed parameter dynamic model of the human hand-arm system. J Sound Vib 57:157–169