Int Arch Occup Environ Health (1990) 62:431–439

International Archives of
Occupational and Environmental Health

Measurements of the impedance of the hand and arm

Lage Burström

National Institute of Occupational Health, P.O. Box 6104, S-90006 Umeå, Sweden

Received December 20, 1989 / Accepted May 25, 1990

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 anthropometric 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 is 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. Figure 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).

In the literature the mechanical impedance of the hand-arm system have been studied in several investigations (see Panzke and Balasus 1985; Lundström and

---

Offprint requests to: L. Burström

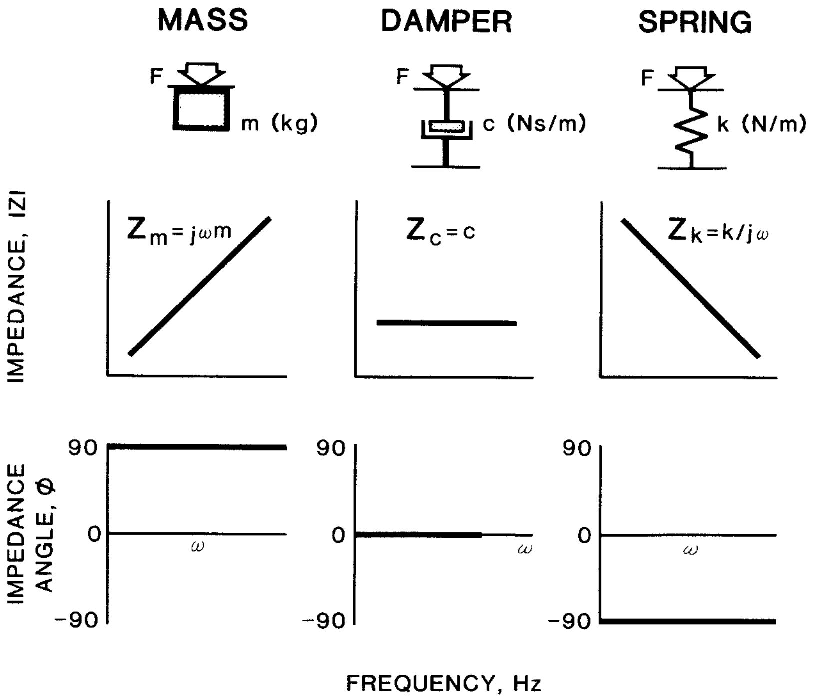

Fig. 1. The separate elements into which the mechanical impedance can be decomposed, mass, spring and damper. The upper part of the figure shows the symbols for separate elements in mechanical models, the lower part shows how the specific magnitude and phase of the impedance are frequency dependent (after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

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

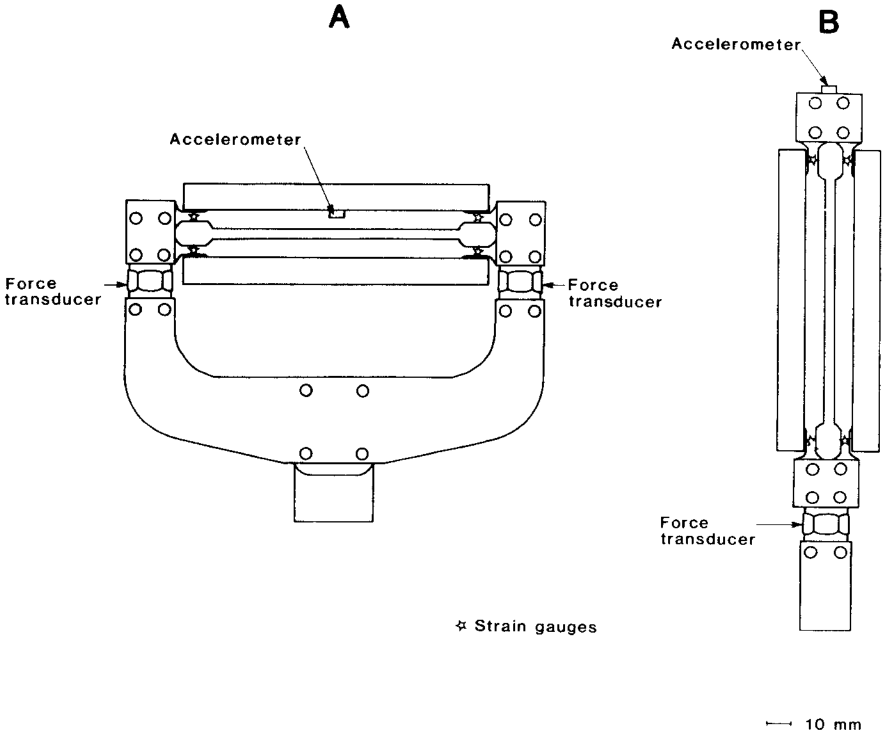

Fig. 2. Handle design and the location of the accelerometer, the force transducers and the strain gauges

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

Subject	Sex	Age	Height (cm)	Weight (kg)	Hand length (cm)	Hand breadth at thumb (cm)	Hand breadth at metacarpal (cm)	Hand tickness (cm)	Hand volume (ml H_2O)	Shoulder-elbow length (cm)	Fore-arm length (cm)	Fore- volume (ml H_2O)	Arm volume (ml H_2O)	Maximum grip-force (N)
1	M	44	186	70	21.0	11.0	9.5	3.0	490	41.0	51.5	1695	3820	62.6
2	M	44	179	72	18.3	10.3	8.5	2.8	360	36.0	46.0	1300	3750	63.7
3	M	29	177	68	18.4	10.4	8.6	2.9	380	38.0	45.5	1345	3530	46.5
4	M	34	175	66	18.5	10.7	8.5	2.9	400	38.0	46.0	1560	3750	60.2
5	M	27	181	82	20.1	11.7	9.2	3.3	450	40.0	49.5	2050	4570	56.5
6	F	42	158	48	16.1	8.6	7.0	2.3	220	33.5	39.0	735	1910	21.8
7	F	39	171	59	17.4	8.8	7.6	2.5	290	37.0	44.0	1055	2640	27.3
8	F	28	170	59	16.7	8.4	6.9	2.5	270	36.0	43.5	1090	3075	28.8
9	F	33	161	54	16.4	9.1	7.6	2.5	260	33.5	40.5	930	2340	27.6
10	F	34	164	59	17.3	9.7	7.8	2.7	320	36.0	43.5	1095	2955	40.4
Mean		35.4	172.2	63.7	18.0	9.9	8.12	2.7	344.0	36.9	44.9	1285.5	3234.0	43.5
SD		6.5	9.12	9.86	1.59	1.12	0.88	0.30	87.33	2.46	3.75	392.76	799.76	16.47

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 fo the handle was 225 g and the size elliptic was 31 × 42 mm.

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 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 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 orientations 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.

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

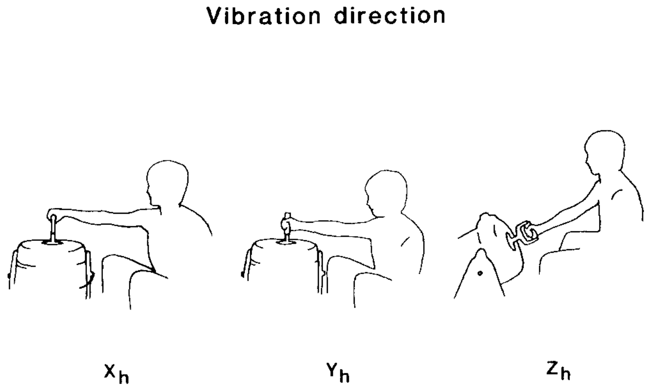

Fig. 3. Hand-arm postures used in order to get a vibration exposure in the three different directions X_h, Y_h and Z_h, as defined in ISO 5349

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 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 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 magntiude 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.

Figure 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.

Figure 4H shows the average magnitude and phase of the mechanical impedance for males and females, respectively. The figure 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*-test (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 highest frequencies. Furthermore, it can be observed that 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

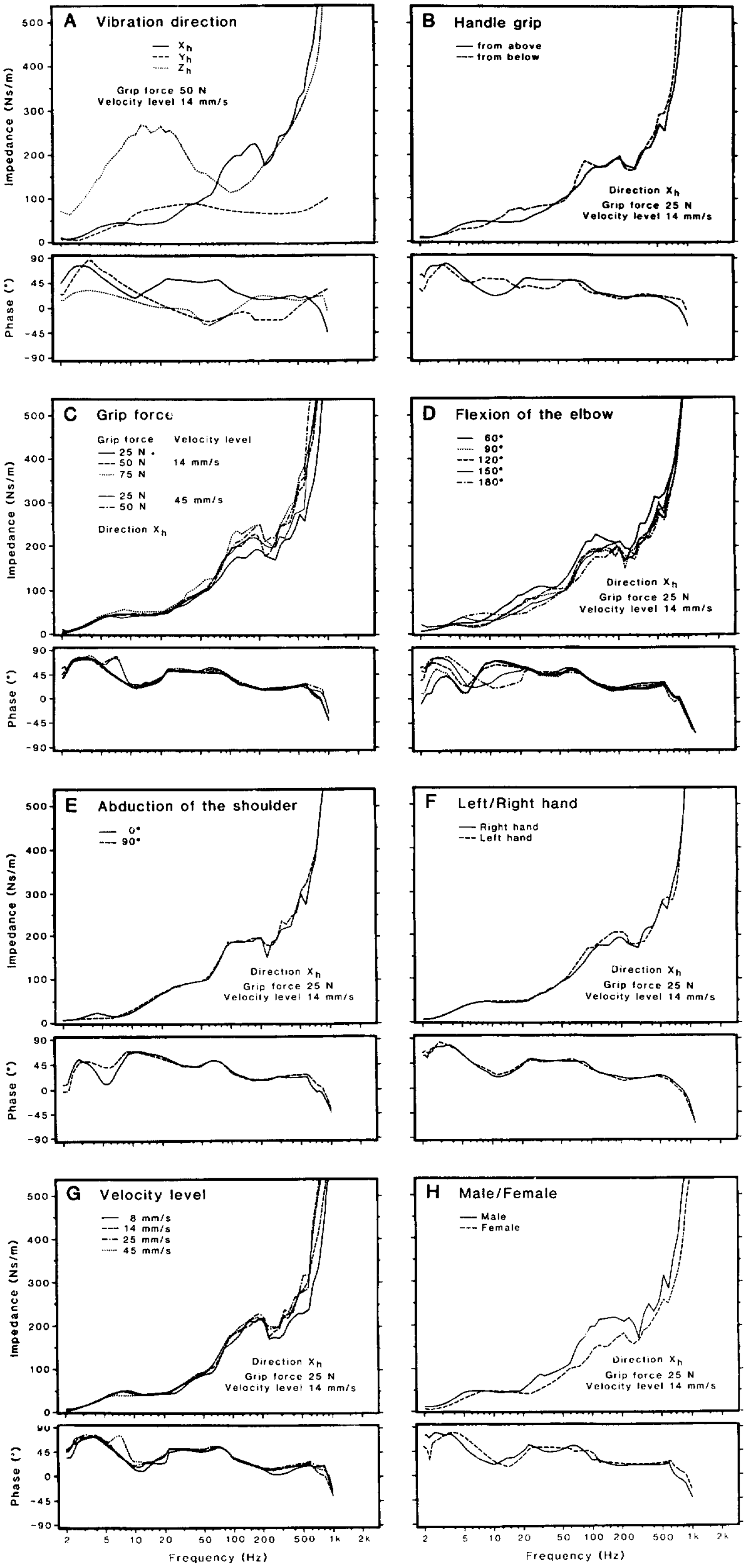

Fig. 4. Mean values for the magnitude and phase of the mechanical impedance for eight different variable combinations. The average values are based on data from ten different subjects

Table 2. Mean values for the magnitude (Ns/m) and phase (degree) of the mechanical impedance for different variable combinations. Standard deviation is given within 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) 2	5	10	20	50	100	200	500	Comments
X_h	14	50	Imped.	7.7 (5.5)	37.3 (7.6)	37.2 (7.9)	34.3 (16.3)	88.6 (27.0)	170.2 (39.0)	175.9 (31.1)	265.0 (91.9)	
			Phase	73 (23)	51 (13)	18 (14)	48 (17)	46 (11)	33 (14)	9 (12)	18 (29)	
Y_h	14	50	Imped.	11.0 (6.1)	28.6 (13.0)	59.7 (30.7)	61.8 (22.9)	73.4 (24.4)	55.8 (13.1)	70.2 (12.2)	44.2 (72.2)	
			Phase	53 (23)	65 (9)	25 (10)	−2 (12)	−19 (20)	−2.6 (23)	−28 (24)	−20 (26)	
Z_h	14	50	Imped.	65.1 (31.0)	160.3 (45.4)	218.9 (62.4)	222.3 (44.7)	142.7 (36.9)	101.9 (30.1)	170.8 (103.0)	276.6 (168.0)	
			Phase	30 (15)	24 (7)	6 (10)	−1 (19)	−25 (13)	−5 (17)	19 (17)	9 (16)	
X_h	14	25	Imped.	7.0 (3.3)	36.9 (10.3)	38.8 (6.9)	40.8 (11.3)	85.1 (16.5)	152.6 (31.7)	164.1 (31.5)	254.6 (64.0)	
			Phase	74 (28)	54 (16)	20 (14)	40 (9)	49 (11)	35 (14)	16 (6)	27 (9)	
X_h	14	25	Imped.	7.9 (3.6)	30.8 (8)	27.0 (6.1)	52.3 (15.9)	83.7 (22.2)	157.9 (37.8)	167.0 (32.8)	245.8 (61.5)	Flexion 150°
			Phase	71 (21)	28 (10)	33 (11)	54 (3)	48 (12)	32 (11)	12 (11)	23 (14)	
X_h	14	25	Imped.	7.8 (2.3)	16.5 (4.5)	28.0 (7.7)	67.0 (32.0)	93.3 (30.5)	170.1 (36.7)	175.6 (36.4)	254.5 (56.0)	Flexion 120°
			Phase	63 (19)	23 (16)	63 (9)	58 (7)	48 (14)	29 (14)	17 (8)	25 (12)	
X_h	14	25	Imped.	6.8 (7.1)	14.0 (4.0)	26.9 (8.7)	60.0 (18.8)	83.9 (22.5)	165.5 (43.1)	172.0 (28.5)	260.1 (48.7)	Flexion 90°
			Phase	40 (23)	11 (25)	69 (5)	57 (6)	44 (11)	30 (14)	16 (8)	23 (8)	
X_h	14	25	Imped.	14.9 (17.3)	22.1 (19.5)	41.9 (35.2)	78.6 (36.1)	107.0 (48.6)	183.0 (43.5)	186.4 (33.3)	281.7 (71.6)	Flexion 60°
			Phase	22 (28)	12 (21)	69 (5)	58 (5)	54 (10)	33 (19)	20 (10)	28 (12)	
X_h	14	25	Imped.	7.7 (4.7)	25.6 (5.8)	41.1 (13.5)	61.6 (21.1)	78.6 (20.2)	159.8 (35.5)	177.7 (38.4)	256.4 (71.8)	Grip from below
			Phase	54 (21)	47 (9)	51 (8)	37 (13)	42 (14)	7 (14)	10 (8)	16 (12)	
X_h	14	75	Imped.	8.5 (5.1)	42.4 (7.8)	45.2 (6.1)	48.2 (14.3)	108.2 (25.7)	203.7 (67.7)	219.7 (36.7)	315.6 (120.8)	
			Phase	70 (22)	54 (13)	21 (11)	53 (11)	50 (12)	39 (14)	17 (10)	27 (9)	
X_h	14	25	Imped.	5.8 (3.3)	10.5 (3.3)	30.9 (10.9)	64.9 (16.0)	86.0 (26.0)	162.6 (48.0)	169.5 (36.2)	278.3 (67.8)	Abduct 90°
			Phase	32 (25)	39 (32)	68 (7)	53 (8)	45 (10)	25 (14)	17 (7)	29 (7)	
X_h	14	25	Imped.	6.8 (4.0)	36.2 (9.3)	40.8 (4.5)	42.2 (14.0)	87.0 (26.3)	149.7 (51.7)	184.4 (28.5)	246.5 (37.7)	Left hand
			Phase	78 (22)	52 (5)	24 (12)	48 (13)	51 (7)	30 (18)	13 (9)	20 (6)	
X_h	8	25	Imped.	7.0 (3.6)	38.8 (10.5)	37.0 (6.9)	37.3 (9.1)	81.6 (18.5)	150.2 (57.9)	185.2 (25.7)	211.8 (36.5)	
			Phase	66 (21)	50 (12)	10 (14)	37 (12)	48 (9)	30 (18)	13 (13)	8 (25)	
X_h	25	25	Imped.	6.3 (4.0)	38.1 (7.5)	36.3 (7.3)	43.5 (11.3)	85.6 (18.4)	165.3 (35.6)	191.4 (17.9)	290.6 (62.8)	
			Phase	74 (22)	57 (12)	21 (12)	43 (9)	52 (10)	35 (13)	14 (6)	27 (9)	
X_h	45	25	Imped.	6.1 (3.3)	35.6 (7.5)	37.3 (6.9)	43.9 (11.6)	83.8 (17.7)	162.0 (29.3)	186.8 (23.8)	253.9 (68.0)	
			Phase	68 (33)	65 (11)	27 (11)	51 (8)	53 (8)	34 (12)	12 (5)	21 (17)	
X_h	45	25	Imped.	7.1 (2.9)	38.8 (8.7)	41.9 (11.0)	46.2 (13.9)	89.0 (16.4)	174.1 (44.6)	222.0 (35.9)	309.9 (68.6)	
			Phase	69 (23)	69 (21)	25 (8)	49 (8)	52 (8)	38 (12)	16 (8)	27 (13)	
X_h	14	25	Imped.	10.9 (2.9)	42.7 (7.9)	38.9 (2.4)	53.6 (8.3)	95.0 (11.8)	180.6 (23.7)	182.0 (32.2)	313.0 (56.7)	Male
			Phase	83 (17)	42 (18)	22 (7)	57 (5)	52 (8)	25 (6)	18 (8)	30 (9)	
X_h	14	25	Imped.	5.0 (1.6)	34.1 (10.8)	40.5 (9.9)	36.2 (5.1)	81.7 (18.4)	135.6 (19.7)	161.6 (13.8)	232.2 (31.5)	Female
			Phase	64 (35)	63 (8)	21 (20)	39 (7)	50 (12)	39 (17)	18 (4)	23 (9)	

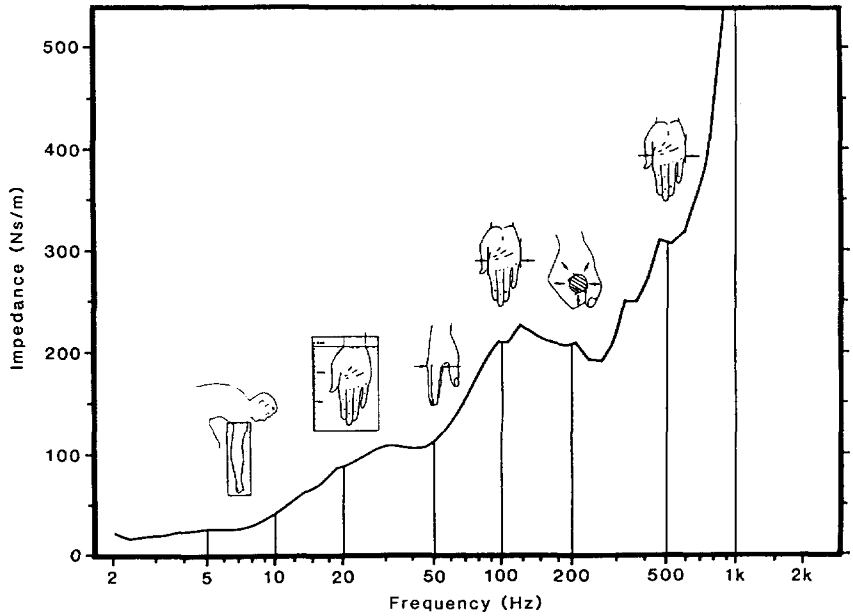

Fig. 5. Correlation between different biological factors of the subjects' hand-arm systems and the mechanical impedance as a function of the frequency (Vibration direction X_h)

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 figure 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.

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.

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

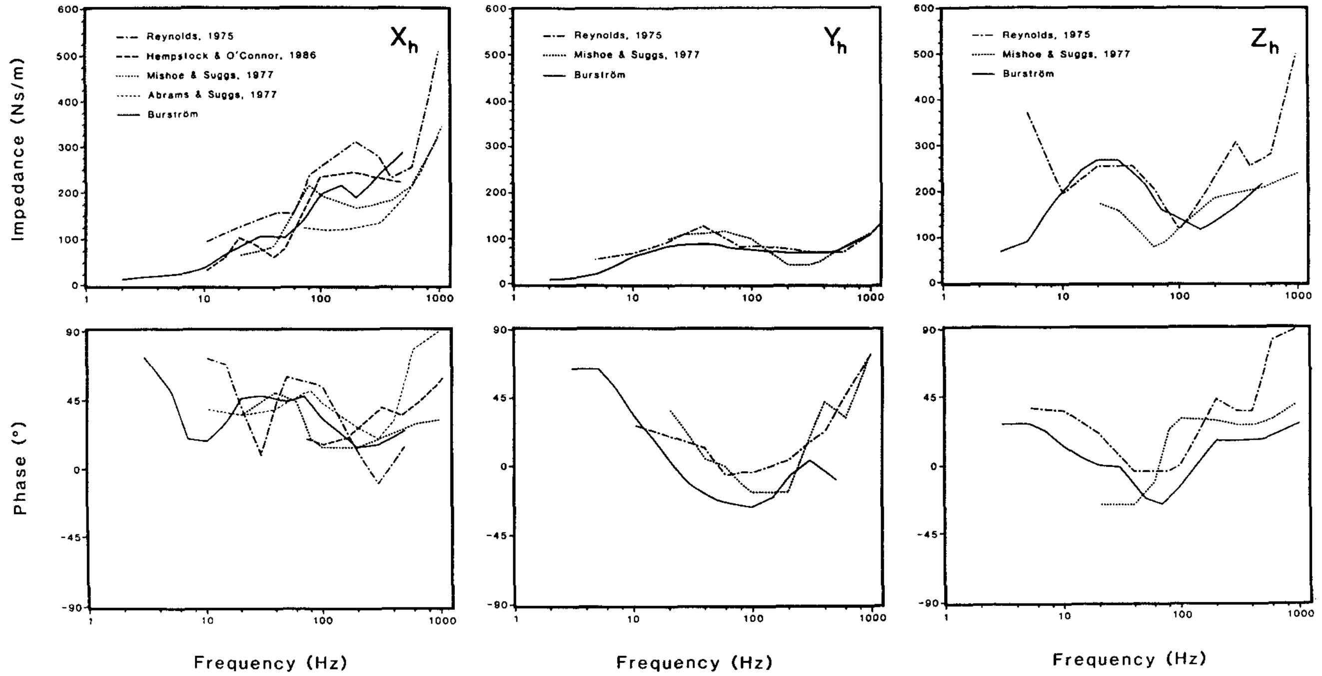

Fig. 6. Comparison of hand-arm impedance curves for the three different vibration directions, as defined in ISO 5349, according to results found in the present study and from earlier investigations

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 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 1400 Hz. The frequency weighting should be done with a filter whose attenuation, expressed in terms of vibration velocity, decreases from the start by 12 dB per octave up to 16 Hz. For higher frequencies of up to 1400 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.

Acknowledgements. The technical assistance of Asta Lindmark is gratefully acknowledged.

References

Abrams CF, Suggs CW (1977) Development of a simulator for use in the measurement of chain saw vibration. App Erg 8:130–134

Box GEP, Hunter WG, Hunter JS (1978) Statistics for experimenters. An introduction to design, data analysis and model building. John Wiley and Sons, New York

Brammer AJ, Taylor W (eds) (1982) Vibrations effects of the hand and arm in industry. John Wiley and Sons, New York

Coermann R (1962) The mechanical impedance of the human body in sitting and standing position at low frequencies. Human Factors 4:277–253

Cundiff JS (1976) Energy dissipation in human hand-arm exposed to random vibration. J Acous Soc Am 1:212–214

Hempstock TI, O'Connor DE (1986) Accuracy of measuring impedance in the hand-arm system. Scand J Work Environ Health 12:355–358

Hixon EL (1976) Mechanical impedance. In: Harris CM, Crede CE (eds) Shock and vibration handbook. McGraw-Hill, New York, pp 10.1–10.46

International Organization for Standardization, ISO 5349 (1986) Guidelines for the measurements and the assessment of the human exposure to hand-transmitted vibrations. ISO, Geneva

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 occurrence of vibration injury. In: Wasserman DE, Taylor W, Curry MG (eds) Proc Int Occup Hand-Arm Vib Conf. NIOSH-publication No. 77–170, Cincinnati, pp 77–83

Lundström R (1984) Local vibrations– mechanical impedance of the human hand's glabrous skin. J Biomech 17:137–144

Lundström R, Burström L (1989) Mechanical impedance of the human hand-arm system. Int J Ind Erg 3:235–242

Mishoe JW, Suggs CW (1977) Hand-arm vibration, Part II. Vibrational responses of the human hand. J Sound Vib 53:545–558

Olesen HP, Randall RB (1979) A guide to mechanical impedance and structural response techniques. Brüel & Kjaer Application Note 17–179, Copenhagen

Panzke KJ, Balasus W (1985) Time dependence and non-linearity of the impedance of the human hand-arm system while expsoed to intense vibration. Int Arch Occup Environ Health 57: 35–45

Reynolds DD (1977) Hand-arm vibration: a review of 3 years' research. In: Wasserman DE, Taylor W, Curry MG (eds) Proc Int Occup Hand-Arm Vib Conf. NIOSH-publication No. 77–170,Cincinnati, pp 99–128

Reynolds DD, Keith RH (1977) Hand-arm vibration, part I: Analytic model of the vibration response characteristics of the hand. J Sound Vib 51:237–253

Reynolds DD, Soedel W (1972) Dynamic response of the hand-arm system to a sinusoidal input. J Sound Vib 21:339–353

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. John Wiley and Sons, New York, pp 133–146

Van Cott HP, Kinkade RG (eds) (1972) Human engineering guide to equipment design. McGraw-Hill Company, Washington