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Analysis of Driving–Point Mechanical Impedance of the Human Hand Arm System

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Systematic Review

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Abstract

This research proposes a synthesis of the measured values of human male hand–arm impedance characteristics, reported in the literature. The driving point mechanical impedance data of the human hand–arm, grasping a vibrating handle, has been compared to highlight the various similarities and differences among the data. The DPMI response of the hand–arm system has been measured in many studies, under controlled test conditions. Considerable differences exist among the data reported by different investigators. The dependence of the impedance response on various intrinsic and extrinsic variables, including the frequency and the direction of vibration, the grip and push forces, the vibration amplitude and individual characteristics, has been widely inestigated in the reported studies. It is proposed an effort to systematically quantify the influences of many of these factors.[DOI:10.12866/J.PIVAA.2013.12.001] [1]

Keywords: Hand–arm vibration, White finger, Mechanical impedance

1 Introduction

The driving point mechanical impedance characteristics of the hand–arm system have been extensively analyzed in order to appreciate the biodynamic response of the hand–arm system to vibration excitations in three orthogonal axes [Jahn and Hesse, 1986]. Such cognition develops effective vibration isolators [Miwa et al., 1979, Dobry et al., 1992, Oddo et al., 2004, Sam and Kathirvel, 2009, Saggin et al., 2012] to reduce effects of dangerous frequencies on the hand–arm

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system. The driving–point mechanical impedance (DPMI) is defined as ratio F/V, where F and V are the dynamic force and velocity, respectively, at the hand–handle interface in the same vibration direction [5349-1, 2004, 10068:2012, 2012]. Some of the principal physical variables, influencing the severity of hand–transmitted vibration, are magnitude of vibration, frequency of vibration, direction of vibration, area of contact with vibration (grip force and push force), finger hand and arm posture, environment (for example, temperature). ISO 10068:2012 specifies the mechanical impedance of the human male hand-arm system at the driving point. Values of the impedance, expressed as modulus and phase, are provided for three orthogonal, translatory directions of excitation. Such directions correspond to the X_h, Y_h and Z_h axes of the coordinate system. The X_h, Y_h and Z_h components of impedance are defined as a function of frequency, from 10 Hz to 500 Hz, for specified arm positions, grip and feed forces, handle diameters, and intensities of excitation. The components of impedance in the three directions are independent. ISO 10068:2012 can be used to define typical values of the mechanical impedance of the hand–arm system at the driving point, applicable to males under the circumstances specified [10068:2012, 2012].

In this study it is proposed the synthesis of the measured human data for postures with elbow angle in the $60°$–$165°$ range, 25–50 N grip force, push force up to 50 N, and handle size in the 19–45 mm diameter range. The idealized ranges are limited to excitation frequency in the 10–500 Hz range, while the data show even larger variability at frequency above 500 Hz.

2 Synthesis of the measured human data

In order to collect data for different directions of input to the hand, Mishoe proposed two different handles: an handle, shaped like an **I**, and the other handle, with the shape of a **T**. The collection of the mechanical impedance data was automated so that the vibration input to a vibration table was controlled at a constant acceleration level while the frequency was swept from 20 Hz to 2000 Hz [Mishoe and Suggs, 1977].

The mechanical response characteristics of individuals to hand–induced vibration are a function of the manner in which a vibrating handle is clasped and of the orientation of the vibration relative to the hand [Reynolds and Keith, 1977].

Mechanical vibrations, transmitted to fingers, may cause the development of vascular disorders of the finger. Mechanical vibrations, transmitted to fingers, should not be confused with ones transmitted into the palm of the hand. The fingers are structurally different and offer a much lower impedance. Lundstrom reported measures of mechanical impedance over the range 20–10000 Hz, by a vibratory probe to 10 points on the finger [Lundstrom and Burstrom, 1989]. The Authors suggested a resonance region between 80 and 200 Hz, depending on the part of the skin which is excited. In this study, the research refines the construction of handle, specially designed for measurements of mechanical impedance [Lundstrom and Burstrom, 1989]. 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.

In the study [Kihlberg, 1995], Kihlberg compares the dynamic response of the hand–arm system due to exposure of two types of vibrations, one from an impact hammer and one from a grinder. Kihlberg considers that the driving–point impedance depends on the exposure frequency, not the type of exposure. If grip and push forces are kept constant, magnitude and phase of the driving–point impedance does not change in exposure of two types of vibrations. The impedance of different people fluctuates in a range of about 2 dB over the whole frequency range.

The driving point mechanical impedance technique qualifies the biodynamic response of the human hand–arm system, subject to sinusoidal and stochastic excitations [Gurram et al., 1995]. The investigation of Gurram et al. analyzed various aspects: inter–subject variations, influences of grip force and influence of amplitude of vibration. The mechanical impedance exhibits a high degree of inter–subject variations that may be attributed to the differences in weights and sizes of hands of the subjects. For against, the intra–subject discrepancies are more controlled than inter–subject variations. The deviations in impedance magnitude data are larger than the deviations recorded in the impedance phase data. The results reveal that amplitude of vibration, sinusoidal or random, affects the driving point impedance of the human hand-arm in a insignificant manner. The peak variation in impedance magnitude, for the range of excitation levels considered in this study, is below 10%. Variations in magnitude of sinusoidal excitation induce variations in impedance phase at frequencies below 80 Hz. If there are random excitations, the impedance phase denotes irrelevant deviations. The investigation of Gurram et al. analyzed the magnitude of driving point impedance using three different magnitudes of grip force. The magnitude of driving point impedance, in general, tends to gain with increase in the excitation frequency. Variations in impedance phase, with changes in grip force, are not clearly evident. The variations in impedance phase are performed mainly at frequencies below 100 Hz.

Burstrom developes the examinations on the following correlations: mechanical impedance in function of angle between upper arm and forearm (the flexion of the elbow) and mechanical impedance in function of angle between shoulder and body (the abduction of the shoulder) [Burstrom, 1997]. In this study 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. Burstrom studied 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 $\mathrm{m/s^2}$) and hand and arm posture (five flexions, two abductions). These experimental conditions affect differently the magnitude and phase of the mechanical impedance. The outcome showed that the vibration direction and the frequency of the vibration stimuli have a significant influence on the impedance of the hand. The impedance increases in function of 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. Firmer handgrips produced a higher impedance for all frequencies and for the three exposure directions (X_h, Y_h, Z_h). An increase in grip and feed forces provoked a gain in impedance for all frequencies. Higher feed forces caused a higher magnitude of the mechanical impedance for all frequencies. The influence of the feed force on the phase is not significant. With regard to hand and arm posture, the results show that the flexion and abduction had a significant contribution for frequencies below 30 Hz. 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. In general, the highest impedance was found for the $180°$ flexion (extended arm) and the lowest for $120°$ flexion. 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 $90°$ produces the highest impedance. The phase of the impedance is not influenced by the abduction. Furthermore, the influence of some of the studied variables had a non–linear effect on the impedance in function of exposure directions. 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 [Burstrom, 1997].

The hand–handle contact force depends on the effective contact area of the hand–handle interface, which further depends on the handle size. The biodynamic response of the hand–arm system can be influenced by the handle dimensions and geometry. The paper [Marcotte et al., 2005] at-

tempts to establish the dependence of the hand–arm DPMI response on the handle size, on the hand forces (grip and push) exerted on the handle, and on the coupling and contact forces developed at the hand–handle interface. Three instrumented cylindrical handles with different diameters (30, 40 and 50 mm) were designed and instrumented to provide measurement of the static and dynamic hand–handle forces and of the hand–arm DPMI response. The experiments were performed under three different magnitudes of grip forces (10, 30 and 50 N) and three push forces (25, 50 and 75 N), resulting in nine different grip and push force combinations. The measurement of the driving–point mechanical impedance of the human hand–arm system exposed to vibration along the Z_h direction was measured for seven subjects, using three handles and nine combinations of push and grip forces.

Mechanical impedence (MI) distribution at the palm may be more directly associated with vibration–induced injuries to the palm–wrist–arm system. It is appropriate to examine the fundamental characteristics of the finger MI and the palm MI in order to identify their distributions at these two parts of the hand at different frequencies. In order to measure the finger MI and the palm MI separately in a hand power grip, it has been developed a practical and reliable methodology [Dong et al., 2005]. This study uses three combinations of hand–handle coupling actions: (a) grip–only (50 N), (b) combined grip (50 N) and push (50 N), (c) either pull–only (50 N) when measuring the MI at the fingers or palm–push–only (50 N) when measuring the MI at the palm. Discrete sinusoidal vibrations with a constant velocity (14 mm/s rms) at 10 different frequencies (16, 25, 40, 63, 100, 160, 250, 400, 630 and 1000 Hz) have been utilized in the experimental investigations. It appears that there is a resonant peak value at 25 Hz for the pull–only and grip–only actions, and a peak value at 40 Hz for the combined grip and push action. There are also valleys at 63 and at 100 Hz, depending on the coupling condition. From the valley point up to the 250 Hz point, the fingers show a mass–like behavior. The finger MI rapidly increases with frequency. At higher frequencies, the finger MI values remain relatively constant, which suggests strong damping–like properties. Other peak values of the MI magnitudes can be observed at 250 or 400 Hz, depending on the subject. The comparisons of the palm MI and the finger MI clearly indicate that the vibration power consumed in the hand–arm system at frequencies below 100 Hz was mainly transmitted through the palm, especially at the low frequencies ($\leq$ 25 Hz).

The theoretical investigation has been completed with a two–dimensional finite element (FE) model, proposed to simulate the biodynamic responses of the fingerpad in vibration tests [Wu et al., 2006]. The fingernail was supported by the rigid ground while the fingerpad was activated by a vibration probe. The fingertip model is composed of skin, subcutaneous tissue, bone, and nail. The soft tissues (i.e., skin and subcutaneous tissues) are considered non–linearly elastic and linearly viscoelastic. The FE model is applied to predict the effects of pre–indentation of the vibration probe onto the fingerpad, the damping of the soft tissues, and probe mass on the magnitude and phase angle of the mechanical impedance. The model predictions showed that the probe mass has non–negligible effects on the measured biodynamic responses in the vibration tests. In order to determine true biodynamic responses of the finger–hand–arm system, the mass effects have to be cancelled using an appropriate approach.

Compared to the study [Marcotte et al., 2005] the research [Aldien et al., 2006] adds influence of hand–arm posture on biodynamic response of the human hand–arm exposed to Z_h–axis vibration. Laboratory measurements of the biodynamic responses were performed on seven healthy male subjects exposed to two levels of broadband random vibration in the 8–1000 Hz frequency range using three instrumented cylindrical handles of different diameter (30, 40 and 50 mm), and different grip (10, 30 and 50 N) and push (25, 50 and 75 N) forces. The investigation includes two postures: the subjects mantain forearm horizontally aligned with the handle and elbow flexed at an angle of 90° (P1); and posture with elbow angle extended to 180° (P2) (Fig.1). The wrist is

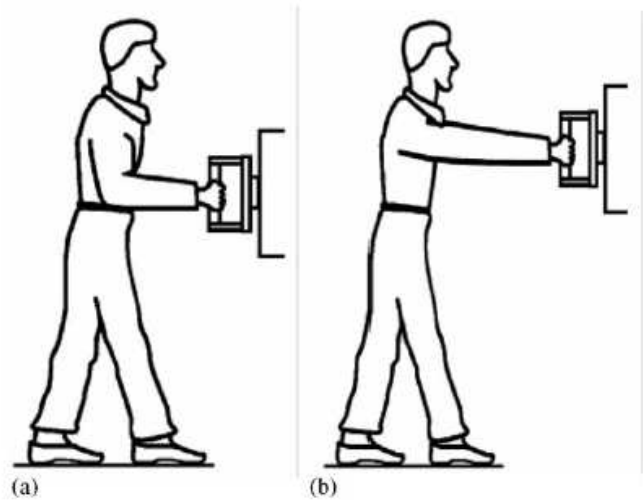

Figure 1: Representations of the postures: (a) posture P1 (b) posture P2

maintained in a neutral position for both postures.

Examining results obtained by different Authors, considerable differences among the reported data of biodynamic responses of the human hand–arm system are observed. Some of the reported data are obviously questionable. It is believed that a significant portion of these differences are likely the result of instrumentation and data processing problems. The results of the study [Dong et al., 2006] confirm that inappropriate instrumentation and insufficient mass cancellation are among the major sources of error in the MI measurement. It is suggested the use of the appropriate methods for instrumentation calibration. Such methods can help improve the design of handle–fixture structures.

The study [Dong et al., 2007] aims at development of appropriate models for analyses of distributed biodynamic responses of the system exposed to vibration along the Z_h–axis. The study correlates the parameters of the 4–DOF model and 5–DOF model to the anthropometry and dynamic properties of the hand–arm system.

The influences of measurement location, handle and supporting fixture resonant frequencies, type and geometry of handle, and mass cancellation, are investigated using experimental techniques [Adewusi et al., 2008]. In this study the reported biodynamic responses are reviewed to identify various sources of variability in the high frequency region. The influences of measurement location, handle and supporting fixture resonant frequencies, type and geometry of handle, and mass cancellation, are investigated using experimental techniques. Handle dynamics and measurement location have significant influences on the measured hand–arm impedance response. The measurement location provokes variabilities of impedance response in the high frequency range. The Authors develop experimental investigations with four subjects gripping the four handles of different natural frequencies. It was concluded that discrepancies in high frequency DPMI magnitudes are attributable to handle natural frequency and to ineffectiveness of handle mass cancellation, apart from the measurement location. Handle design guidance is proposed in view of its dynamic response. The results suggest that the handle natural frequency must be 5.4 times the highest frequency of interest for impedance measurement. The ratio of handle natural frequency to the upper limit of measurement frequency reduces to 2.6, when the measurement is performed in the vicinity of the hand. Further efforts are necessary to seek alternate methods for compensating for the handle inertia effects. It is recommended that measurements of handle apparent mass can be reported up

to 2000 Hz or more. Such measurements can help in identifying the influence of handle dynamics on the reported values and the frequency at which the reported values could be considered reliable [Adewusi et al., 2008].

In the study [Concettoni and Griffin, 2009] the Authors measure simultaneously the driving point biodynamic response of the entire hand–arm system (in terms of apparent mass and mechanical impedance) and the transmissibility to many points on the surface of the hand–arm system. It is obtained the visualization of the vibration pattern on the finger–hand–arm system through the calculation of spectral operating deflection shapes. The stimulus is an approximately flat constant–bandwidth acceleration power spectrum in the range 5 to 500 Hz at 17 m/s^2 rms (unweighted).

The research [Adewusi et al., 2012] presents biomechanical models consisting of different substructures of the hand-arm system and of the trunk of the body in different postures, subject to Z_h–axis vibration. The trunk was considered to observe vibrations at the shoulder and of the head. The models parameters were derived through error minimization using three different target biodynamic functions namely: driving–point mechanical impedance alone; localized vibration transmissibility responses alone; and combined simultaneously measured impedance and transmissibility responses. The results showed that the models' parameters and responses were strongly dependent on the type of the target function. The results suggest that the transmissibility responses characterize the dynamics of the local tissues/muscles of the human hand–arm at different locations, while impedance characterizes the entire hand–arm system with emphasis around the driving–point. The results showed a strong coupling between the human hand–arm system and the whole–body.

Adewusi and other researchers [Adewusi et al., 2013] analyze distributed vibration power absorption (VPA) of different hand–arm substructures in the bent–arm and extended arm postures. VPAs are estimated using biomechanical models of the hand–arm system derived from both the driving-point mechanical impedance and distributed vibration transmissibility. The distributed VPA has been estimated using different condition of measurements of vibration of percussion chipping hammer. The measurements are obtained for two operating speeds, defined as *low speed* (1800 BPM) and *high speed* (2600 BPM); and for two different levels of push force (78 N and 118 N). The posture adopted by the operator provides a 90–degree angle at the elbow and an angle of 30–degrees of adduction of the shoulder. The peaks in the VPA responses of different segments of the hand–arm occur at different frequencies. Some peaks can be related to the reported resonant frequencies of different substructures. The peak value of VPA in the fingers occurs around 160 Hz. The peak value of VPA in the palm appears at around 60 Hz. The peak values of VPA in the wrist and elbow joints are materialized in the lower frequency range, 5 and 16.5 Hz, respectively .

In case of cylindrical handles, the tool can be gripped in different ways independently from the vibration direction. In this case, X_h and Z_h ISO 10068 curves can be conveniently substituted by a unique parameter, referred to as *radial impedance*. The results of an experimental investigation [Tarabini et al., 2013] identify the hand–arm driving point mechanical impedance (DPMI) in presence of a stimulus having an unknown direction.

3 Comparison of hand–arm impedance reported by different investigators

The magnitude and phase characteristics of the mean driving point impedance are presented as a function of excitation frequency in Figures 3–8. These curves offer the basis for the definition of the most probable values for the phase of the human male hand–arm impedance in the X_h direction in the 10–1000 Hz frequency range. Upper and lower contours of phase may be constructed to encompass the mean values of the data sets.

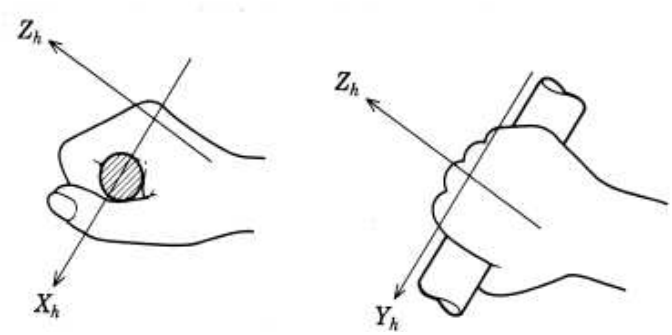

Figure 2: The biodynamic coordinate system of the hand–arm system

Magnitudes of the driving–point impedance measured in the X_h direction

The mean values of the magnitudes of the driving point impedance for the X_h direction demonstrate similarities and differences (Figure 3). A lot of curves reveal following aspects:

- a peak in the 100–200 Hz frequency range;
- the trend to increase in magnitude with excitation frequencies above 300 Hz.

At higher excitation frequencies, the hand–arm impedance can be subject to significant measurement errors. The raw data must be adequately controlled for the large coupled mass of the handle.

The data reported by Hesse represent an exception. In the 10–50 Hz frequency range, Hesse obtains high values of the impedance magnitude [Hesse, 1989]. In the 100–200 Hz frequency range, the impedance magnitude reaches lower values respect to mean values.

Gurram offers the comparison of the mechanical impedance, measured under random and sinusoidal excitations in the X_h direction [Gurram et al., 1995]. Analyzing the measured data by Gurram, it is noticed a remarkable difference between the values of mechanical impedance, obtained by random and by sinusoidal excitations.

Driving–point impedance phase angles measured in the X_h direction

The differences and similarities among the mean values of the impedance phase measured in the X_h direction can be analyzed in Figure 4. Results display a positive phase angle between the driving force and the velocity measured at the driving point.

The data reported by Hesse displays negative phase angle at frequencies in the 50–140 Hz frequency range and above 500 Hz [Hesse, 1989]. The data reported in reference [Hesse, 1989] also form outliers in the 50–150 Hz frequency range as shown in Figure 4. The impedance phase data, obtained by random vibration excitations, form outliers at frequencies above 300 Hz [Gurram et al., 1995]. The magnitude and phase data, reported in reference [Hesse, 1989] and [Gurram et al., 1995] (acquired under random excitations), have thus been excluded from the synthesis of the mean values of impedance in the X_h direction.

Magnitudes of the driving–point impedance measured in the Y_h direction

A comparison of mean values of driving–point impedance magnitude, measured in the Y_h direction, is offered in Figure 5. Most data sets display a peak in the 30-50 Hz frequency range. At frequencies above 300 Hz impedance magnitude, measured in the Y_h direction, tends to increase with excitation frequency. Analyzing measurements obtained by [Gurram et al., 1995], it is noted

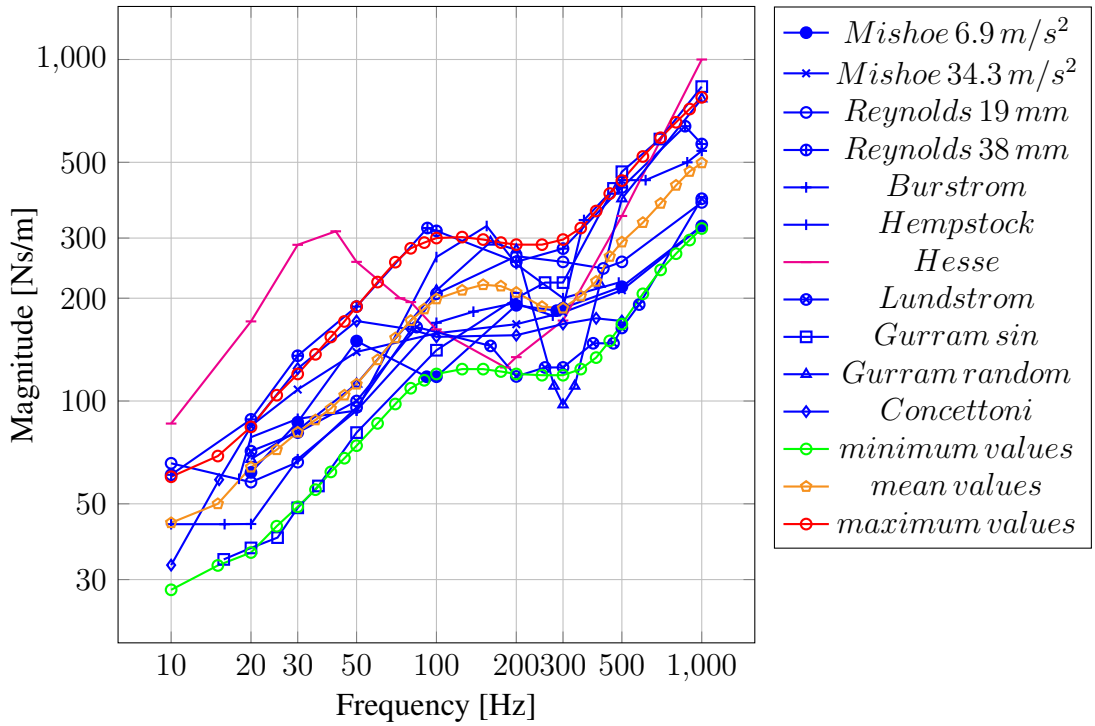

Figure 3: A comparison of the magnitudes of the driving point impedance measured in the X_h direction

that the impedance magnitude measured under random excitations is comparable to those measured under sinusoidal excitations at frequencies above 80 Hz. In reference [Hesse, 1989], driving–point impedance magnitude, measured in the Y_h direction, assumes outliers at frequencies above 300 Hz.

Driving–point impedance phase angles measured in the Y_h direction

The discrepancies and affinities among the mean values of the impedance phase measured in the Y_h direction can be analyzed in Figure 6. Results exhibit a positive phase angle between the driving force and the velocity measured at the driving point in the 10-50 Hz frequency range.

The data, described in reference [Hesse, 1989], appear outliers above 500 Hz. Also the measurements, reported in reference [Mishoe and Suggs, 1977], differ from other trends above 400 Hz as shown in Figure 6.

Magnitudes of the driving–point impedance measured in the Z_h direction

The mean values of the driving–point impedance magnitude, acquired in the Z_h direction, are compared in Figure 7. Data exhibit a peak in impedance magnitude in the 20–50 Hz frequency band. The magnitude, illustrated by Mishoe, deviated considerably from the general pattern in the frequency ranges 30–100 Hz [Mishoe and Suggs, 1977]. The magnitude values reported by Jandak exceed the tendency in the frequency ranges 20–50 Hz and above 500 Hz [Jandak, 1989].

Driving–point impedance phase angles measured in the Z_h direction

The impedance phase data, proposed in Figure 8, do not indicate a common trend. Results exhibit a positive phase angle between the driving force and the velocity measured at the driving point in the 10-30 Hz frequency range.

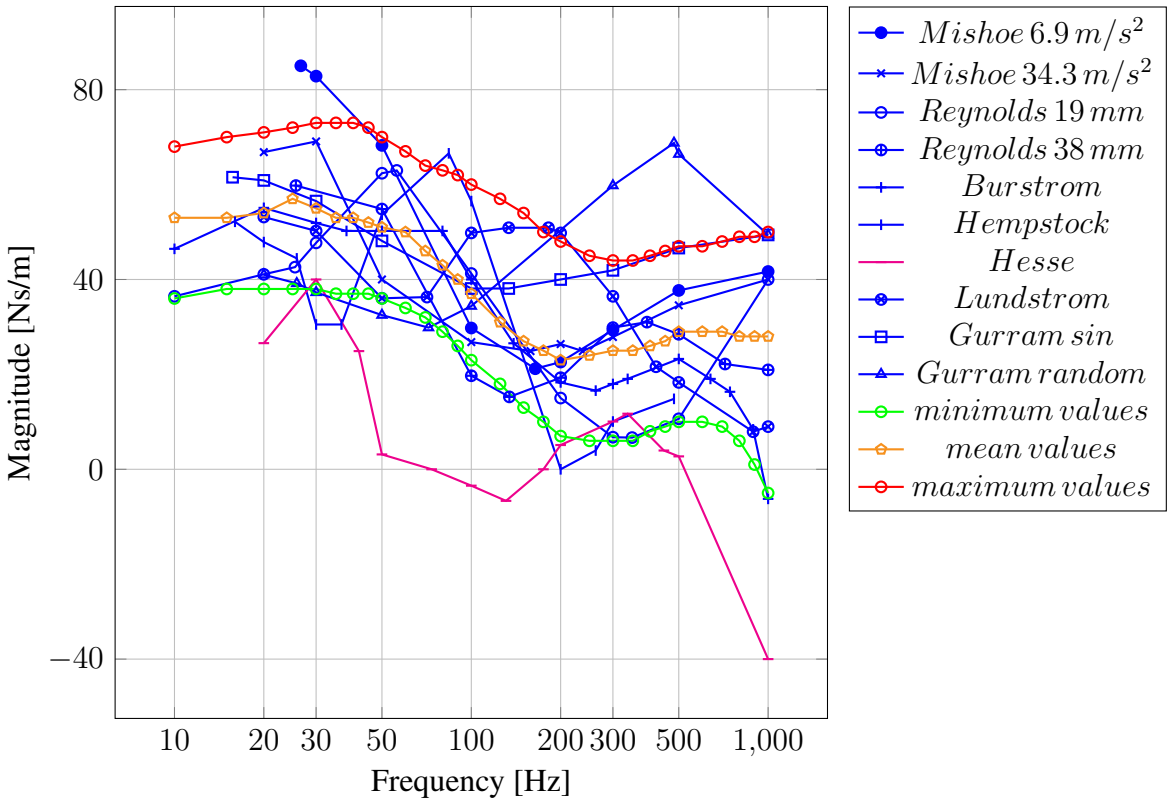

Figure 4: A comparison of the driving–point impedance phase angles measured in the X_h direction

The measurements, reported by [Lundstrom and Burstrom, 1989, Hesse, 1989] and [Gurram et al., 1995] (acquired under random excitations), represent the outliers.

4 Discussion

The model of the hand has to describe the physical orientation and the coupling that exists between the epidermis, dermis, subcutaneous and muscle tissues and the skeletal system in the fingers and hand. The results of the mechanical impedance tests indicate the vibration response of the hand, due to a vibration input to the hand, and the local response characteristics of the hand and fingers. The results of the mechanical impedance tests demonstrate that most of the energy, directed into the hand and fingers at frequencies above 100 Hz for vibration in the vertical direction and at all frequencies for vibration in the horizontal and axial directions, is dissipated in the hand–arm system (Figure 2). Figure 9 shows some of the physical aspects.

We observe following aspects:

- *Inter–subject variations*. In this research measurements are summarised under selected test conditions. The results clearly illustrate large inter–subject variations in magnitude. Inter–subject variation in impedance magnitude as well as phase, measured under random vibration, are considerably smaller than those measured under swept–sine vibrations [Gurram et al., 1995]. The measured impedance data exhibits a high degree of inter–subject variations that may be attributed to the differences in weights and sizes of the hands of the subjects.

  For all three handles (30, 40 and 50 mm) with 30 N grip and 50 N push force, and two different vibration excitation magnitudes $a_{h,w} = 2.5\,\mathrm{m/s^2}$ and $a_{h,w} = 5.0\,\mathrm{m/s^2}$ [Marcotte

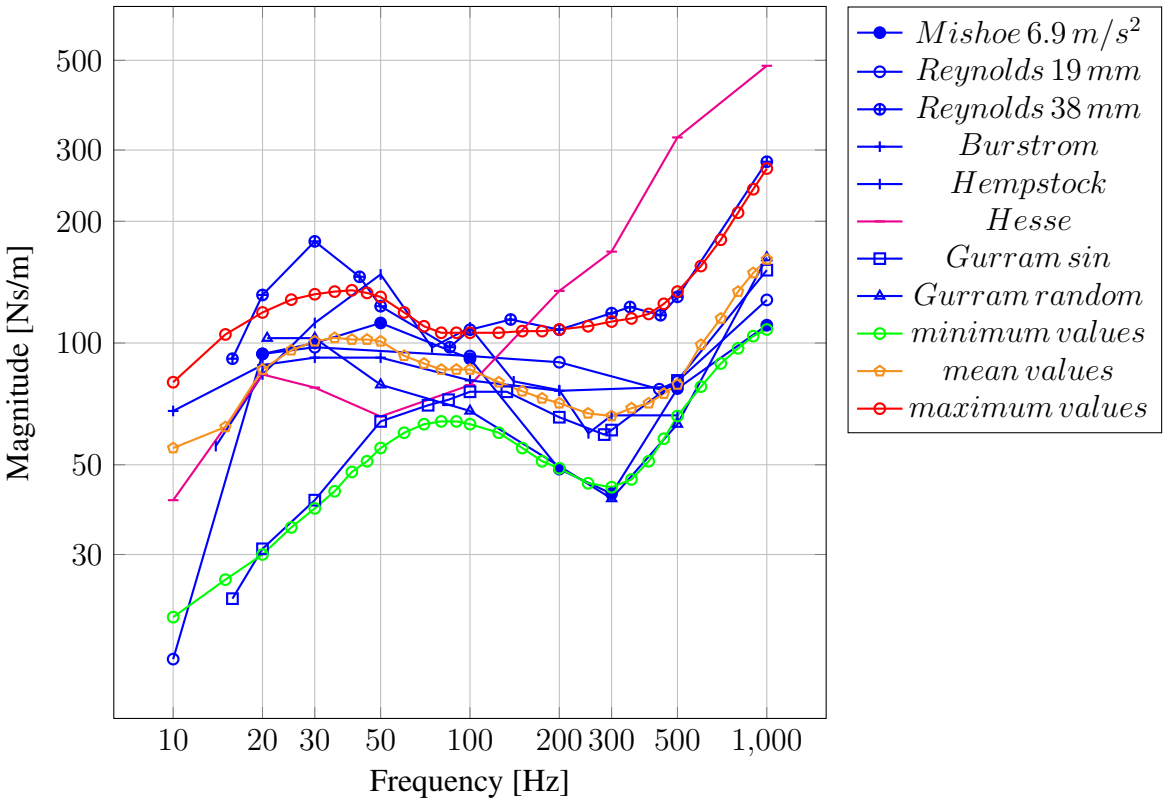

Figure 5: A comparison of the magnitudes of the driving point impedance measured in the Y_h direction

et al., 2005], the peak variations in the magnitude response among subjects are observed in the 30–100 Hz frequency range. It should be noted that the data obtained for the 30 mm handle show considerable variations in the magnitude response in the 300–400 Hz frequency range.

- *Influence of frequency of the vibration stimuli on DPMI*. The outcome shows that the mechanical impedance of the hand–arm system depends on the frequency of the vibration stimuli (Tab. 1). Above 200 Hz, the impedance increases quite rapidly, from about 150 Ns / m up to about 500 Ns/m at 1500 Hz. At lower frequencies, however, different 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 value at 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 value at about 100 Hz [Lundstrom and Burstrom, 1989].

- *Influence of vibration magnitude on DPMI*. The measurements, performed by Lundstrom et al., demonstrated that lower excitation amplitudes cause higher impedance magnitudes at low frequencies and lower impedance magnitudes at higher frequencies [Lundstrom and Burstrom, 1989]. Burstrom observed that the DPMI amplitude increases slightly with in-

[1]Measured in the X_h direction only.
[2]Not reported.
[3]Root mean square.
[4]Peak acceleration.

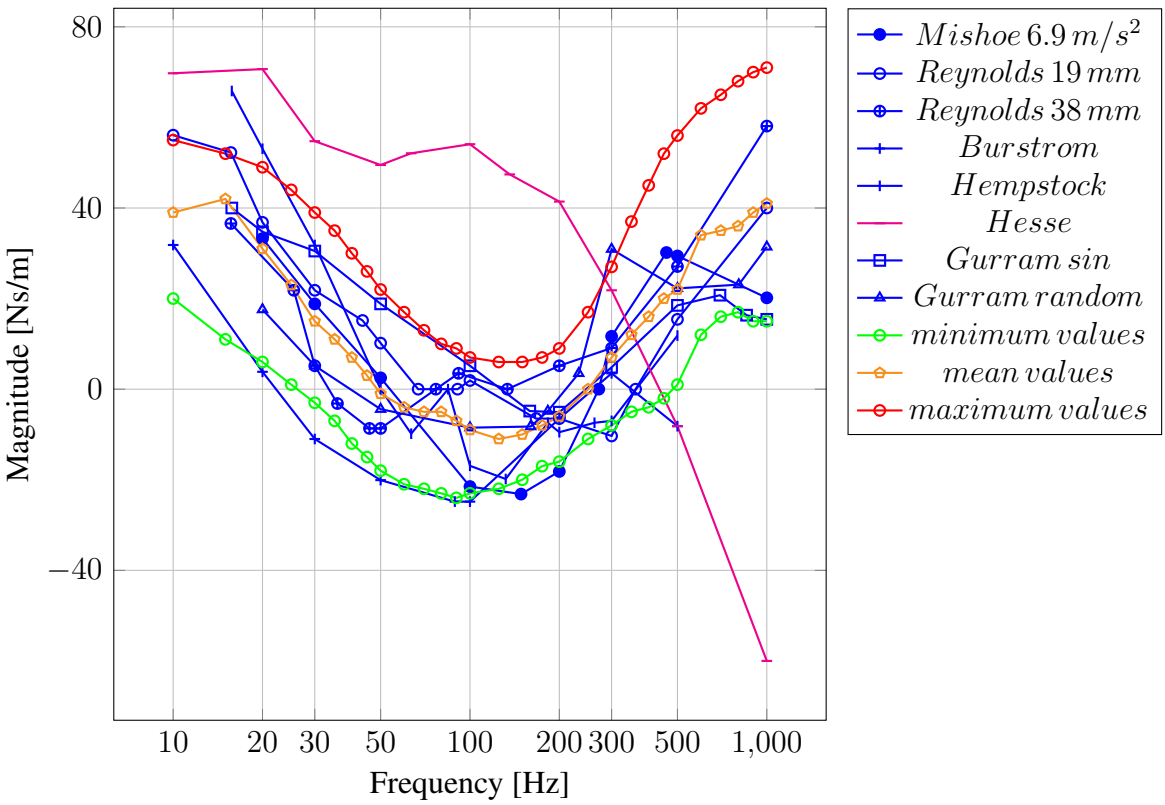

Figure 6: A comparison of the driving–point impedance phase angles measured in the Y_h direction

crease in the vibration level, and the increase is more pronounced in the frequency range above 200 Hz [Burstrom, 1997].

Analyzing sinusoidal or random vibration, the results of Gurram et al. reveal that amplitude of vibration affects the driving point impedance of the human hand–arm in an irrelevant manner [Gurram et al., 1995].

For three different handles (30, 40 and 50 mm) the results show small influence of the excitation amplitude on the DPMI magnitude and negligible effect on the phase response. The results also suggest nonlinear characteristics of the hand–arm system, specifically at lower frequencies, although the effect of excitation amplitude is relatively small [Marcotte et al., 2005].

- *Influence of handle diameter on DPMI*. The results show that the DPMI response of the human hand and arm is strongly influenced by the handle diameter (Tab.2) . The effect depends upon the magnitudes of hand forces applied to the handle in a nonlinear manner. Higher levels of hand forces, however, yield an opposite trend, i.e. the peak DPMI magnitude increases as the handle diameter increases. At low frequencies (below 25 Hz), the DPMI magnitude increases nearly linearly with frequency and tends to be higher for larger handles. The handle diameter also has a significant influence on the DPMI phase, specifically in the 100–600 Hz frequency range, where the phase response is higher with increasing handle diameter [Marcotte et al., 2005].

- *Influence of grip and push forces on DPMI*. Push and grip forces influence the biodynamic response of the hand–arm system (Tab.3). Grip and push force change the driving–point

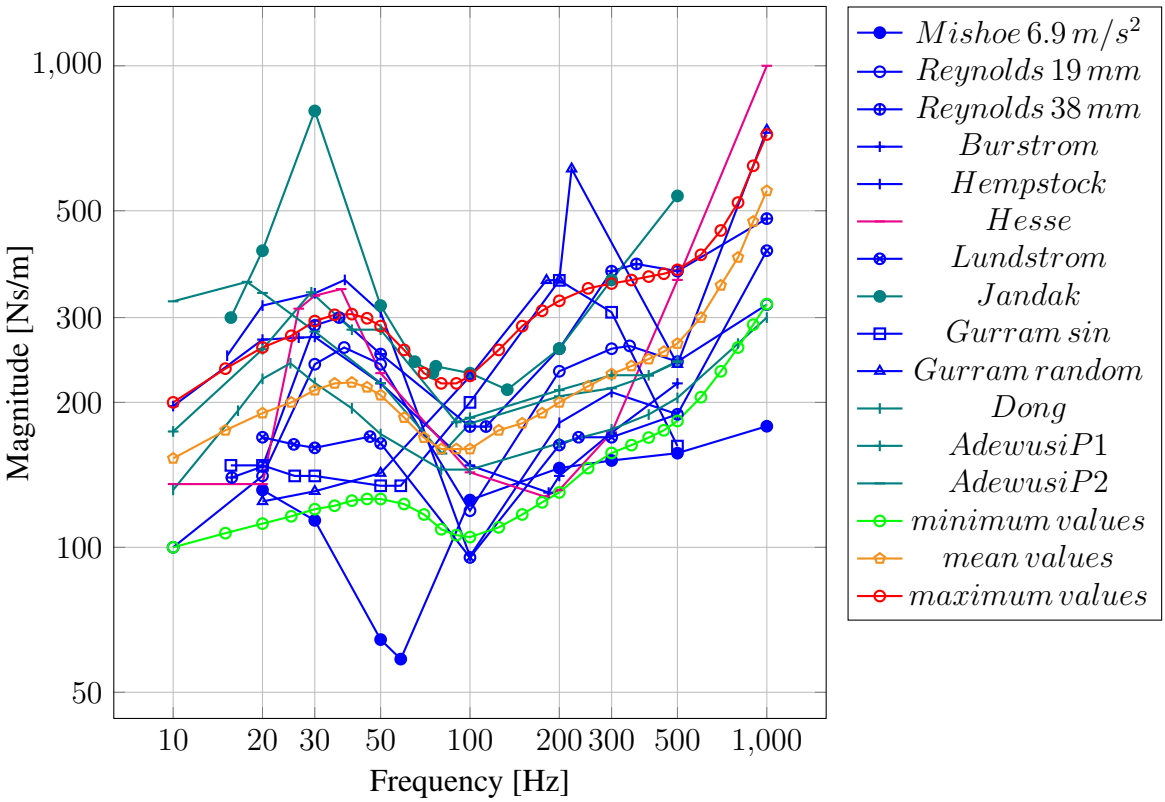

Figure 7: A comparison of the magnitudes of the driving point impedance measured in the Z_h direction

impedance. Impedance increases with increasing force, both in resonance frequency and magnitude. That is because the subjects, increasing the grip or push forces, tight their muscles. A tightened muscle means a *stiffer spring* in a mechanical model of the hand–arm system. A stiffer spring increases the resonance frequency of the system [Kihlberg, 1995]. Gurram et al. confirmed that the impedance magnitude is observed to increase with increase in grip force and frequency [Gurram et al., 1995]. Burstrom deduced that an increase in push force leads to higher DPMI magnitude [Burstrom, 1997].

In addition, the results of Marcotte et al. suggest that at frequencies above 20 Hz, the DPMI magnitude tends to increase when grip and push forces increase. Such effect is more emphasized near the frequencies corresponding to peak responses [Marcotte et al., 2005]. The investigation of Marcotte et al. shows that the fundamental frequency, corresponding to the peak DPMI magnitude, decreases with decreasing grip force. This aspect suggests a softening effect of the hand–arm system. Increasing the push force yields considerably higher DPMI magnitude response in the 30–200 Hz frequency range. At last, the DPMI phase response on the other hand appears to be more influenced by variations in the push force than in grip force.

In order to identify the characteristics of the dynamic responses of different parts of the hand, Dong et al. develop knowledge of the distribution of the DPMI at the fingers and the palm of the hand[Dong et al., 2005]. The study finds that the characteristics of the hand DPMI distributed at the fingers and the palm are very different. The information may also be used to simulate the finger–hand–arm system for the development of effective vibration–reducing devices.

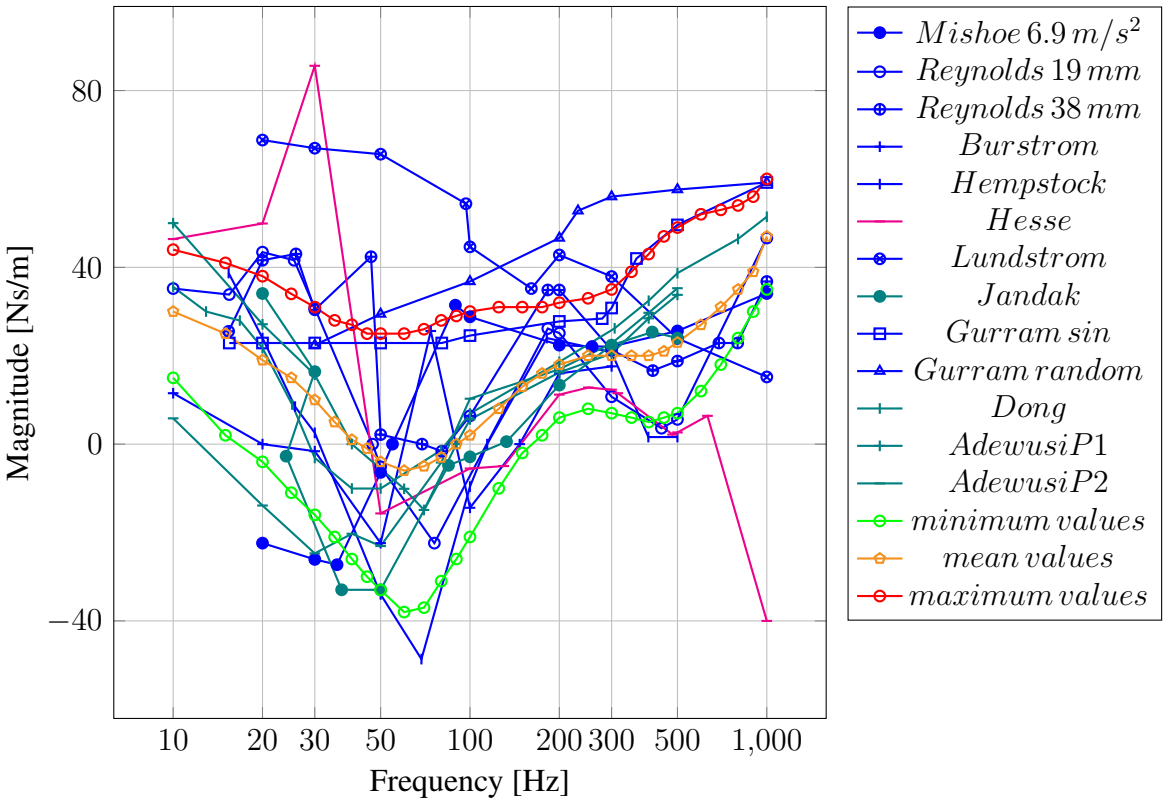

Figure 8: A comparison of the driving–point impedance phase angles measured in the Z_h direction

- *Relationship with coupling and contact forces*. It can be stated that total hand–handle contact force, measured on different handles, results from a linear combination of push and grip forces. The contribution due to grip force is approximately three times larger than the push force [Marcotte et al., 2005]. The investigation of Marcotte et al. demonstrate different aspects:

  ✓ The results suggest that the mean DPMI magnitude is more closely correlated with the coupling force at frequencies below 200 Hz.

  ✓ A better correlation with the contact force, however, is attained at frequencies above 200 Hz. The strong correlation of the DPMI magnitude response with the coupling force, at lower frequencies, is attributed to its strong dependence on the push force in this frequency range.

  ✓ At higher frequencies, the driving–point mechanical impedance is mainly caused by the skin tissues of the hand–arm system. The grip force contributes far more than the push force, because of a larger contact area between the handle and the hand skin. The contact force, which increases in proportion to approximately three times the grip force, becomes the dominating factor at higher frequencies.

- *Influence of hand–arm posture on mean DPMI magnitude and phase response*. The posture of an operator of the hand–held power tool depends on the tool type and the kind of operation being performed (Tab.4). The posture of an operator of a road breaker is about 155° elbow angle with about 30° abduction angle (the angle between the trunk and upper–arm). This is close to the extended arm posture (180° elbow angle). The posture assumed by an operator

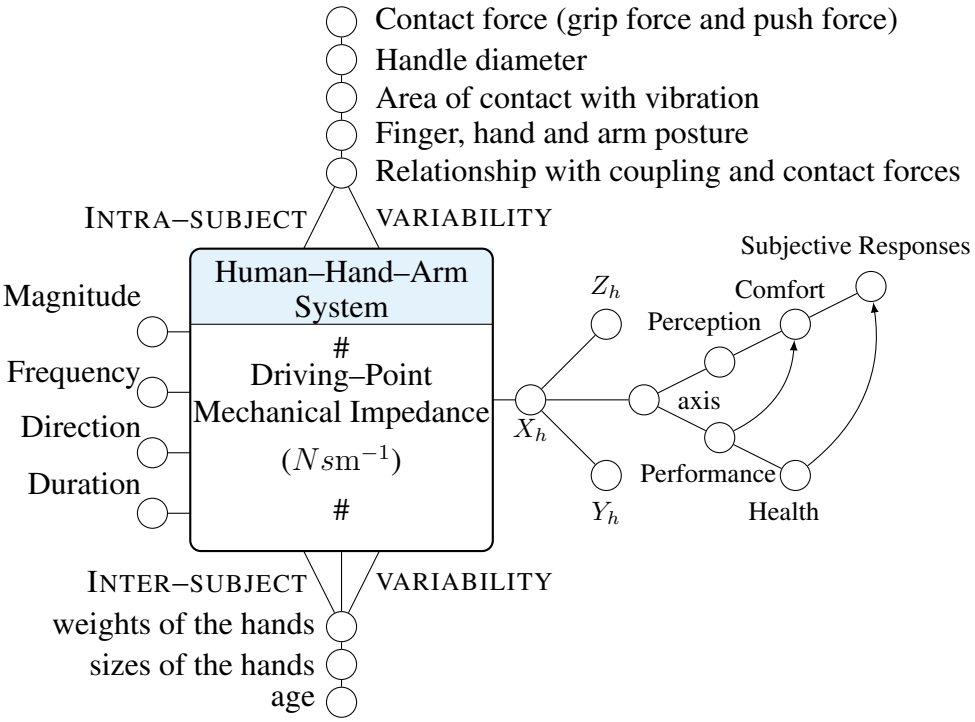

Figure 9: Physical variables relevant to the effects of hand–transmitted vibration

of a nut runner is close to the bent-arm posture ($90°$ elbow angle) with about zero degree abduction angle. However, the majority of the laboratory studies on biodynamic responses with effects of hand–arm posture considered the bent–arm (P1) and extended arm ($90°$ elbow angle with $180°$ abduction angle) (P2) postures. Therefore, the DPMI distribution in the hand–arm substructures may also be considered for the two extreme postures namely the bent–arm and extended arm postures [Adewusi et al., 2013].

The measured data, acquired under different postures, handles, hand forces and excitations, illustrate the important trends in the responses [Aldien et al., 2006]:

- □ The posture P2 yields higher mechanical impedance magnitude at lower frequencies (below 30 Hz). At low frequencies, this posture exhibits damper–like behavior, which is also evident from nearly zero phase response. The peak magnitude occurs around 20 Hz, while the posture P1 yields peak magnitude around 33 Hz for 40 mm handle with 30 N grip force and 50 N push force. At low frequency, higher impedance magnitude for the P2 posture suggests a higher mass coupled with the handle. Such aspect permits the flow of low frequency vibration energy through the hand–arm to the whole body. The higher effective mass is further believed to contribute to lower resonant frequency, when it is compared to that obtained for posture P1.
- □ Influence of hand–arm posture on mean DPMI magnitude and phase response are slight for frequencies higher than 100 Hz.

- *Influence of handle size on the mean DPMI magnitude and phase responses for different postures*. The variations in the handle size influence the magnitude and phase responses under both postures. The P1 posture yields higher low–frequency magnitude and lower frequency

Investigator	Excitation type	Excitation Magnitude	Frequency range (Hz)	Direction and type of grip
[Mishoe and Suggs, 1977]	Sine sweep	6.9,20.6,34.3 (1)	20–2000	X_h,Y_h,Z_h palm
[Reynolds and Keith, 1977]	Sine sweep	NR (2)	5–1000	X_h,Y_h,Z_h palm
[Daikoku and Ishikawa, 1989]	Stepped sine	6.9 m/s^2 (2)	8–200	X_h,Y_h,Z_h palm
[Hempstock and O'Connor, 1989]	Random	0.5 m/s^2 (3)	16–500	X_h,Y_h,Z_h
[Hesse, 1989]	Pseudo–random	9.8 m/s^2	5–1000	X_h,Y_h,Z_h palm
[Jandak, 1989]	Impulse	NR (3)	5–500	Z_h palm
[Lundstrom and Burstrom, 1989]	Sine sweep	27–53 mm/s	20–1500	X_h, Z_h palm
[Gurram et al., 1995]	Sine sweep Random	10, 20, 30 m/s^2 (4) 0.2, 0.5, 0.7 m/s^2 (4)	10–1000	X_h,Y_h,Z_h palm
[Burstrom, 1997]	Sine sweep	8–45 mm/s	2–1000	X_h, Y_h, Z_h palm
[Marcotte et al., 2005]	Random	2.5, 5.0 m/s^2	8–1000	Z_h palm
[Dong et al., 2005]	Sinusoidal	14 mm/s (4)	16, 25, 40, 63,100 160, 250, 400, 630, 1000	Z_h palm
[Aldien et al., 2006]	Random	2.5,5.0 m/s^2	$8-1000$	Z_h palm
[Concettoni and Griffin, 2009]	Sine sweep	17.2 m/s^2 (4)	5–500	Z_h
[Adewusi et al., 2012]	Random	5.25 m/s^2	2.5–3000	Z_h palm

Table 1: Summary of vibration stimuli employed by different investigators

of peak magnitude as the handle size increases. The effect of handle size on the magnitude, in the 40–100 Hz frequency range, is not evident. However, the impedance magnitude increases with the handle size at frequencies above 100 Hz. The P2 posture exhibits higher DPMI magnitude but nearly opposite effect with the handle size on the impedance magnitude at lower frequencies, although the effect is relatively small. The P1 and P2 postures, however, exhibit similar effects of handle size on the impedance magnitude at higher frequencies (above 250 Hz) [Aldien et al., 2006].

- *Effect of variation in the hand forces on the mean impedance magnitude under different postures*. Gripping the handle under posture P2, the subjects experienced higher levels of low frequency vibration of the head and neck, and of the upper body, as well as higher stress in the upper arm. An increase in the push as well as grip forces tends to shift the peak impedance towards a higher frequency for P1 and P2 postures. The influence of push and grip forces in the low–frequency region is not evident under the P1 posture. The P2 posture shows higher magnitude response at low frequencies, suggesting stronger coupling between the hand–arm and the handle [Aldien et al., 2006].

- *Effect of vibration magnitude on the mean impedance magnitude under two postures*. At low frequencies, the effect of vibration magnitude is more pronounced under the P2 posture. For against, the effect of vibration magnitude is not pronounced under the P1 and P2 postures at high–frequency [Aldien et al., 2006].

- *Area of contact with vibration*. Minimization of contact force exerted on tool handle is desiderable since the pressure applied to the fingers reduces finger blood flow [Bovenzi et al., 2006].

5 Conclusion

In this paper we propose a systematic review to provide an exhaustive summary of current literature relevant to a research question about driving–point mechanical impedance of the human hand–arm system. The impedance characteristics, acquired on human subjects under controlled

test conditions, attest substantial differences among the impedance data reported by different researchers. These differences depend on exogenous and endogenous factors. It should be noted that following aspects:

(i) the forces exerted by the hand on the object grasped;

(ii) the posture adopted by the hand–arm and the torso;

(iii) anthropometric parameters of the hand and arm;

(iv) the inherent non–linear dynamic properties of biological materials.

operate an important rule on mechanical impedance of the human hand–arm system.

The measured impedance data exhibit a high degree of inter–subject variations. The effect of grip force and excitation frequencies on the driving point impedance is significant.

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Investigator	Handle
[Mishoe and Suggs, 1977]	Cylindrical with diameter 25 mm
[Reynolds and Keith, 1977]	Cylindrical with diameter 19.1 and 38.1 mm
[Daikoku and Ishikawa, 1989]	Cylindrical with diameter 10, 30 mm
[Hempstock and O'Connor, 1989]	Cylindrical with diameter 10 mm
[Hesse, 1989]	Cylindrical with diameter 5, 45.0 mm
[Jandak, 1989]	Cylindrical with diameter 25 mm
[Lundstrom and Burstrom, 1989]	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.
[Gurram et al., 1995]	Cylindrical with diameter 38.1 mm and orientation in three orthogonal direction of vibration
[Burstrom, 1997]	Handle mounted on an electrodynamic shaker, equipped with two force transducers and one accelerometer for force and velocity measurements
[Marcotte et al., 2005]	Three instrumented cylindrical handles with different diameters (30, 40 and 50 mm)
[Dong et al., 2005]	The handle structure, cylindrical with diameter 40 mm, is basically composed of an aluminum handle base and a magnesium measuring cap. Two piezoelectric single-axis force sensors (Kistler 9212) are sandwiched between the two parts along the centerline of the handle to measure the static and dynamic hand–handle coupling forces.
[Aldien et al., 2006]	Three instrumented cylindrical handles of different diameter (30, 40, 50 mm)
[Concettoni and Griffin, 2009]	Vertical vibration of the hand was provided by a 20×15 cm aluminium plate mounted on an electrodynamic vibrator
[Adewusi et al., 2012]	40 mm diameter handle

Table 2: Summary of handle employed by different investigators

Investigator	Grip force (N)	Push force (N)
[Mishoe and Suggs, 1977]	13.5, 27 and 40.5	NR$^{(2)}$
[Reynolds and Keith, 1977]	25.4	NR$^{(2)}$
[Daikoku and Ishikawa, 1989]	33	NR$^{(2)}$
[Hempstock and O'Connor, 1989]	25	NR$^{(2)}$
[Hesse, 1989]	10 and 90	NR$^{(2)}$
[Jandak, 1989]	25.4	NR$^{(2)}$
[Lundstrom and Burstrom, 1989]	25, 50 and 75	NR$^{(2)}$
[Gurram et al., 1995]	10,25 and 50	NR$^{(2)}$
[Burstrom, 1997]	25, 50 and 110	NR$^{(2)}$
[Marcotte et al., 2005]	10, 30 and 50	25, 50 and 75
[Dong et al., 2005]	50	50
[Aldien et al., 2006]	10,30,50	25, 50 and 75
[Adewusi et al., 2012]	10, 30 and 50	25, 50 and 75

Table 3: Summary of grip and push force employed by different investigators

Investigator	Elbow angle (degrees)
[Mishoe and Suggs, 1977]	NR$^{(2)}$
[Reynolds and Keith, 1977]	NR$^{(2)}$
[Daikoku and Ishikawa, 1989]	NR$^{(2)}$
[Hempstock and O'Connor, 1989]	120
[Hesse, 1989]	60–180
[Lundstrom and Burstrom, 1989]	90–180
[Jandak, 1989]	90
[Gurram et al., 1995]	90
[Burstrom, 1997]	60–180
[Marcotte et al., 2005]	90
[Dong et al., 2005]	90
[Aldien et al., 2006]	90
[Concettoni and Griffin, 2009]	90
[Adewusi et al., 2012]	0,90

Table 4: Summary of hand–arm posture employed by different investigators