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Hand-Transmitted Vibration and Biodynamic Response of the Human Hand-Arm: A Critical Review

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ABSTRACT: Hand-arm vibration syndrome (HAVS) has been associated with prolonged exposure to vibration transmitted to the human hand-arm system from hand-held power tools, vibrating machines, or hand-held vibrating workpieces. The biodynamic response of the human hand and arm to hand transmitted vibration (HTV) forms an essential basis for effective evaluations of exposures, vibration-attenuation mechanisms, and potential injury mechanisms. The biodynamic response to HTV and its relationship to HAVS are critically reviewed and discussed to highlight the advances and the need for further research. In view of its strong dependence on the nature of HTV and the lack of general agreement on the characteristics of HTV, the reported studies are first reviewed to enhance an understanding of HTV and related issues. The characteristics of HTV and relevant unresolved issues are discussed on the basis of measured data, proposed standards, and measurement methods, while the need for further developments in measurement systems is emphasized. The studies on biodynamic response and their findings are grouped into four categories based on the methodology used and the objective. These include studies on (1) through-the-hand-arm response, expressed in terms of vibration transmissibility; (2) to-the-hand response, expressed in terms of the force-motion relationship of the hand-arm system; (3) to-the-hand biodynamic response function, expressed in terms of vibration energy absorption; and (4) computer modeling of the biodynamic response characteristics.

KEY WORDS: hand-arm vibration, hand-transmitted vibration, biodynamics, vibration transmission, hand-arm system, power tools vibration, modeling

I. INTRODUCTION

The operators of hand-held power tools, commonly used in several industries, are exposed to extensive hand-transmitted vibration (HTV) arising from the tool-hand interface. Continued occupational exposure to such vibration has been related to an array of disorders in the vascular, sensorineural, and musculoskeletal structures of the hand-arm system, which have been collectively defined as the hand-arm vibration syndrome (HAVS).[1] A study conducted by NIOSH estimated that in 1983 approximately 1.45 million workers in the US were subject to some risks for developing

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HAVS. The prevalence of HAVS ranged from 6 to 100%, with an average of approximately 50%.[2] Although HAVS relates to the disorders of the peripheral neurological and vascular systems, musculoskeletal structure, bones and joints, and the central nervous system, the vascular component is the most easily observed component. The vascular effects, which appear as episodes of fingers blanching together with tingling and numbness in the exposed hand, have been studied and documented more than the other components. All the components of the HAVS, however, appear to be coupled in their mechanisms, and occur in a certain sequence with varying degrees of severity, depending on the nature of vibration exposure and individual conditions.[3] The vascular component of HAVS has been denoted by several different terms, such as Raynaud's phenomenon of occupational origin, traumatic vasospastic disease (TVD), and vibration-induced white finger (VWF).[4]

Symptoms of HAVS (hand-arm vibration syndrome) were recognized as early as the beginning of the 20th century[5,6]; comprehensive investigations into the disorders were conducted in 1918 by Hamilton and Rothstein (cited in Wasserman,[7] Brammer,[8] and Pelmear and Wasserman[9]). These studies concluded that exposure to combinations of vibration, cold temperature, and poor workplace ergonomics were responsible for VWF, and that the affected areas are asymmetrically distributed on the hands. Ironically, at the same location where Hamilton did her initial study, the prevalence of HAVS among the present workers remains almost unchanged and many are relatives of participants in her 1918 study.[13]

In the 80 years following Hamilton's historical study, a large number of investigations involving varied methodologies have been carried out on HAVS. Although these studies have significantly contributed to the advancements in understanding HAVS, many challenges and gaps remain regarding the characterization of HTV (hand-transmitted vibration), injury mechanisms, tool designs, and dose-response relationships. The international standard, ISO-5349[10] and its revised draft ISO/DIS-5349-1,[11] document the measurement and reporting methodology, the dose-response relationship, and the weighting filter for assessment of HTV. The standards, however, have been subjected to many criticisms regarding the weighting functions, daily and lifetime exposures, and the lack of considering important factors, such as vibration direction, coupling forces, temperature, and so forth. Some researchers have emphasized the need for developing improved weighting functions and dose-response relationships.[12] Presently, no method for the clinical diagnosis of HAVS has been standardized. Furthermore, definite and generally acceptable dose-response relationships for various components of HAVS remain elusive.[12] Most workers using hand-held power tools continue to be exposed to the risk of developing HAVS.[9] It is therefore vital to undertake further systematic investigations to enhance our understanding of HAVS, and to develop effective assessment methodologies, tool designs, and workplace ergonomics. One critical element needed to better understand HAVS and to develop better standards is the biodynamic response of the human hand-arm under HTV.[14]

The reported studies on biodynamics associated with HAVS can be divided into four groups based on the measures used: (1) transmission of hand vibration to different segments of the body, such as the nail, finger, wrist, elbow, shoulder, and head; (2) force-motion response of the hand-arm system, expressed as driving-point mechanical impedance (DPMI) or dynamic compliance, and apparent mass (APMS); (3) absorption of vibration energy; and (4) analytical models. Although definite similarities have been observed among the biodynamic response data reported by various investigators, considerable differences have also been noted. Furthermore, the contributions owing to various intrinsic and extrinsic variables have not been fully characterized. In this paper, the studies on biodynamic-response behavior of the human hand-arm to HTV and its relationship with HAVS are reviewed and discussed to highlight the advancements in research into the disorder and the need for further investigations. Because the biodynamic response of the human hand-arm is directly affected by HTV, the studies are first reviewed to enhance an understanding of the characteristics of HTV and the related issues.

II. CHARACTERIZATION OF HAND-TRANSMITTED VIBRATION

Vibration is the oscillatory motion of an object, which is described as the oscillation frequency and amplitude of displacement (D), velocity (V), or acceleration (A). Alternatively, the force that causes the motion could also be used to describe the mechanical vibration. Although the above motion parameters are related to each other, they often reveal different aspects of the dynamic response. The biodynamic response of the human hand-arm has been investigated using a variety of motion parameters to describe vibration. It has been suggested that the motion parameter used should be correlated with the injury that may be caused by the vibration.[3] The studies on hand-arm vibration (HAV) are mostly based upon the acceleration response, which is directly associated with the force or stress and is believed to have a strong positive correlation with the physical damage caused by HTV. Furthermore, HTV and tool vibration can be conveniently measured in terms of acceleration, which exhibits appropriate sensitivity for the ranges of frequencies and magnitudes of major concern. The hand-arm response to vibration is thus described as acceleration in the majority of the studies, and in current national and international standards.[2,10,15,16]

The human hand-arm possesses complex inertial and viscoelastic properties, and it exhibits motions along the 6 degrees-of-freedom (DOF): translational motions along the orthogonal axes (X_h, Y_h, and Z_h), and rotational motions along the roll (φ_h), pitch (θ_h), and yaw (ψ_h) axes (in medical terms these would refer to pronation-supination, flexion-extension of the wrist, and abduction-adduction of the hand, respectively), as shown in Figure 1. The hand-arm response characteristics along the three translational axes have been the primary focus of studies, but its rotational motions have been ignored. Two coordinate systems, anatomical and basicentric, have been defined to quantify the linear motions of the human hand along the three orthogonal directions.[17]

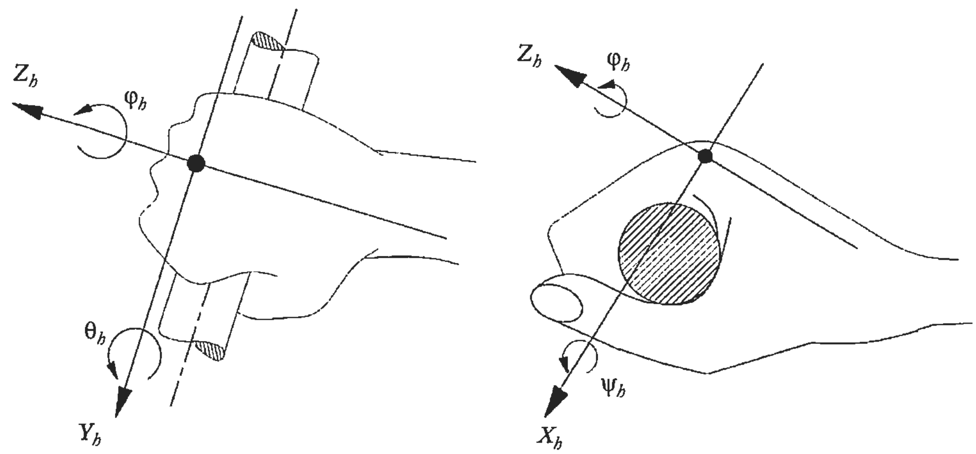

FIGURE 1. Schematics of the hand-tool interface illustrating the basicentric motion coordinates.

A. Transmission of Vibration into the Hand-Arm System

The current standards on HAV (hand-arm vibration) provide guidelines pertaining to the measurement and assessment of the severity of vibration generated in the immediate vicinity of the hand.[2,10,11,15,16] HAVS has been associated with the vibration that is transmitted to the skin, fingers, hand, arm, and the head. Conversely, epidemiological studies have yielded dose-response relationships that describe the risk of VWF (vibration-induced white finger) as a function of the vibration in the immediate vicinity of the hand. Hence, current standards recommend that the measurement should be made on the vibrating tool, machine, or hand-held workpiece at or near the surface where the vibration enters the hand(s). The tool or machine vibration occurring at the hand-handle interface is transmitted to the hand(s), arm(s), and whole-body of the operator in a highly complex manner. The biodynamic response characteristics of the hand-arm system have been extensively evaluated to enhance understanding of the transmission of the source vibration to the hand-arm system.[18–24] There seem to be many disagreements about the characterization of HTV regarding ranges of vibration frequency and magnitudes, axis of vibration, frequency weighting, coupling forces, and so forth. The identification of generally agreed-upon and applicable characteristics of HTV forms one of the major issues relating to measurements, evaluations, and assessments.

B. Frequency Range of Hand-Transmitted Vibration

The frequencies and magnitudes of hand-transmitted vibration caused by the operation of hand-held power tools are known to vary over a wide range, depending upon the type of tool, operation, and hand-tool orientation, as illustrated in Table 1. The reported studies on clinical assessments and biodynamics have invariably concluded that human hand-arm response to vibration is strongly affected by the frequency of vibration.[18,25,26] The results of the clinical studies suggest that the peripheral vascular and neural effects are generally sensitive to vibration below 700 Hz. Although the dominant frequencies of vibration generated by various power tools lie in the 25 to 320 Hz range,[27,29,30] substantial levels of vibration have been reported to occur at significantly higher frequencies, well above 2000 Hz.[3,9] Handgrips and gloves, however, may attenuate such vibration at frequencies above 1000 Hz. Since the reported cases of VWF are typically associated with tools having dominant vibration frequencies in the 25- to 250-Hz range, the majority of the disorders, particularly the vascular disorders, have been attributed to HTV at frequencies well below 1000 Hz.[28]

Considering the above, the measurement frequency range of 5 to 1500 Hz specified by the current standard[10] could be thought quite adequate. Several studies, however, have suggested that high-frequency HTV could cause more damage than once believed.[31,32] The percussive tools yield vibration at considerably higher frequencies, which may be attributed to repetitive impacts of the tool with the workpiece and the impacts of the tool components occurring within the tool. Measurements performed on the drills used by dentists revealed vibration occurring at frequencies up to 40 kHz. Although the magnitudes were relatively low, exposure

TABLE 1.
Predominant Ranges of Frequencies and Magnitudes of Vibration Generated by Different Power Tools

Tool	Dominant frequency; range of vibration (Hz)	Reported acceleration levels (m/s^2)
Chipping hammers	25–125	251–2014
Riveters	50–200	10[a]–1183
Pedestal grinders	≈ 250	125–382
Jackleg drills	6–1250	121–362
Grinders	20–205	40–63
Chain saws	63–150	2.7[a]–11[a]
Orbital sanders	60–100	2.5[a]–5.0[a]
Stationary grinders	< 250	2.2[a]–5.4[a]
Representative tools often used in automobile manufacturing (e.g., palm orbital sanders, reciprocating sanders, polishers, heavy-duty grinders, trimming shears)	20–160	10–300

Source: Refs. 27, 29, 30.
[a] Frequency-weighted rms acceleration.

to such high-frequency vibration has been associated with elevated finger vibrotactile thresholds or distal nerve dysfunctions among dental technicians.[33,34] The measured vibration transmissibility of the human hand-arm system reveals that vibrations above 250 Hz become localized within the operator's hand and are not transmitted to the wrist and the forearm.[35,36] It has been further reported that nearly half the energy absorption in a bare hand is associated with HTV above 1,000 Hz.[37] These findings raise a number of concerns on the upper bound of the vibration-frequency range specified in the standards and suggest the use of a higher frequency range. This may necessitate revisions of the current frequency-weighting function, the development of additional weighting function, or both.

The measurement of HTV at low frequencies also poses various difficulties associated with involuntary movements of the operator. Because there is little evidence on the contribution of low-frequency vibration to VWF, it has been suggested that the lower bound of the recommended frequency range be increased from 5 to 20 Hz. The large displacements caused by high magnitudes of low-frequency acceleration, however, may be directly transmitted to the elbow, shoulder, and head in the form of whole-body vibration.[35,38,39] Such high magnitudes of displacements may cause undesirable effects at these locations and therefore should be mitigated.[40,41] These arguments suggest the need for further investigations into vibration transmission of the human hand-arm system to derive an optimal and generally acceptable lower bound of the frequency range.

C. Magnitudes of Hand-Transmitted Vibration and Frequency Weighting

The magnitudes of hand-transmitted vibrations measured on various power tools vary significantly depending upon the tool, application, speed, feed force, feed rate, measurement location, and so forth. In the current standards, the frequency-weighted or effective magnitude of vibration is considered approximately equal in importance to the yearly exposure and much more significant than the duration of daily exposure.[10,15] The risk assessment is virtually controlled by the weighting functions. The determination of appropriate frequency-weighting function(s) is therefore vital for exposure evaluations. The use of weighted or unweighted HTV and the determination of a generally accepted weighting function still remain the major issues associated with characterization and assessment of HTV.

The weighting function described in ISO-5349[10] suggests that the greatest risk for injury is associated with vibration in the 6.3- to 16-Hz range. The weighting function decreases rapidly at the rate of 6 db/octave above 16 Hz, as illustrated in Figure 2. The revised version of the standard, ISO/DIS 5349-1,[11] requires consideration of the direction of hand-transmitted vibration owing to different tools. It has been reported that the weighting function was originally established from the experimental data on the sensation of discomfort, but such data relate to acute sensory effects rather than chronic peripheral vascular functions.[42] Other studies have reported

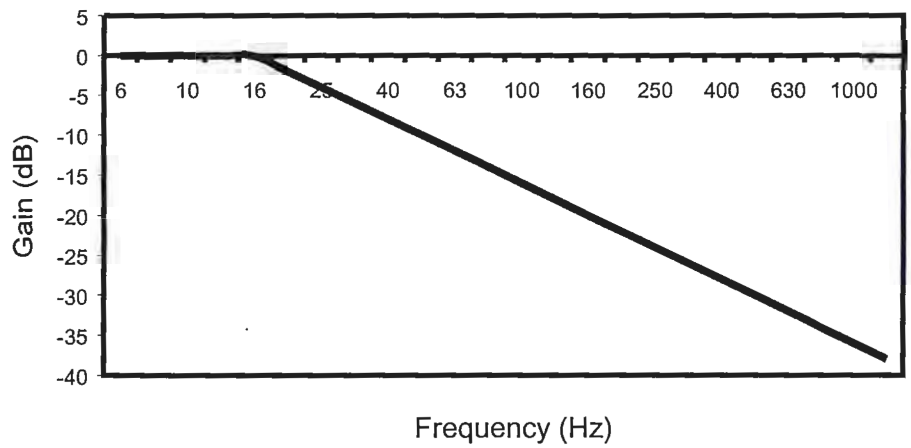

FIGURE 2. Weighting function proposed in ISO-5349, 1986 (from Ref. 10).

that the recommended weighting function is not based on either physiological or pathological effects of vibration, and offers only a minimal consideration of the biodynamic responses to vibration.[3,9] Furthermore, the subjective data used in deriving the function were measured only up to 300 Hz, whereas the values at higher frequencies up to 1,000 Hz were based upon extrapolations. Consequently, many concerns have been raised regarding the foundation of the current weighting function.

Apart from the frequency weighting, a number of concerns have also been raised regarding the dose-response relationship appearing in ISO-5349.[10] Although some investigators have reported that the dose-effect relationship yields an overestimate of the potential health risks,[43–47] others have shown that it underestimates the prevalence of HAVS.[26,31,48–53] These studies suggest that the current frequency weighting and the dose-effect relationship may not be generally applicable for all tools and all operating situations. Although the use of unweighted accelerations for the assessment of HTV has been recommended by NIOSH,[2] a number of alternate weighting functions have also been proposed.[46,54] The consideration of separate weighting functions for assessment of vascular and neurologic disorders has been suggested by Pelmear et al.[55] In view of the wide range of frequencies of HTV of different tools, different frequency ranges need to be considered for each type.[54] Because the energy transferred to the hand is differentially attenuated in each of the three orthogonal directions of transmission,[56] it is highly likely that risk assessments could be improved via the development and application of direction-specific weighting.

D. Direction of Hand-Transmitted Vibration

The characterization and assessment of HTV in the current standards is based only upon the largest component of the rms (root-mean-square) accelerations measured along the three orthogonal axes. Hand-held power tools, in general, transmit vibration to the human hand along all three translational directions, whereas some tools may cause considerable magnitudes of rotational components of HTV. Very few tools or processes exhibit a truly dominant axis of vibration.[57] The direction of predominant vibration and the corresponding magnitudes of HTV for such tools may vary with variations in operating conditions that include working posture, change-of-acting angle, contact force, hand posture, and the shape of the object.[58] The vector sum or root-sum-of-squares (RSS) method has been proposed to account for transmission of vibration along more than 1 axis.[58,59] The revised ISO standard also proposes using the RSS method, assuming that the HTV in each of the three directions is equally detrimental.

Consideration of HTV along the different axes raises major concerns regarding the application of frequency weighting. The human hand-arm system exhibits varying sensitivity to vibration along different axes, as evident from biodynamic responses and discomfort contours.[35,56,60] Therefore, transmitting vibration into the tissues of the hand-arm system and to other parts of the body under motions normal to the surface differs from that under motions in the shear axes. The above studies suggest that the identification and application of various weighting functions for different axes of HTV necessitate further studies into biodynamic- and pathophysiologic-response behavior.[61] With only a few exceptions in the previous studies, the effects of vibration directions are invariably considered 1 axis at a time using a single-axis vibration test system. Additionally, the majority of the reported studies ignore the effects of coupled modes of vibration of the human hand and arm. Figure 3 illustrates a typical measurement setup used in such studies. A 3-axis vibration test system would be desirable to inves-

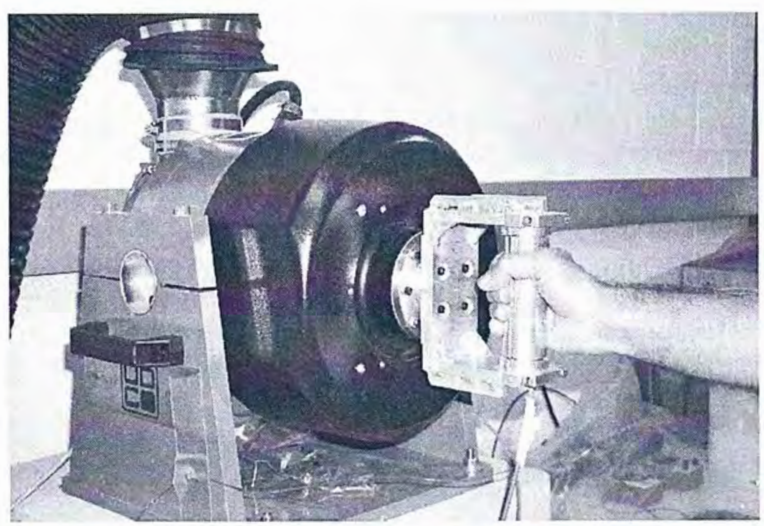

FIGURE 3. View of a single-axis vibration test system used in studies on HTV.

tigate the coupling effects (e.g., response under multiaxial vibration) of vibration transmitted along different directions. The design of such a system, however, poses several complexities and challenges owing to high-frequency vibration requirements and the mechanical resonances and cross effects of complex-coupling mechanisms. Only one 3-axis hand-arm vibration test system, based upon servohydraulic exciters with limited bandwidth, has been reported in the literature.[62,63]

E. Contributions Owing to Extrinsic and Intrinsic Variables

The magnitude and frequency of HTV are further influenced by additional extrinsic and intrinsic variables, such as coupling forces, grip type and grip-force distributions, dynamic torque, handle geometry, and other interindividual operator characteristics. A number of investigators have attempted to study the effects of some of these variables on HTV; they are discussed below.

1. Coupling Force and Its Distribution

The coupling force at the hand-handle interface, often considered a combination of grip and push/feed forces, permits the flow of vibration energy from the tool into the hand; it consequently affects the vibration of the tool and the hand. It has been generally agreed that this coupling force substantially effects the severity of vibration transmission.[3,64,65] Consideration of this force as a weighting function has also been suggested to account for its strong effects on exposure-assessment and biodynamic response.[66,67] The biodynamic response of the hand-arm, measured as DPMI (driving-point mechanical impedance), increases considerably with increases in the grip force.[20,22,31,68] The influence of feed force on HTV and on the biodynamic response has been addressed in few studies. On the basis of synthesis of the reported data, it has been concluded that the biodynamic response of the human hand-arm is relatively less sensitive to variations in the feed forces.[22,69,70]

The measurement of the grip force is thus emphasized in the current ISO (International Standards Organization) standard, although a standardized measurement method does not yet exist. Moreover, the measurement of grip and feed forces in the tools used within the field environment remains a formidable task. An estimate of grip force may be realized from measuring grip-pressure distribution at the hand-handle interface. A few investigators have measured the distribution of grip forces on the fingers using diverse techniques.[71–74] The results of these studies suggest that about 55 to 70% of the total grip force is distributed in the lateral side of the hand. Matrices of thin-film and flexible resistive and capacitive pressure sensors have been used to measure the distribution of interface pressure on a cylindrical handle under both static and vibration conditions.[75] Although the measurement of grip force on typical tool handles with ribbed plastic coverings or soft rubber grips has not been attempted, such measurements can be undertaken with thin-film sensing grids. The study of grip-pressure distribution at the hand-handle interface of a vibrating tool could provide considerable insight into the transmission of vibration, contact stresses at the hand, and ergonomic design of tool handles.

It has been reported that the grip-pressure distribution under vibration yields a high concentration of interface pressure on the lateral side of the hand, as shown in Figure 4. This finding is consistent with the asymmetric nature of the distribution of VWF symptoms observed in the affected hands in some cases.[8,75] Concentration of high-magnitude grip pressure may affect the hemodynamic forces in the arterial walls and, accordingly, the finger blood flow.[76] It has been speculated that the occurrence of high pressure at the middle of the index and middle fingers under tool vibration, and its possible effects on the arterial blood flow, may be one of the factors leading to the development of VWF. This hypothesis, together with reported evidence of reduced finger blood flow, merit further investigations into grip-pressure distribution on tool handles. Although flexible and thin-film sensors have been used to measure normal contact pressure, further measurement efforts along the shear direction could provide considerable insights into characterizing and assessing HTV.

2. Dynamic Torque

Rotary tools may transmit dynamic torque and high reaction forces in the operator's hand and arm. The nut-runners that account for 75% of the hand-held power

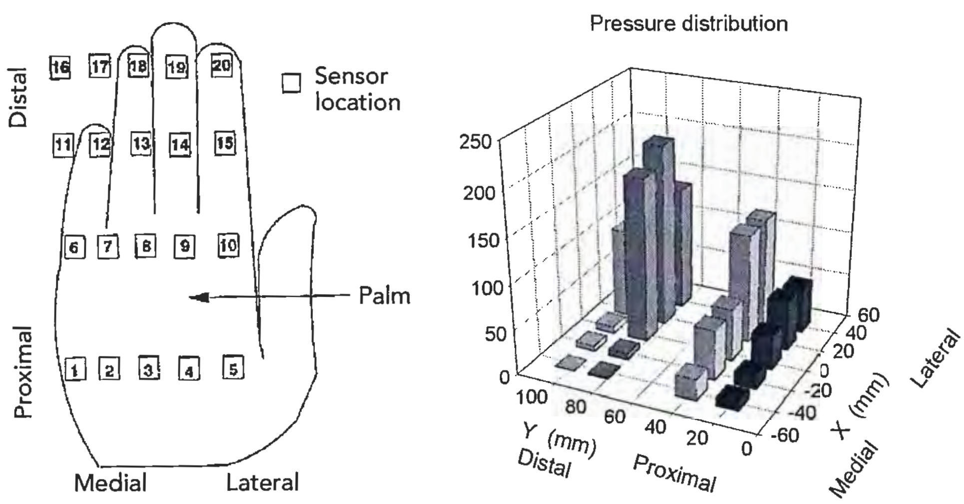

FIGURE 4. Grip-pressure distribution at the hand-handle interface: axis of vibration, Y_h; amplitude, 3.0 g peak sinusoidal; frequency, 100 Hz (from Ref. 29).

tools used in the automobile industry impose considerable moments on the hand and arm.[77] The exposure to dynamic torque and vibration generated by such tools has been related to the occurrence of cumulative trauma disorders among workers.[78–83] Although the methods for measurements and evaluations of dynamic torque and impulse transmitted by threaded fasteners have been standardized (ISO-6544),[84] the effects of reaction torque on HTV and biodynamic behavior of the hand-arm system have not been reported.

3. Intrinsic Factors

The intrinsic factors, such as body size, body posture, hand and arm size, and muscle tension, influence HTV. The effects of some of these factors have been investigated in a few studies. Although their contributions have not been quantified, the effects of most intrinsic variables are thought of minor importance.[85] Variation in body posture, however, is considered an important factor affecting HTV, although it has not been quantitatively considered in exposure evaluations. ISO-5349,[10] however, addresses body posture to a limited extent by recommending the reporting of hand-arm posture or angles of the wrist, elbow, and shoulder joints for specific test conditions. In its revised version, the draft document (ISO/DIS 5349-1; 1999)[11] recommends the use of representative working postures. The role of hand-arm posture on the development of HAVS may be classified into three effects:

1. Effects on blood circulation in the hand and the ability of joints and tissues to resist damage or injury. For example, the operation of overhead tools causes reduced blood flow in hand, while the joints may become more susceptible to injuries with an awkward posture.
2. Effects on the biodynamic response of the hand-arm system and, consequently, the vibration spectra of the tool that, to an extent, is incorporated within the recommended measurement and reporting methodologies.
3. Effects on the transmission of vibration to the hand-arm system and the whole-body, and, specifically, the effects of wrist angle, elbow angle, and shoulder abduction.

The size of the hand and arm may further affect the coupled hand-tool dynamics, that is, the vibration generated by the tool and the biodynamic response of the hand-arm to vibration. Such effects, however, have not been clearly identified. Considering similar contact area, the magnitude of vibration transmitted to a particular location of the hand may vary with variations in the hand-arm size. The effective contact area is likely to vary considerably with the hand size. The variations in the stiffness, mass density, and damping ratio of the skin and other tissues of different individuals may further affect the characteristics of HTV.

F. Measurement Methods

Mechanical damage and/or stimulation of local tissues, nerves, or arteries is most likely one of the major causes of HAVS. The characterization of vibration at a particular location or in the vicinity of tissue known to be more susceptible to vibration-induced injuries may play a vital role in identifying mechanism(s) that lead to disorders. Invasive methods may be required to measure the vibration dose interior to the hand-arm system, but they are neither convenient nor practical with live subjects and may raise many ethical concerns. Such measurements, however, have been performed on a cadaver arm by attaching the accelerometers directly to the bone to eliminate contributions caused by the flexibility of the skin.[86] Considering the differences in elasticity and damping properties between living and cadaver tissues, the biodynamic behavior of a cadaver arm will differ from that of a living arm. Furthermore, efforts to simulate hand grip and feed forces with cadaver arms pose considerable complexities that are known to strongly affect vibration transmission. Invasive probes for measuring vibration inside a soft tissue, alive or dead, may also alter its original structure and dynamic response.

Because of the complexities associated with invasive measurement methods, the majority of the studies have relied upon measurements performed on the surface of the hand-arm using either accelerometers or noncontact, laser-based sensors.[35,65,87–94] Various studies have explored various accelerometer mounting methods including adhesive, tape, ring, braces, or straps. Depending on the objective of the study, miniature or subminiature accelerometers have been mounted on fingernails, phalanges, metacarpals, wrists, elbows, and shoulders. The possible contaminating effects of the sensor mass on the measured response have been ignored.

In an effort to eliminate these confounding sensor-mass effects, noncontacting laser vibrometers or Laser Doppler Velocimeters (LDVs) have been employed in some studies to measure the vibration transmitted to the hand-arm system.[95–97] The majority of commercially available LDVs can measure velocities up to 1 m/s over a wide frequency range. The LDVs may be considered inadequate for tools generating vibration of high frequencies and high magnitudes. Some LDVs can measure velocities up to 10 m/s and are considered better suited for such studies. Laser vibrometers, however, have significant limitations in situations involving nonaxial movement of the object. Effective measurements can be performed only when (a) the measurement location remains in the immediate vicinity of the central axis of the vibrometer's laser beam, and (b) the principal direction of movement is along the axis of the laser beam. The use of such vibrometers is therefore limited to laboratory applications. Rossi and Tomasini[98] and Deboli et al.[99] employed a scanning vibrometer and reported encouraging results with their measurement technique. Several types of advanced devices for vibration measurement, such as multiaxial, rotational, and in-plane laser vibrometers, are available commercially. They offer considerable potential for the noncontact study of detailed vibration patterns and characteristics of HTV.

Transmission of vibration to different segments of the body could be accurately measured using infrared cameras. Commercially available infrared cameras with sampling frequencies up to 1 kHz and resolution of more than 0.1 mm could be effectively used for measuring low-frequency components of motion, such as those transmitted to the head and those induced by whole-body vibration. Although such a system offers the conventional benefits of noncontact sensors, unlike single-axis LDVs (Laser Doppler Velocimeters), this camera permits measurements on objects under nonaxial movements. High-speed digital cameras with sampling frequencies above 2,000 Hz have also been available for measuring body motions at higher frequencies, but their limited resolution or sensitivity poses certain concerns. The applications of these emerging motion-measurement systems for studies on HTV, however, need to be explored.

III. HAND-ARM RESPONSE TO VIBRATION: BIODYNAMIC MEASURES

The biodynamic response behavior of the hand-arm system can be described as *through-the-hand-arm* and *to-the-hand* response functions. The through-the-hand-arm response function describes the transmission of vibration; it is expressed as the ratio of the motion magnitude at a specific segment of the hand-arm system to that at the hand-handle interface. The biodynamic response in terms of the to-the-hand function relates the vibration in the vicinity of the hand to the force at the driving point. This function may be expressed as dynamic stiffness, DPMI (driving-point mechanical impedance), or APMS (apparent mass):

$$K(j\omega) = \frac{F_q(j\omega)}{q(j\omega)} \qquad Z(j\omega) = \frac{F_q(j\omega)}{\dot{q}(j\omega)} \qquad M(j\omega) = \frac{F_q(j\omega)}{\ddot{q}(j\omega)} \tag{1}$$

where K, Z, and M are complex dynamic stiffness, DPMI, and APMS, respectively. q, $\dot{q}$, and $\ddot{q}$ are the displacement, velocity, and acceleration, respectively, measured at the driving point, and F_q is the driving force along the axis of the motion. ω is the circular frequency of vibration, and $j = \sqrt{-1}$. The dynamic stiffness, DPMI, and APMS functions may also be expressed by the respective displacement mobility or compliance, velocity mobility, and accelerance that are computed from the inverse of the functions described in Eq. (1).

The to-the-hand biodynamic response of the hand-arm has also been expressed as the energy absorbed by the hand and arm. The power (P), amount of energy per unit time, the hand-arm is exposed to is computed from the force and the velocity at the driving point:

$$P(j\omega) = F_q(j\omega)\dot{q}(j\omega) \tag{2}$$

The real component of the power describes the energy absorbed by the hand, which is transformed into the heat caused by friction within the tissues. The imaginary component of the power relates to the energy stored within the hand-arm system.

The biodynamic response of the human hand-arm has been extensively investigated on the basis of all the functions described above, but the majority of the studies are based upon either DPMI or transmission of vibration energy. Although various measures of to-the-hand responses are directly related, different measures may yield different aspects of the hand-arm response to vibration. Moreover, a relationship among different biodynamic measures has not yet been established for hand-arm vibration, although such a relationship has been analyzed through studies of the biodynamic response of seated occupants under whole-body vibration.[100]

The biodynamic response characteristics of the human hand-arm system have, invariably, been measured on human subjects under carefully controlled conditions. Nonetheless, considerable differences are known to exist among the measured data reported by investigators. These differences have been partly attributed to variations in intrinsic and extrinsic variables, test conditions, and the methodologies employed in the various studies.[22]

A. Vibration Transmission Characteristics of the Hand-Arm System: Through-the-Hand-Arm

The direct relationship between the severity of HAVS and the characteristics of HTV has prompted the strong desire to enhance understanding of the vibration transmission of the hand-arm system. A study of vibration transmissibility of the hand-arm can provide significant insight into HTV, relative motions of various components of the hand-arm, design of vibration isolators, and assessments of vibration-attenuation performance of protective devices such as antivibration gloves. Although many studies have been performed to assess the vibration attenuation performance of protective devices, only limited efforts have been made to study the vibration transmission through the hand-arm system. This may be attributed to the lack of appropriate sensors and measurement methodologies. [88,94,96,101–104] Using the measurement systems described in the previous section, few investigators have studied the biodynamic response of the hand-arm through its vibration transmissibility for the purpose of quantifying the vibration transmitted to different segments of the hand and the arm.[24,35,87–88,92,105–108]

The majority of these studies were performed using miniature and subminiature accelerometers attached to the skin. The measurement of vibration transmitted to parts of upper limbs, however, has posed difficulties caused by attaching transducers to the skin and the flexibility of skin. The transmissibility studies, specifically for the upper limbs, have thus been limited to low-frequency vibration. Abrams[105] measured the transmitted vibration by attaching accelerometers to the bones of cadaver arms to minimize measurement errors caused by relative motions between the skin, muscle tissues, and the bone. The measurements performed along the radius bone revealed the presence of resonance near 125 and 500 Hz.

The vibration transmission characteristics of the human hand-arm system have been derived in the laboratory under controlled-grip conditions and deterministic vibration.[24,35,87,106] Other investigators have performed these measurements in the field during tool operation to assess the vibration performance of diverse tools and protective devices.[108] Pyykko et al.[87] measured the longitudinal (Z_h) vibration transmitted to the wrist, elbow, and upper-arm under excitations in the 20- to 630-Hz range while using different magnitudes of grip force. Vibration transmission of the hand-arm system has been extensively investigated by Reynolds and Angevine[35] under different magnitudes of palm- and finger-types of grips, and three independent axes (X_h, Y_h, Z_h) of handle vibration. In this study, 8 miniature accelerometers were mounted on phalanges of the finger, wrist, elbow, and shoulder.

The above studies have invariably concluded that magnitudes of vibration transmitted to the hand-arm decrease with increasing frequency and the distance from the vibration source. Less than 10% of vibration at frequencies more than 250 Hz is transmitted to the wrist and beyond, and only vibrations of less than 100 Hz can be effectively transmitted to the forearms. Vibration less than 40 Hz can be transmitted to the forearm and upper arm without any noticeable attenuation.[95] Vibration transmitted to the fingers and carpal bones, however, could be amplified.[29,35] Although the resonant-peak values for the phalanges reported in various studies differ considerably, the peak values occurred in the 80- to 200-Hz range.[35,88,95] All the studies have further concluded that hand-tool vibration more than 200 Hz is primarily limited to the hands and fingers. Thus, for the majority of hand-held power tools usage, the hands absorb most of the vibration energy associated with HTV.

The reported frequency range attributed to the resonances of the hand is consistent with the resonant frequencies of the skin reported by Lundström.[109] This further coincides with the range of predominant vibration frequencies associated with many hand-held power tools (20–250 Hz), and lies within the range that is known to be most critical in view of the health effects (30–350 Hz).[26] The presence of resonances of the wrist and elbow have also been reported in the 10- to 40-Hz range.[38,65,110] Studies performed under different levels of grip force have concluded that increasing the grip force causes a shift in the resonant peak to a higher frequency. These shifts were attributed to increased skin contact stiffness and joint stiffness.[65,90,92] It was found that the vibration magnitude is not noticeably reduced when it passes through a joint, while large relative motion was observed across the joint.[35] It is believed that the mechanical energy associated with vibration up to approximately 500 Hz propagates within the skin as shear waves, and the energy caused by higher frequency vibration probably propagates as bulk shear waves though the underlying tissues.[111]

The HTV may also be transmitted to the whole-body depending upon the characteristics of HTV, body posture, and hand posture. Sakakibara et al.[39] measured the vibration transmitted from the operator's hand to the head and concluded that the vibration transmitted to the head was highly dependent on the angle of the elbow. A straight-arm posture generally transmitted more vibration to the head than an arm with a bent elbow. The vibration transmitted to the head was shown to alter continuous manual control and oculomanual coordination; the effect was found to be frequency-dependent.[112] Mussan et al.[113] reported that back pain or stiffness was the most common complaint among workers (54%) using impact power tools even though back pain is not often mentioned as a disorder of exposure to hand-arm vibration. Pope et al.[110] further investigated the transmission of HTV and impacts through the hand-arm system to the spine. Their study concluded that the simulated vibration and impacts could be effectively attenuated by the hand-arm system, and that their transmission to the lumbar spine was of little concern, at least under the conditions employed in their study. Considering the incongruous conclusions drawn by investigators, further studies are essential to examine the transmission of hand-arm vibration to the spine and its effects on the back complaints among power-tool operators. The contributions of body posture, hand posture, characteristics of HTV, and grip and feed forces to the biodynamic response behavior of the hand-arm need to be clarified.

The studies on vibration transmissibility of the human hand-arm have been generally limited to frequencies up to 1250 Hz. Since many hand-held tools, specifically the percussive tools, generate vibration at very high frequencies, it is recommended that such studies be performed under vibration at frequencies up to 5000 Hz.[2] Although there is a lack of knowledge on vibration transmissibility of the hand-arm at frequencies more than 1250 Hz, the transmission of high-frequency vibration energy is not expected to occur through the entire thickness of the fingers or the hand. A distribution of transmitted vibration in the hand in this frequency range can perhaps be realized by measuring the vibration through the thickness of the finger or the hand. It is also expected that at very high frequencies the vibration transmission will be limited to the skin that is in contact with the handle. Sörensson and Burström[127] conducted vibration tests up to 5000 Hz, but the detailed vibration distribution was not reported.

The majority of the studies on hand-arm vibration transmissibility have been performed under controlled laboratory conditions, and idealized vibration excitations, grip forces, and postural conditions. Although such laboratory studies have provided considerable insight into the biodynamic response of the human hand-arm to HTV, the findings may not truly replicate the real-world conditions associated with tool operations that cause vibration injury. Many investigators have quantified the actual vibration transmitted to the hand-arm system using real tools. Similar to the laboratory tests, the accelerometers in these studies were attached to the finger, back of the hand, wrist, and elbow.[128,129] The measurement of vibration on the back of the hand[93] was proposed as an alternate approach to the standard measurement method.[10] Although this method permits partial considerations of the contributions of grip and feed forces, working postures, and working directions, subjects tend to better adapt to the sensors at the back of their hands than to the palm adapter. This methodology, however, assumes that the vibration on the back of the hand is identical to that at the palm. From the measured data, it was concluded that this assumption is valid for frequencies below 150 Hz, while the vibration measured on the back of the hand in the 150- to 250-Hz range differed from that at the interface by 1–3 dB.[93,128] The measurement method, however, may be considered appropriate because the current weighting function proposed in ISO-5349 significantly suppresses the magnitude of vibration at frequencies above 100 Hz.

B. Special Cases of Through-the-Hand-Arm: Effects of Gloves and Mitigating Materials on Vibration-Transmission and Standard-Test Methods

High levels of hand-held power tool vibration, the high prevalence of VWF symptoms among exposed workers, and severe health effects have all prompted various developments in vibration-attenuating devices. In general, control of HTV is achieved through reducing the source vibration and using vibration isolators. Reductions in the source vibration have been realized through tool operation at suitable speeds, tool and drive maintenance, and through improved designs of the drives.[114] The attenuation of HTV is primarily attained using two methods: (1) isolation of the tool handle from the source vibration, and (2) isolation of the hand from the tool handle.[115,116] Tool-handle isolators, integrated within chain saws, have proven effective in attenuating the tool vibration transmitted to operators.[86,117] The general implementation of such isolators, however, has been limited because of the design complexities of many tools. Alternatively, handle grips and antivibration gloves have been widely recommended for isolating the hand from the vibrating handle.

Although conventional gloves are used to protect the hands against cuts, bruises, chemicals, and burning metal particles, a number of antivibration gloves have been developed to attenuate HTV. Physically, gloves or glovelike materials introduce a third component in the hand-machine interface and form a more complex viscoelastic system that may alter the characteristics of HTV and the vibration transmissibility of the hand-arm system. Depending on the glove materials and tool-operating conditions, this may have either positive or negative effects. The vibration transmissibility of conventional and antivibration gloves has been investigated using various measurement methods. The vibration transmissibility of the hand with gloves made of PVC and knitted-texture nylon have been evaluated by mounting a 3-axis accelerometer on the back of the hand.[102] The study concluded that the gloves do not attenuate vibration in the test frequency range of 8 to 1000 Hz, and they tend to amplify vibration in some of the frequency bands. Similar measurements have been performed to establish an objective method for assessing glovelike materials in the 10- to 500-Hz range by mounting miniature accelerometers on the index fingernail and the skin over the third metacarpal bone.[88] From the measurements, it was concluded that these glovelike materials attenuate vibration at frequencies above 100 Hz and may amplify vibration below 100 Hz caused by the resonance of the coupled hand-glove system.

Gurram et al.[96] proposed assessing vibration-attenuation performance of gloves through measurement of vibration transmitted to the head of the third metacarpal bone using a laser vibrometer. The study involved assessments of 9 different gloves, made of nylon, cotton, polyurethane, and Sorbothane, under different magnitudes of grip force and acceleration excitation. The results showed definite amplification of vibration below 100 Hz and attenuation above 100 Hz. The vibration transmissibility of the glove-hand system, however, was observed to be higher than that of the bare hand in the majority of the frequency range. The dependence of the vibration transmissibility on the vibration magnitude and grip force was further reported, and was attributed to the nonlinear viscoelastic properties of the glove materials.

The effects of gloves on the vibration transmission of the human hand-arm have also been studied by many other investigators.[94,103,104] These studies have invariably drawn conclusions similar to those cited above by Griffin et al.[88] and Gurram et al.[96] It has been stated that about 90% of the commercially available gloves referred to as *antivibration gloves* do not provide significant attenuation of vibration.[118] Overall, only a few gloves have shown good attenuation of vibration.[118–121] Glove designs based upon an air bladder were probably the best among those evaluated. Subjective evaluations also reveal that in some situations the gloves interfered with the workers' ability to perform their tasks because of dexterity loss.[102,104]

Upon recognizing the lack of uniform measurement and evaluation methods, the ISO and CEN (Comité Européen de Normalisation) have jointly developed a standard method to assess the vibration-attenuation performance of the gloves (ISO-10819; 1996).[122] A palm-held adapter with a single-axis transducer is used to measure the vibration transmitted through a glove, as shown in Figure 5. The vibration-attenuation performance of a glove is evaluated on the basis of vibration transmissibility through the hand, computed from the accelerations measured on the adapter and the handle. Many researchers have closely examined the standard since its publication and have proposed several alternatives and improvements.[61,118,121,123,124] Although the methodologies proposed in the standard have been widely accepted, the majority of the researchers have identified many fundamental defi-

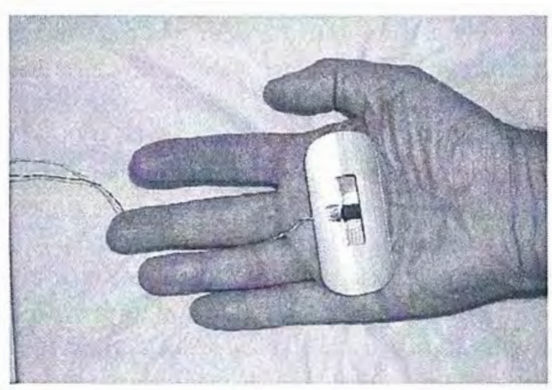

FIGURE 5. The palm-held adapter recommended in ISO-10819, 1996 (from Ref. 122).

ciencies. These are mostly associated with the characteristics of HTV and the issues relevant to the biodynamic behavior of the human hand and arm, which can be summarized as follows:

- The test spectra specified in the standard may not be representative of most hand-held power tools. The method, therefore, does not allow for selecting an antivibration glove that may be suited for a specific tool or operation.
- The proposed data-processing and evaluation method makes it difficult to distinguish between the antivibration and non-antivibration gloves in some cases because test errors together with the inter- and intrasubject variations could exceed the differences among the tested gloves. The recommended number of subjects is also considered to be insufficient to make appropriate distinctions among different gloves.
- The vibration transmissibility of a glove depends upon the biodynamic response of the hand-arm system, which is strongly affected by variabilities among individual subjects and hand-arm posture. A single posture specified in the standard may be insufficient to represent common operation conditions. The generalization of the resulting performance of the gloves may thus be questionable.
- The proposed design of the instrumented handle in the standard may exhibit resonances or undesired dynamic behaviors in the specified test-frequency range that may affect vibration transmissibility. Some test results have suggested that the grip force has only a marginal effect on the transmissibility as long as the feed force is applied properly.[124] This feature may allow designers to simplify the handle design considerably, which would provide better control of the vibration excitation.
- Many concerns have been expressed regarding the potential misalignments of the palm-held adapter, which can yield erroneous evaluations of the gloves. Alternate methods to ensure adequate alignment of the adapter are therefore highly desirable. Further studies are also required to study the dynamics of the handle-glove-adapter-hand system and its contributions to the vibration transmissibility of the gloves.
- The standard recommends evaluations along only one direction of vibration. It is not clear whether a glove that can attenuate vibration in the compression axis could also equally attenuate vibration in the shear axis.
- It is not clear whether an antivibration glove identified from this test method can be assumed to provide benefits in terms of vibration transmitted to the fingers.

Griffin[61] described these ISO-10819–related deficiencies and technical concerns in more detail. An interlaboratory evaluation of the reproducibility of the standard test method that involves 8 different laboratories over the world is underway.

In the United States, an ANSI standard for assessing the efficiency of antivibration gloves and their ability to reduce vibration impinging on the hands of vibrating-tool users was developed in 1989.[125] The test could be either carried out in the workplace on a real tool or in the laboratory using a vibration-shaker test system. The laboratory evaluations could be performed under field-measured vibration excitations synthesized in the laboratory, swept sinusoidal vibration, or random excitations in the 5.6- to 1400-Hz range. The ANSI method offers some advantages and limitations over the ISO-10819. Unlike the ISO standard, which measures the vibration transmitted to the palm via an adapter, ANSI recommends the measurement of vibration transmitted through the hand at the head of the third metacarpal. As a result, the potential errors caused by coupling effects of the handle-adapter-glove-hand system could be eliminated. The performance of the antivibration glove can be evaluated for specific tools and operating conditions. Furthermore, the effectiveness of the gloves can be evaluated under vibration along different directions. The proposed method, however, does not define the test conditions or the number of subjects, but does require reporting of the conditions. This approach will most likely engender considerable variations in the results reported by different investigators because of expected variations in test conditions. Considering the many concerns that have been expressed in various studies, further investigations are desirable to develop sound and generally applicable standardized measurement and assessment methods.

The ISO has also outlined a procedure for assessing vibration-attenuation performance of resilient materials used in handle grips and gloves (ISO-13753; 1998).[126] The proposed method does not involve human subjects. The vibration transmissibility of a material is derived from the impedance characteristics of the material and the human hand and arm. The standard requires the measurement of impedance of the material sample, which is a circular section of radius not less than 45 mm, placed between a 2.5 kg mass and a rigid vibrating surface (shaker). The proposed method may permit ranking materials for handle-grips and gloves on the basis of computed vibration transmissibility, but it may not necessarily predict the vibration transmissibility of the gloves fabricated from the materials. Several researchers have reported the lack of relationship between the vibration transmissibility of a material, measured using the method outlined in ISO-13753, and that of a glove made of the same material, derived using the method prescribed in ISO-10819.[118,119]

C. To-the-Hand Biodynamic Response: Driving-Point Mechanical Impedance

The human hand-arm system is a complex biodynamic system; a simple approach to study the hand-arm system is to consider it a "black box," and to describe its dynamic response at its driving point through the force-motion relationship. The to-the-hand biodynamic response of the hand-arm, invariably described as dynamic stiffness, DPMI, or APMS, is computed from the force-motion relationship at the driving point, as described in Eq. (1). These response functions are complex, and yield modulus and phase response.

The determination and use of the to-the-hand response does not involve the internal relationships among the tissues and musculoskeletal structure of the hand

and arm. The modulus and phase response, however, fully describe the mass spring and damper-like behavior of the hand and arm, and the associated variations under different vibration excitations and operating conditions. Consequently, the measured response permits analysis of effective masses, spring constants, and damping factors as functions of the magnitude, frequency, and direction of handle vibration; grip force; posture, and so forth. The mechanical energy transmitted to or dissipated into the hands can be further computed from the to-the-hand biodynamic response.[68] The biodynamic response characteristics of the human hand-arm system have been extensively measured to enhance understanding of its dynamic behavior, develop effective vibration isolators and operating conditions, and to derive mechanical models of the hand-arm for further developments in hand-arm simulators.[21]

DPMI has been widely used to describe the to-the-hand biodynamic response of the hand-arm. All the reported studies have measured the biodynamic response of the hand-arm system under controlled laboratory-test conditions using a single-degree-of-freedom vibration-test system. Consequently, the possible coupling effects of the hand-arm system response have been ignored. An instrumented handle or dynamometer is used to measure the grip, feed, and dynamic vibratory forces, and acceleration at the driving point.

1. Contributing Factors

The driving-point mechanical impedance characteristics describing the "to-the-hand" biodynamic response of the hand-arm system have been extensively investigated under a wide range of vibration excitations and test conditions.[18,20,22,31,68,85,130–139] Even though impedance has been measured on human subjects under carefully controlled test conditions, there are considerable differences among the impedance data reported by different investigators. Precise reasons for such differences have not been established, but it is generally believed that these are caused by differences in the experimental and measurement techniques employed. Table 2 summarizes the range of operating conditions in various studies. The operating conditions varied considerably, especially relative to the range of vibration excitation, frequency range, handle size, grip force, and posture. The lower and upper limits of the frequency of excitation in these studies ranged from 2 to 20 Hz and 200 to 2000 Hz, respectively. Although the majority of the studies have employed sinusoidal excitations, the biodynamic response of the hand-arm system to random vibration has been addressed in some studies.[134,140–142] The DPMI of the hand and arm subject to random vibration excitation is computed from the cross-correlation functions of the force and velocity:[142,143]

$$Z(j\omega) = \frac{G_{F\dot{q}}(j\omega)}{G_{\dot{q}\dot{q}}(j\omega)} \qquad (3)$$

TABLE 2.
Ranges of Test Conditions Employed in Various Studies on Characterization of Biodynamic Response of the Human Hand and Arm

Investigator(s)	Response function	Nature of source vibration			Grip force (N)	Handle diameter	Elbow angle (°)
		Magnitude/ type of excitation	Frequency range (Hz)	Direction			
Gurram[29]	DPMI	1–3 g peak; sine 0.2, 0.5, 0.7 m/s^2 rms; random	10–1,000	X_h, Y_h, Z_h	Palm: 10, 25, 50	38 mm	90
Burström[68]	DPMI	8–45 mm/s; sine	2–1,000	X_h, Y_h, Z_h	Palm: 25, 50, 100	31 × 42; elliptic	60–180
Mishoe and Suggs[20]	DPMI	6.93, 20.58, 34.3 m/s^2 rms; sine	20–2,000	X_h, Y_h, Z_h	Palm: 13.5, 27, 40	25 mm	NR
Daikoku and Ishikawa[133]	DPMI	6.9 m/s^2 rms; stepped-sine	8–200	X_h, Y_h, Z_h	Palm: 33	10 mm; 30 mm	NR
Reynolds and Falkenberg[23]	Compliance	NR; sine	5–1,000	X_h, Y_h, Z_h	Palm: 25.4, 35.6 Finger: 8.9, 35.6	19 mm; 38 mm	NR
Griffin et. al.[88]	APMS	2.5–6.0 m/s^2 rms; stepped sine	10–1,000	X_h, Z_h	Palm: 0–186	NR	90–180
Lundström[31]	DPMI	27–53 mm/s, sine sweep	20–1,500	X_h, Z_h	Palm: 25, 50, 75	31 × 42; elliptic	90–180
Hempstock and O'Connor[134]	DPMI	0.5 m/s^2 rms; random	16–500	X_h, Y_h, Z_h	Palm: 25	NR	120

TABLE 2.
Ranges of Test Conditions Employed in Various Studies on Characterization of Biodynamic Response of the Human Hand and Arm

Investigator(s)	Response function	Nature of source vibration: Magnitude/ type of excitation	Frequency range (Hz)	Direction	Grip force (N)	Handle diameter	Elbow angle (°)
Bernard[69]	APMS	6.0, 12.0 m/s^2 rms; random	10–200	Z_h	Palm: 30, 50, 70	NR	Near 180
Meltzer[174]	Accelerance	10 N force; stepped sine	3–300	Z_h	NR; Palm	32 mm	50 and 120
Hesse[70]	DPMI	9.8 m/s^2 weighted; pseudo-random	5–1,000	X_h, Y_h, Z_h	Palm: 10–90	45 mm	60–180
Jandak[144]	DPMI	NR; impulse	5–500	Z_h	Palm: 20–200	NR	90
Burström and Lundström[148]	Absorbed energy	8.0, 14.0, 25.0, 45.0 mm/s rms; sine sweep	2–2,000	X_h, Y_h, Z_h	Palm: 25, 50, 75	31 × 42; elliptic	60–180
Burström[18]	DPMI	6.5, 13, 19.5, 26 mm/s; random	4–2,000	X_h, Y_h, Z_h	Palm: 25, 50, 75	31 × 42; elliptic	60–180

where $G_{F\dot{q}}$ is the cross-spectral density of the force F and velocity $\dot{q}$, and $G_{\dot{q}\dot{q}}$ is the power spectral density of the velocity.

The studies have employed sinusoidal excitations of magnitudes ranging from 8 to 53 mm/s velocity to 34.3 m/s^2 rms acceleration; the largest magnitude of random excitation was limited to 12 m/s^2. A 10-N force excitation has also been used in another study.[174] The magnitude of the grip force in the studies ranged from 0 to 186 N. The studies also involved varying numbers of human subjects, ranging from 1 to 75 male adults with elbow angles varying from 60 to 180°.[22] Such variations in the test conditions are most likely attributed to the lack of generally accepted characteristics of HTV.

The differences among the biodynamic response data have been further attributed to the potential dependence of the biodynamic response on various contributory factors, such as grip and feed forces, hand and arm postures, anthropometric parameters or individual differences, and the inherent nonlinear dynamic properties of the biological materials. Because of the extensive variations in the test conditions and discrepancies among the data, Gurram et al.[22] performed a synthesis of selected datasets based upon criteria considered representative of the most common range of test conditions. These included the range of 20–500 Hz, grip forces in the 25- to 50-N range, and elbow angles close to 90°. Although performed on the basis of selected datasets for similar test conditions by various investigators,[20,23,29,31,68,70,134,144] the synthesis still revealed considerable differences, especially among the phase responses. Certain similarities and general tendencies, however, were clearly observed. This enabled identification of the most probable ranges of the to-the-hand biodynamic response of the human hand-arm under a selected range of test conditions. On the basis of this synthesis, the ranges of free mechanical impedance of the hand-arm system at its driving point have been standardized in ISO-10068.[145]

Although the majority of the studies have employed widely varied test conditions, the data clearly emphasize the considerable contributions caused by many intrinsic and extrinsic factors. The review of such studies has provided an understanding of the effects of different contributory factors in a qualitative sense, although the contributions caused by various factors have not been investigated in a single study under carefully controlled test conditions. However, based on the data reported, the major contributory factors can be classified into two broad categories: (1) the nature of vibration excitations employed in the test considered to represent the range of HTV; and (2) the biodynamic variables employed considered to represent the range of working conditions. The first category includes the type (sinusoidal, random, pseudo-random, or impulsive), frequency, and magnitude of vibration excitation. The biodynamic variables include the direction of vibration, the grip and feed forces, the posture, and the anthropometric variables.

Despite the significant variances in test conditions used by investigators, all the studies have invariably demonstrated the strong dependence of the to-the-hand biodynamic response on the frequency and direction of vibration. The DPMI is therefore always expressed as a function of these two variables.[17,145] These studies have also concluded that excitation amplitude has little effect on biodynamic response.

The magnitude of DPMI of the hand-arm system, however, decreases slightly with an increase in the vibration amplitude.[29,68]

The type of vibration excitation (e.g., discrete frequency sinusoid, combination of several sinusoid, or random) may also influence the DMPI response of the human hand and arm. However, there have been relatively few studies to quantify such effects. Based on the DPMI response of 4 male subjects under both sinusoidal and random excitations, one study concluded that the biodynamic response of the hand-arm system differs under different types of vibration, especially at frequencies above 200 Hz.[60] The study performed by Kihlberg[139] under impulsive and harmonic excitations, on the other hand, did not show a significant influence of these types of vibration excitation on the DPMI, dissipated energy, or transfer function of the hand-arm. Such incongruous conclusions suggest the need for further systematic investigations into the effects of types of vibration on DPMI.

Only a few studies have investigated the contributions caused by variations in the feed force.[88,69] The results of these studies show the magnitude of feed force to have little effect on the DPMI at frequencies above 100 Hz, and less than 10% variation in DPMI magnitude in the 20- to 70-Hz range. A number of studies have reported a strong influence of hand-grip force on DPMI magnitude, while its quantitative contribution is not yet established. Because of the wide variations in test conditions employed in studies, the effect of variation in the grip force could be quantified only through analysis of the data in a single study that examined different magnitudes of grip force. Based on the limited data reported by Burström,[68] Lundström,[31] and Mishoe and Suggs,[20] a methodology has been proposed to quantify the effect of variations in the grip force.[22] In general, the DPMI magnitude tends to increase with increase in magnitude of the grip force, particularly at frequencies above 50 Hz.[145]

2. Discussion and Potential Topics for Further Study

From the above, it can be concluded that the to-the-hand biodynamic response of the hand-arm system, expressed as DPMI, is strongly affected by the frequency and direction of vibration and the grip force, although more data are required to quantify the effects of grip force. Furthermore, insufficient data are available to quantify the effects of other contributory factors, such as posture and the anthropometric variables. Considering the important differences among the data, it is also essential to perform future studies of hand postures and excitations that represent the HTV encountered in the workplace. The range of idealized values of the biodynamic response of the hand-arm system, established in ISO-10068 (1998),[145] represents a synthesis of the widely varying datasets. The range of DPMI data, therefore, appears as a wide envelope of magnitude and phase values within ISO-10068. Peak variations in the impedance magnitude about the mean are as high as 69, 69, and 63%, respectively, for the X_h, Y_h, and Z_h directions. Even larger variations observed in the impedance phase values are presented in ISO-10068.[145]

Furthermore, the maximum frequency of the standardized data in ISO-10068 is only 500 Hz, which may be considered too low in view of the characteristics of HTV and the upper limits considered in other pertinent ISO documents.

The reported variations in the future studies of magnitude and phase response of the hand-arm system could be considerably reduced through the application of consistent and generally accepted test conditions involving a broad frequency range. ISO-10068 (1998)[145] does not address the role of various contributory factors, such as grip force, feed force, hand posture, shoulder abduction, elbow angle, reaction torque, handle geometry, and individual differences. This absence is attributed to the lack of available data and the inconsistent test conditions employed by different investigators. Furthermore, because nearly all extant studies (with few exceptions) have considered only male subjects, further studies should also be undertaken to study the biodynamic responses of the hand-arm system of the female worker.

Although the reported studies have provided considerable insight into the global biodynamic behavior of the hand-arm system measured at the driving point, the individual modes of vibration and their relative participation could be vaguely defined from the measured data. Further studies into the characterization of global as well as localized to-the-hand biodynamic responses are therefore extremely vital. Only a few investigators have studied the response behavior of the skin and individual fingers in an attempt to identify the predominant modes of vibration. Lundström[109] studied the point impedance of glabrous skin over the 20- to 10,000-Hz range by applying a vibratory probe to 10 points on the fingers and the palm. The results indicated that the resonance of the skin at these points occurs in the 80- to 200-Hz range depending on the part of the skin exposed to point excitation. Above 100 Hz, the impedance of the skin measured at the test points revealed some similarities to the impedance of the entire hand-arm system. Calado[146] studied the dynamic response of the finger using both experimental and modeling approaches. The study concluded that finger bending about the distal, medial, and proximal joints was responsible for successively lowering the frequency of vibration modes of the finger, and the flesh at the contact point was responsible for the high-frequency vibration modes. Mann and Griffin[147] also investigated the influence of various physical factors on the point mechanical impedance measured at the palmar surface of the finger. The results showed that the transmission of vibration to the fingers is highly dependent on the magnitude of the contact force. The contact area, individual differences, and finger flexing further influence the point mechanical impedance.

The study of localized vibration behavior of the hand-arm system poses numerous challenges because of the lack of appropriate measurement systems and methodology. Mann and Gtiffin[147] investigated the effects of additional mass placed on the fingernail, such as that caused by a measurement system, on the hand-handle coupling effects. The results suggested that the addition of a mass of 0.5 g or more to the fingernail would considerably alter the coupling between the fingers and the source of vibration. In view of these findings, it is believed that the scanning laser vibrometers offer an effective alternative for studying modes of vibration of the skin, fingers, and the hand, although no attempts have yet been made.

D. To-the-Hand Biodynamic Response: Absorption of Vibration Energy

The to-the-hand biodynamic response behavior of the human hand-arm system has also been expressed as the absorbed energy, which is similar to the DPMI. The magnitude of energy per unit time to which the hand and arm system is exposed (the power associated with HTV) is estimated directly from the force transmitted to the hand and the velocity at the driving point. The measure of absorbed energy can thus be expressed as the "to-the-hand" biodynamic response. The vibration energy at the driving point is computed from the parameters used in calculating the DMPI, as described in Eq. (2). The energy absorbed by the human hand can also be related to the DPMI in the following manner:

$$P = \mathrm{Re}[Z(j\omega)]\dot{q}^2 \tag{4}$$

where P is the complex rate of energy transmission or power and Re refers to the real component of the complex impedance function $Z(j\omega)$. The real component of the complex power relates to the energy absorbed by the hand-arm system and the imaginary component relates to the energy stored within the system.[148] The average transferred energy is thus expressed in the frequency domain within the cross-spectrum.[143] Similar to the DPMI, the absorbed energy is strongly influenced by the intensity, frequency and direction of the vibration, and contributory factors such as grip force, feed force, posture, and individual factors.

Although similar to DPMI, the vibration energy absorbed in the human hand and arm has been claimed to provide a good correlation with vibration-induced injuries or HAVS. Some investigators have suggested that the energy absorption in the hand would serve as a better measure of potential vibration injury than the currently used vibration acceleration measure.[149–151] Within a related context, a reasonably good correlation between the energy absorbed by the body exposed to the whole-body type of vibration and the subjective sensation of comfort has been reported by Pradko et al.[152] The epidemiological study conducted by Lidström[149] showed that the prevalence of VWF was related to the energy transmitted to the hand-arm system. A study conducted by Reynolds and Angevine[85] suggested the existence of a correlation between the subjective annoyance data and energy absorption in the hand and arm.

The energy-absorption approach may offer many advantages over the use of DPMI or vibration acceleration. The energy method can effectively account for contributions caused by various intrinsic and extrinsic factors, such as the grip and feed forces, hand-arm postures, and individual differences; the measure of power is derived from the vibratory force measured at the hand-tool interface during tool operation. This is an important advantage: Hand forces are known to vary considerably as a function of the amplitude of acceleration owing to increased muscle contraction and tonic vibration reflex.[87,153]

A recent study[154] on the relationship between the vibration dosage and the absorption of mechanical power in the hand has emphasized the significant role of vibration-free interruptions or rest periods during a vibration-exposure cycle, which is inadequately dealt with in ISO-5349.[10] The draft standard, ISO/DIS-5349-1,[11] requires that assessments be based upon typical work patterns. The power absorption decreases with the rest periods, and it increases with higher acceleration levels. The assessments of vibration-exposure or vibration-dose values are primarily based upon the daily exposure. One of the major difficulties in assessing the daily vibration dosage is the lack of available objective data that could help evaluate the effects of daily exposure time, rest periods, and intermittent tool usage. It has been suggested[154] that the energy-absorption approach could effectively account for the number and lengths of rest periods in estimating vibration doses. The results of the above studies suggest that the measurement of the transmitted-vibration energy may serve as an effective method for assessing HAV.

The majority of the reported studies on the basic characteristics of energy transmission have been carried out in the laboratory.[20,68,155,156] Since energy transmission relates to the to-the-hand response, the measurement systems required in such studies are identical to those for measuring DPMI. Laboratory studies have generally concluded that energy transmission is strongly affected by the vibration frequency and direction, as established by the studies on DPMI.[37,157.158] Energy transmission in the high-frequency range is further affected by the intensity of vibration and the magnitude of the hand-grip force. The contributions resulting from the posture of the hand and arm to energy transmission have also been described in these studies.

Sörensson and Burström[37] investigated the energy absorption among male and female human subjects exposed to HTV in the range of 20–5,000 Hz and concluded that nearly half the energy absorption is associated with vibration above 1,000 Hz. A comparison of the absorbed energy under different types of excitations revealed that the energy absorption under impulsive (shock) excitations is approximately 10% higher than that attained under nonimpulsive vibration excitations. These results suggest that exposure to impulsive or shock-type motions, such as those encountered in operating percussive tools, may pose increased risk of vibration injuries. Such differences in the absorbed energy were observed to be even higher under excitations representative of percussive and nonpercussive tools.[156] These studies also reported the influence of grip force on energy absorption. A gradual reduction in grip force may not reduce energy absorption, but it may cause the slightly higher energy absorption that is most likely associated with increased peripheral circulation and, thus, higher viscous effects and grip damping.[159] The study further revealed notable gender effects on the absorbed energy and concluded that females show consistently lower absorbed energy over almost the entire frequency range. These effects were largely attributed to physiological differences including age, weight, height, hand size, hand volume, and blood pressure.[37,158]

Although the assessment method based upon power absorption has been proposed for more than 30 years, very few epidemiological studies have been performed to demonstrate its correlation with HAVS. Additional epidemiological studies are required to examine the hypothesis adequately and to provide sufficient data for establishing the dose-response relationship. The use of the energy-absorption method may be further limited owing to the lack of suitable measurement systems for field investigations; specifically, the lack of suitable dynamic-force measurement systems that can be applied to various hand-held power tools. Burström and Lundström[160] designed an instrumented tool-handle adapter to overcome this difficulty. The adapter is equipped with a triaxial piezoelectric force transducer and a triaxial piezoelectric accelerometer. The adapter has been used in field measurement studies and the results have been reported as encouraging.[161] While the adapter offers considerable potential to conveniently measure the hand-dynamic force and acceleration, its effectiveness needs to be evaluated through additional experiments and experience. The potential for field applications of the adapter may be further enhanced through the use of microsensors. The thin and flexible film pressure-sensing grids also offer an attractive alternative for measuring vibratory hand forces in the field. The application of such pressure sensors, however, would require systematic fundamental studies into the relationships among the hand-contact force, integration of the pressure distributed over the contact area, and the feed and grip forces.

Alternatively, the energy absorption may be indirectly derived from the DPMI using Eq. (4). In this method, the DPMI function $Z(j\omega)$ is obtained from the laboratory tests, as discussed in the preceding section. The estimation of power absorption of a given tool in the field thus requires field measurement of the velocity at the hand-handle interface. Owing to the simplicity of such an indirect approach, many investigators have conducted field assessments using this method.[20,23,144,162,163] Many concerns, however, have been raised on the validity of the method. These concerns derive primarily from questions regarding the general applicability of the laboratory-measured DPMI and its dependence upon many intrinsic and extrinsic variables, as discussed in the previous section.[3] The DPMI characteristics of the human hand-arm have been invariably measured in the laboratory under constant levels of grip and feed forces, vibration levels, and specified postures. The generalizability of such laboratory-measured DPMI characteristics may be questioned because the selected laboratory-test conditions differ considerably from those encountered in the field where pertinent factors vary continuously. The estimation of absorbed power, derived from Eq. (4), may also cause various errors owing to the associated assumption that the human hand and arm can be treated as a linear dynamic system, an assumption that is at odds with many studies that have recognized its nonlinear behavior.[164]

1. Discussion and Potential Topics for Further Study

The validity of the indirect method of estimating the energy absorption has been examined in a laboratory study conducted by Burström.[165] The measured vibration spectra of 5 different hand-held power tools in each of the three orthogonal directions were replicated in the laboratory with a vibration exciter. Measurements were obtained to derive the absorbed energy using both direct and indirect methods. From the comparison of the results, it was concluded that the effectiveness of the indirect method relies upon the validity of the impedance data. The impedance data measured under random excitations resulted in considerably better correlations between the direct and indirect techniques than that which could be obtained with the impedance data derived under sinusoidal excitations. Because of the simplicity of the indirect method and the considerable influence of various contributory factors on DPMI, further investigations into the effectiveness of the indirect method of estimating energy absorption in field applications are extremely desirable.

As stated earlier, the energy absorption in the hand and arm is estimated from the total force transmitted to the hand measured at the driving point and the driving-point velocity, and the contributions of vibration modes associated with different segments are ignored. It is believed that the segmental vibration modes may cause variations in the absorbed energy depending upon the measurement location. The resulting total vibratory energy transmitted to the hand, derived on the basis of driving-point measurements alone, may not sufficiently reflect vibration-exposure conditions. A better estimate of vibration exposure or dosage may be realized upon consideration of the distribution patterns of the energy at the interface. It is, perhaps, reasonable to assume that the local contact pressure determines the transmission of vibration energy at a particular location, even though the exact form of the local pressure has not yet been critically examined. Moreover, the product of the oscillatory contact pressure and velocity can be related to the power absorption normalized with respect to the local contact area. This normalized absorbed power may thus be used to describe the localized energy flow density, given by

$$\bar{P} = p \cdot \dot{q} \tag{5}$$

where $\bar{P}$ is the rate of energy flow density, which describes the local vibration energy flow. The variables p and $\dot{q}$ are local contact pressure and velocity, respectively. The measurement of the local vibration energy may provide considerable insight into both the effects of transmitted vibration at a particular contact location and potential injury mechanisms. Integrating the local vibration energy over the contact area may yield a better correlation with the vibration exposure. The measurement of the local grip force and the vibratory pressure is currently being attempted using a single-button flexible sensor.[166] The proposed system, if successful, could be effectively applied in field investigations.

Sörensson and Burström[167] extended the basic concept of energy transmission at the driving point to study the energy absorption at different locations of the hand and arm, specifically, the knuckle, wrist, and elbow. Assuming constant grip- and feed-forces, the velocities at various locations were measured to estimate the energy transmission at different locations. Since the actual forces transmitted to various locations are expected to differ from the force at the driving point in terms of the magnitude and phase, the computed energy values may not truly describe the energy absorption at different locations. Further studies are thus vital to explore the potential applications and implications of such an energy-absorption concept.

IV. BIODYNAMIC MODELING OF THE HUMAN HAND-ARM SYSTEM

The vibration-transmission of power tools and vibration-attenuation mechanisms are investigated in both the laboratory and the field. Owing to the complex nature of the tool vibration and coupled hand-tool system dynamics, such assessment methodologies, require repetitive measurements involving representative human-subject samples and test conditions. Such measurement-based methodologies are also known to pose considerable complexities in the data analysis because of their inter- and intrasubject variabilities. Alternatively, biodynamic models of the hand and arm have been proposed to characterize the vibration amplitude and power flow in the coupled hand, tool, and workpiece system; to analyze the potential performance benefits of vibration-attenuation mechanisms; and to develop test rigs and hand-arm simulators to assess the vibration transmission of different tools.[21,36,131,168]

The majority of the reported models are mechanical models that comprise lumped mass, stiffness, and damping elements in which the lumped parameter values are identified upon the curve fitting of the measured data. A number of biodynamic models, from simple single-degree-of-freedom (DOF) to many-DOF, have been developed to characterize the to-the-hand biodynamic response in terms of DPMI or dynamic stiffness, and through-the-hand-arm biodynamic response in terms of the vibration transmissibility of the hand. These models provide little insight into the pathological changes caused by HTV, but they have served as effective tools to study the effects of direction and magnitude of vibration on HTV.[23,117] Although the majority of the models are derived to characterize the biodynamic response of the entire hand-arm system, only a few models focus on the biodynamic response of the fingers alone.[146,169] The HAV models, invariably, comprise linear and time-invariant inertial, restoring, and dissipative elements such that convenient linear analytical methods may be implemented. The models, therefore, do not adequately represent the biomechanical properties of the human hand and arm.[145] Furthermore, the models characterize the uncoupled biodynamic behavior of the hand and arm along the three independent orthogonal axis of vibration. All the models thus neglect the dynamic coupling effects of the hand and arm.

A. HAV Models Based on To-the-Hand Biodynamic Response

The majority of reported biodynamic models have been developed to characterize the to-the-hand biodynamic response of the hand and arm either in the form of DPMI or dynamic stiffness. These models may be classified into two broad groups based on their structure: lumped-parameter and distributed-parameter models. The lumped parameter models, in general, do not relate to the anatomical or physiological representation of the hand-arm system (although some investigators have suggested a few vague relationships), whereas the structure of distributed-parameter models is derived from the anatomy. A distributed-parameter model of the hand and forearm was proposed by Wood and Suggs,[170] in which the forearm is modeled by 2 parallel, uniform beams representing the radius and ulna bones, as shown in Figure 6a. The distributed viscous damping used in the model represents the soft tissues along the arm. The hand was considered as two lumped masses coupled through the 2 beams. An additional beam representing the upper arm was introduced to realize the total hand-arm model, as shown in Figure 6b. The model parameters are identified upon curve fitting of the measured DPMI data using trial-and-error. The dual-beam forearm model resulted in a reasonably good correlation with the measured DPMI, but relatively poor agreement was achieved with the total hand-arm model. The authors indicated that a more detailed hand model would be required to obtain better agreement with the measured data, especially at higher vibration frequencies.

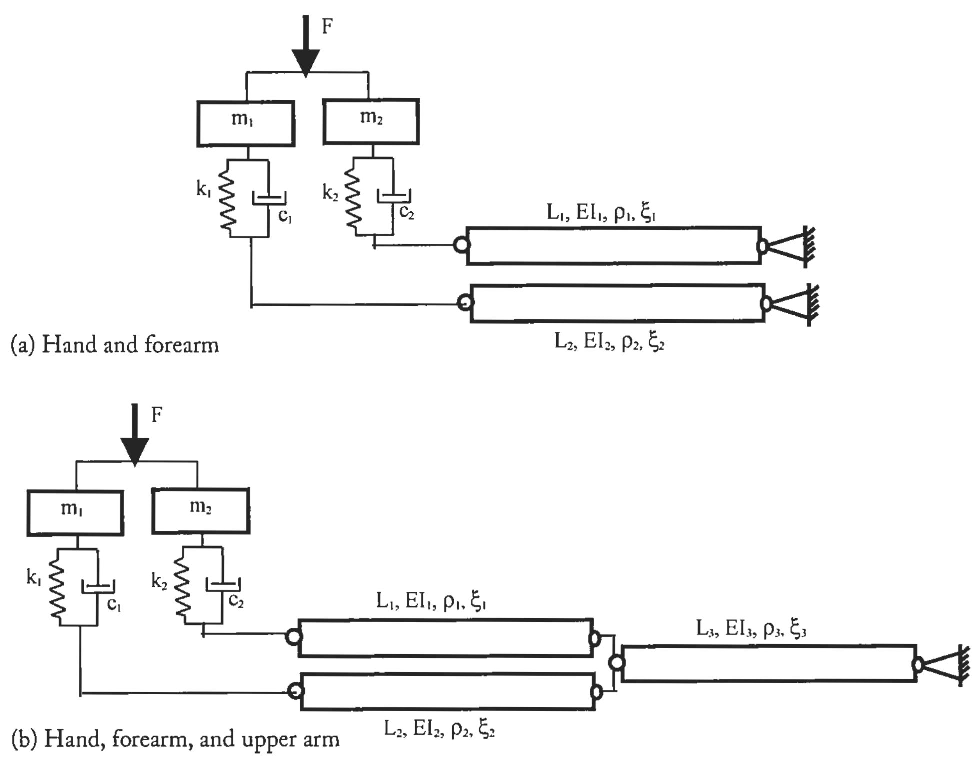

FIGURE 6. Schematics of the distributed-parameter models of the human hand and arm (from Ref. 170).

All the reported biodynamic models, with the exception of that reported by Woods and Suggs,[170] are the lumped-parameter type. These models can be further represented in 3 subgroups based upon the properties of the lumped elements. The first subgroup comprises the models developed on the basis of linear stiffness and damping elements, assuming negligible influence of grip force and vibration intensity on the viscoelastic properties of the hand and arm. These include (a) the single-DOF models, reported by Dieckmann,[171] Reynolds and Soedel,[172] and Abrams and Suggs[86]; (b) 2-DOF models proposed by Miwa et al.[173] and Mishoe and Suggs[20]; and (c) 3-DOF models proposed by Reynolds,[85] Meltzer,[174] Mishoe and Suggs,[20] Daikoku and Ishikawa,[133] and Gurram[29]; and (d) 4-DOF models developed by Reynolds and Falkenberg[23] and Gurram.[29] The second subgroup of models comprises linear, but grip-force dependent, parameters to characterize the grip-force dependence of the biodynamic response. The 2-, 3- and 4-DOF grip force-dependent models proposed by Mishoe and Suggs,[20] and Gurram[29] would fall within this subgroup. The third subgroup comprises 3- and 4-DOF nonlinear lumped-parameter models used to characterize the nonlinear biodynamic behavior of the hand and arm. Figure 7 illustrates the structure of some of the reported models. The human hand and arm is a continuous system, and a higher-order model is thus expected to yield improved accuracy with relatively more complexities associated with the analytical solutions.

The parameters of the lumped-parameter models along each independent axis are characteristically derived from the measured to-the-hand biodynamic response using curve-fitting techniques. Such methods may yield some errors when a broad frequency range is considered. Alternatively, multiparameter, nonlinear programming-based optimization techniques have been used to identify the model parameters by minimizing a weighted error function of the DPMI magnitude and phase response.[175] However, the linear lumped-parameters within the first subgroup of models do not yield the contributions caused by variations in vibration intensity and grip force. The proposed models can thus be considered valid in the vicinity of the selected magnitudes of vibration excitation and grip force. Based on the measured biodynamic response, many studies have concluded that the hand-arm system exhibits nonlinear biodynamic behavior, and that the DPMI is strongly affected by many factors, such as frequency, coupling force, vibration magnitude, direction of vibration, and posture.[18,20,23] Although the effects of vibration direction and frequency have been adequately described, the quantitative effects of grip force on the biodynamic response have been only vaguely defined. No attempts have been made to quantify the effects of other contributory factors.

Mishoe and Suggs[20] proposed 2-DOF models for X_h and Y_h axis vibration, and a 3-DOF model for the Z_h axis vibration to characterize the DPMI under different magnitudes of the grip force. The study yielded different model parameters for three different constant values of the grip force. The proposed models could thus be considered valid in the vicinity of selected magnitudes of grip force (13, 27, and 40 N). Gurram[29] proposed 3- and 4-DOF models with parameters as continuous functions of the grip force to characterize the biodynamic response of the hand and arm

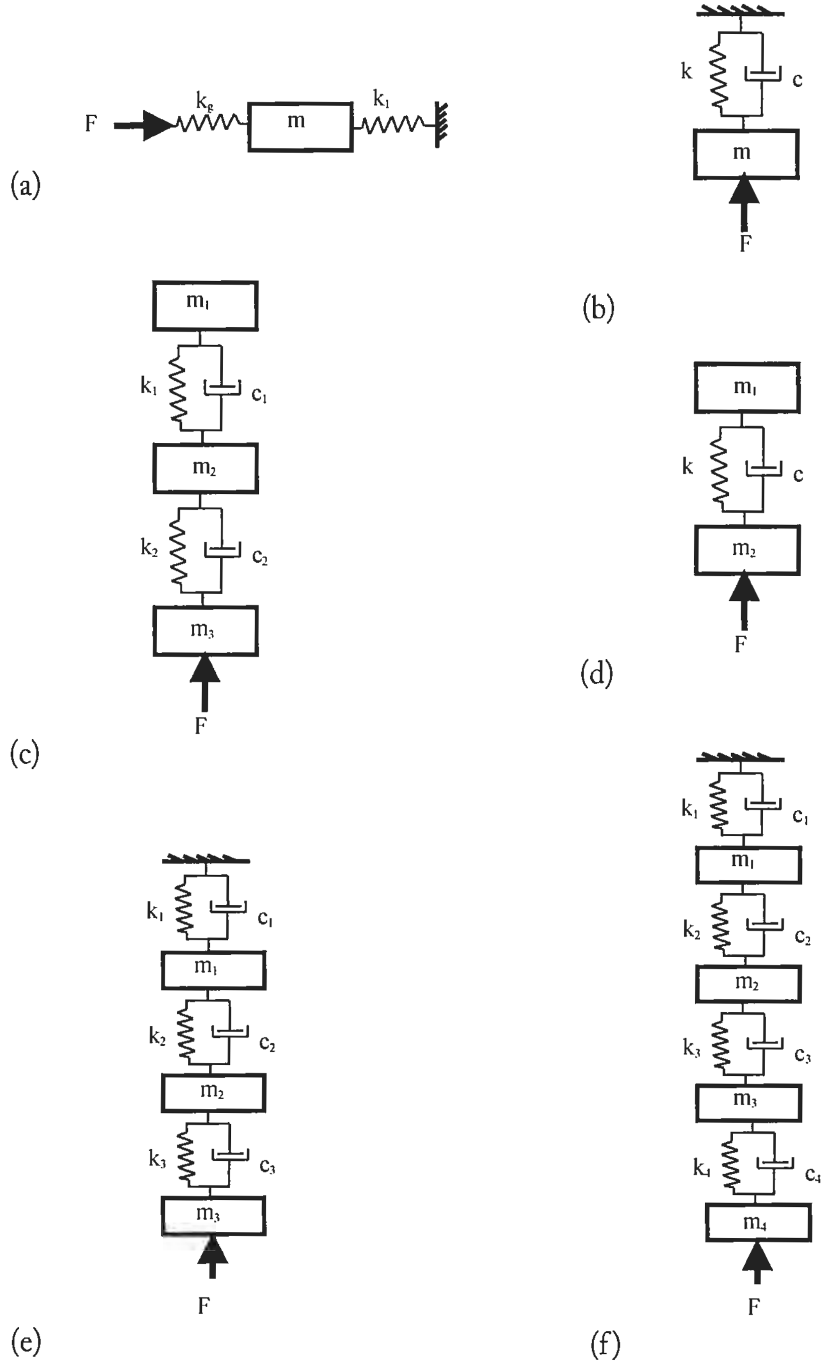

FIGURE 7. Lumped-parameter biodynamic models of the human hand and arm (a) from Ref. 171; (b) from Refs. 86, 172; (c) from Ref. 20; (d) from Ref. 173; (e) from Refs. 20, 29, 85, 133,174; (f) from Refs. 29, 85.

over a wide range of the grip force. The stiffness and damping parameters of the models were expressed as linear functions of the grip force, and the parameters were identified from the DPMI data acquired under different magnitudes of grip force. The model results showed reasonably good correlation with the data acquired under grip forces ranging from 10 to 50 N. Gurram[29] further proposed 3- and 4-DOF lumped-parameter models with nonlinear stiffness and damping elements to account for the effects of grip force and vibration intensity. The proposed models were developed using progressively increasing stiffness and damping properties with increasing grip force and vibration intensity. The nonlinear models of the hand-arm were analyzed using a local equivalent linearization algorithm for a wide range of grip force and vibration magnitudes.[175] These studies also recognized that the identified model parameters do not represent a unique solution, and it is possible to realize a vast number of model parameter sets that would equally satisfy the error criterion. The total mass considered in the model was thus constrained to lie within the range of mean values of the hand-arm system to enhance the uniqueness of the derived biodynamic models[29,176] The results showed that the proposed nonlinear models yield better agreement with the measured DPMI data over the range of grip force considered.

B. HAV Models Based upon Through-the-Hand-Arm Biodynamic Response

Few investigators have proposed HAV models to study (1) the vibration transmissibility of the hand while the subject is wearing protective or antivibration gloves, and (2) the characteristics of vibration transmitted to different locations on the hand and arm. Such models offer considerable potential for evaluations of vibration-attenuation mechanisms. The HAV models based on the to-the-hand biodynamic response cannot be applied to studying the vibration-transmission characteristics of the hand and arm because the models do not relate to the anatomical structure. Gurram et al.[96] and Griffin et al.[88] proposed linear lumped-parameter models of the hand and arm to characterize vibration transmissibility of the human hand and to assess the vibration-attenuation performance of various gloves or glovelike materials. The model parameters of the 2-DOF HAV models were identified from the laboratory-measured vibration transmissibility of the hand and arm; the model structure did not relate to the anatomical structure.

Fritz[177] proposed a 3-DOF biomechanical model to study the vibration transmitted to different locations on the hand and arm. The model, as shown in Figure 8a, consists of 4 masses coupled through damped springs; the first 2 masses represent the hand and the palmar tissues, and masses m_3 and m_4 represent the forearm and upper arm, respectively. Damped torsional springs are introduced between the masses and the shoulder support. Cherian[24] proposed a similar 5-DOF biomechanical model, as shown in Figure 8b, to study the vibration transmitted to different locations and to explore the performance potential of a vibration-attenuation concept based

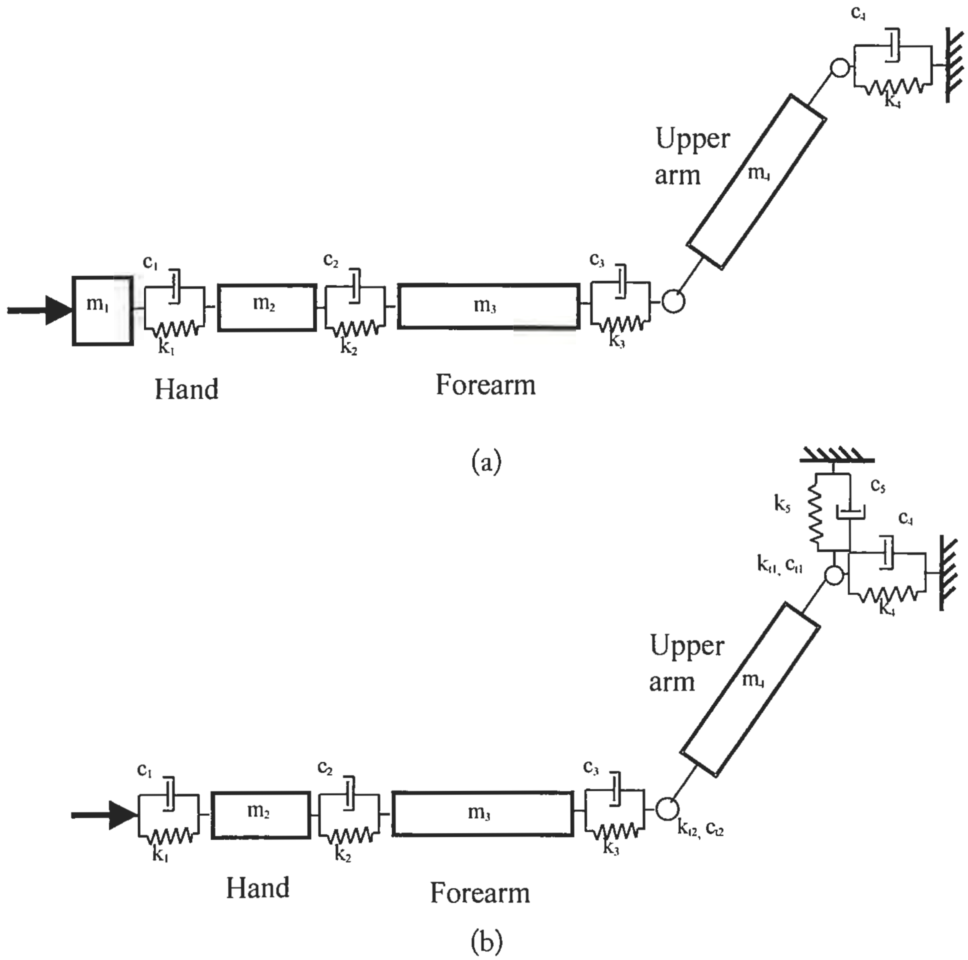

FIGURE 8. Schematics of the biomechanical models of the human hand and arm (from Refs. 24, 177).

on splitting the vibration-energy flow. In this model, the masses caused by the hand and forearm are constrained to translate along the Z_h axis, while the upper-arm mass experiences motions along the vertical, longitudinal, and pitch axes. The different masses and dimensions of the model are taken from the anthropometric data for a 70-kg subject. A comparison of the model response with the laboratory-measured acceleration data at the wrist, elbow joint, and upper arm revealed reasonably good agreement under Z_h-axis harmonic excitations. The model was further used to study the modal behavior of the hand and arm.[178] The results of the complex modal analysis revealed resonant frequencies near 11.2, 25.8, 82, and 105 Hz with damping ratios ranging from 0.24 to 0.92. The modal analysis also revealed relatively large motions of the hand mass and the shoulder support near the resonant frequency of

82 Hz. It was thus concluded that the hand experiences considerably larger vibration near this frequency.

The reported HAV models can serve as useful tools to predict the biodynamic response and vibration transmission of the hand and arm under certain ranges of excitation and test conditions. The models can be further applied to study the dynamic behavior of the coupled hand-tool system and to assess the performance potential of vibration-attenuation mechanisms.[21,179] The biodynamic models have also been used to realize mechanical equivalents of the hand that, when coupled with the tool, could serve as an efficient means of accomplishing relative assessments of various power tools.[168] The effectiveness and validity of the models over a wide range of operating conditions, however, need to be explored through further laboratory and field measurements, and model refinements. The reported models also need to be enhanced to help understand the vibration-transmission and energy-absorption behavior of different segments of the hand and arm. An anatomically analogous model of the hand and arm incorporating the rotational degrees-of-freedom and coupling effects would be highly desirable for studying the characteristics of the transmitted vibration and, possibly, the injury mechanisms. The development of such a model, however, would require considerable efforts to identify the distributed-parameters for the hand and arm, to properly accommodate anthropometric considerations to represent operating conditions encountered in the field, and to develop detailed models of the arteries, tissues, and so forth. The advances in finite element (FE) techniques could facilitate the analysis of models involving complex geometry, boundary conditions, and nonlinear material properties. Such a model could be effectively used to study the local dynamic behavior in terms of local strains and stresses in bending, shear, and torsion that go well beyond current capabilities. The FE-based biomechanical models could further provide significant insight into the impact of HTV upon arterial blood flow and possible occlusions as well as better understanding of the local concentration of stresses within different anatomical components.

V. SUMMARY

The biodynamic-response behavior of the human hand-arm to HTV and its relationship with HAVS is critically reviewed and discussed to highlight the advances and the needs for further research. Considering the strong dependence of the biodynamic response of the human hand and arm on the nature of HTV, the reported studies are first reviewed to enhance understanding of the characteristics of HTV and the related issues. The major highlights of this critical review, together with the essential directions for future research, are summarized below.

1. The biodynamic response of the human hand and arm to HTV forms an essential basis for effective measurements, evaluations of vibration exposure, vibration-attenuation mechanisms, and potential injury mechanisms. Although many investigators have reported the biodynamic response of the hand-arm system,

the data are far from sufficient for general application. This restriction is mostly attributed to the complexities associated with the human hand and arm, the lack of standardized measurement and reporting methods, and the lack of generally accepted characteristics of HTV. Significant differences are thus observed among the data. Further investigations on the biodynamics of hand-arm system, specifically under field-representative conditions, are therefore vital to improve existing standards and to develop new standards, prevention methods, and devices.

2. Numerous factors determine or influence the transmission of tool vibration into the hand and arm. Many of them have not been sufficiently understood to incorporate into standard methods. The factors that require more study include grip and feed forces, posture, interindividual differences in anthropometry, mass, and strength, and vibration intensity. In addition, the lack of satisfactory methods for measuring contact forces (e.g., the grip and feed forces for typical tools) necessitates further development and standardization.
3. To-the-hand biodynamic measures describe the response behavior of the total hand-arm system measured at the driving point. The nature of localized vibration transmitted to different locations on the hand and arm as well as the biodynamic behavior of different segments is perhaps most vital to the study of vibration-induced injuries and their prevention. Only a few investigators have studied the vibration transmitted to different locations of the hand-arm system in the 5- to 1250-Hz range. Additional systematic studies are necessary to increase an understanding of the local propagation and transmission of vibration under high frequencies. Determining the relationship between hand-grip pressure distribution and vibration transmission and power absorption in general grasping conditions could provide significant insight into vibration dosage and potential injuries. The influence of localized pressure distribution on finger blood flow and possible arterial occlusion may provide further insight into the mechanisms leading to VWF. Studies have been unable to quantify the natural frequencies and amplification or attenuation tendencies of the fingers, hand, and arm owing to the extreme variations in test conditions and the challenges of measurement techniques. Scanning laser vibrometers may help determine the vibration-propagation mechanism and the natural frequencies of different segments. The advances in pressure-measurement technologies may provide a potential approach for obtaining dynamic and high-resolution measurements of finger- and hand-pressure distribution while operating typical tools. Such capabilities may enable the determination of power absorption on the basis of localized forces.
4. The measurement of vibration energy absorbed by the hand and arm may offer a superior means of assessing vibration exposure and is believed to show better correlations with vibration-induced injuries and HAVS. Although standardization efforts have evolved into the range of DPMI of the human hand-arm, only limited efforts have been made to validate and explore the potential of absorbed-energy-based methods. The range of DPMI has been applied for designing and ing tools and for developing mechanical simulators of the human

hand and arm. Its application for estimating vibration energy transmission on real tools has realized some success. Continued efforts are required to develop this alternative approach for measuring absorbed-vibration energy. The range of DPMI proposed in the standard is a relatively wide envelope and is limited to frequencies up to 500 Hz. Further studies may provide more precise impedance data; however, it should not be assumed that a single set of impedance data would apply to all individuals or over all working conditions. More test data also are needed to study gender effects and to include the biodynamic response of female workers within ISO-10068. Finger-transmitted vibration is apt to be considerably important in developing vascular disorders of the finger, but further studies of the underlying pathomechanics are needed. The application of the energy concept to vibration exposure is greatly impeded by the complexities associated with measuring dynamic force at the hand-tool interface, particularly, in field applications. Further efforts are thus necessary to develop reliable devices for real-world applications.

5. Computer modeling of HAV has been conducted to simulate the measured to-the-hand and through-the-hand-arm biodynamic response to specific vibration excitations and operating conditions. These models can be considered valid only in the vicinity of the selected test conditions. The effect of various contributory factors and stressors imposed on different segments of the hand and arm cannot be assessed using these models. The need exists for developing high-density, anatomically analogous models of the hand-arm system. Finite-element (FE) techniques offer considerable potential for developing and analyzing such models, which would allow the study of localized stresses as well as the detailed characteristics of the transmission of vibration.
6. The ability of gloves to mitigate vibration has not been well demonstrated in the scientific literature. The standard glove test and evaluation methods at the palm of the hand are in need of improvements regarding the instrumented handle, the palm-held adapter, vibration spectra, test procedures, and evaluation methodology. The evaluation of effectiveness of gloves in attenuating the vibration transmitted at the fingers may require a different test method.

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