Industrial Health 2005, **43**, 449–471

Review Article

Recent Advances in Biodynamics of Human Hand-Arm System

Ren G. DONG*, John Z. WU and Daniel E. WELCOME

Engineering & Control Technology Branch, National Institute for Occupational Safety and Health, 1095 Willowdale Road, Morgantown, West Virginia 26505, USA

Received January 27, 2005 and accepted April 14, 2005

Abstract: The biodynamics of human hand-arm system is one of the most important foundations for the measurement, evaluation, and risk assessment of hand-transmitted vibration (HTV) exposure. This paper presents a new conceptual model relating factors influencing cause-effect relationships for HTV exposure, a new study strategy, and a comprehensive review of the recent advances in the biodynamics closely associated with HTV exposure. The review covers the following five aspects: theoretical modeling of biodynamic responses, vibration transmissibility, driving-point biodynamic responses, evaluation of anti-vibration gloves, and applied forces. This review finds that some significant advances in each of these aspects have been achieved in the recent years. Several important issues and problems in the biodynamic measurement have been identified and resolved, which has significantly helped improve the reliability and accuracy of the experimental data. The results reported in recent years suggest that, from the point of view of biodynamics, the frequency weighting specified in ISO 5349-1 (2001) overestimates the low frequency effect but underestimates the high frequency effect on the fingers and hand. The major problems, issues, and topics for further studies are also outlined in this paper. It is anticipated that the further studies of the biodynamics of the system will eventually lead to establishment of a robust vibration exposure theory. Although this review focuses on the biodynamics of the hand-arm system, the fundamental concepts and some methodologies reviewed in this paper may also be applicable for the study of whole-body vibration exposure.

Key words: Hand-transmitted vibration, Hand-arm vibration, Hand-arm vibration syndrome, Biodynamics of hand-arm vibration, Whole-body vibration

Introduction

The biodynamics of human hand-arm system is a branch of biomechanics that applies laws of physics and engineering concepts to describe the motions and forces on the system, as well as their relationships. While a general review of the hand-arm system biodynamics closely related to hand-transmitted vibration (HTV) exposure was reported a few years ago[1)], this review focuses on the recent advances in this area.

The theoretical foundations for the future developments and standardizations of the measurement, evaluation, and assessment of HTV exposure can be classified into the following four groups[2)]: (i) biodynamics of hand-arm system; (ii) psycho-physics studies of subjective perception or discomfort; (iii) physiological and pathological mechanisms of the vibration-induced injuries and disorders; and (iv) epidemiological studies of hand-arm vibration syndrome (HAVS). Whereas the first foundation addresses the issues related to vibration stimuli input to the system and acting

*To whom correspondence should be addressed.

on the tissues and cells, the other three foundations focus on the effects or outputs of the vibration stimulation. This relationship suggests that biodynamics is a fundamental component in vibration studies. Hence, knowledge of the biodynamics is not only important to engineers for the designs and analyses of the tools and anti-vibration devices but it may also be useful to researchers and scientists for the studies of the other three foundations. For example, rat tail models have been used to conduct the physiological and pathological studies[3]. A recent measurement using a laser vibrometer showed that the rat tail constrained on a vibrating surface could resonate in the neighborhood of 125 Hz[4]. The resonant magnitude could be more than two times the input vibration and it could result in a significant increase in the physiological and pathological effects. Without conducting any measurement and quantifying the actual vibration magnitude on the tail, such changes could be exclusively attributed to the frequency dependencies of these medical effects, although both the magnitude and the frequency could play important roles in these responses.

The hand-arm system is a very complicated mechanical structure and biological system. Probably for this reason, many researchers believed that it would be hopeless to give a detailed description of the complex system through the study of the biodynamics of the system[5]. Hence, the biodynamics was traditionally studied by investigating the overall responses of the system in terms of the vibration transmissibility from the tool to the surface of the system and the force-motion relationships such as the apparent mass and mechanical impedance of the system at the hand-driving point[1]. Many studies using these two approaches were reported in the last 40 yr[1]. Based on some of these studies, the International Organization for Standardization (ISO) has set forth a standard (ISO 10068, 1998) on the mechanical impedance of the hand-arm system[6]. Although the general knowledge of biodynamics has helped explain some phenomena observed in the HTV studies, so far, it has had limited impact on the most important standard (ISO 5349, 2001)[7] for the measurement, evaluation, and risk assessment of the HTV exposure. Limited information on biodynamics is described in the books on hand-transmitted vibration[8, 9]. The actual role of biodynamics has not matched with its scientific importance. Although some reported biodynamic data and computer models are doubtful[10, 11], the lack of interest in biodynamics is primarily because the state of the art of biodynamics may not have reached a sufficiently high level such that it could generate significant impact. On the other hand, this suggests that there may be many research opportunities in the area of biodynamics.

In recent years, a new conceptual model relating factors influencing the cause-effect relationships has been formed. Based on this model, a new study strategy has been used and a set of methodologies developed. The new study concept has not only helped identify the limitations of the traditional total energy and impedance methods and resulted in advances of the driving-point biodynamic response[12, 13], but it has also brought about the application of the advanced finite element (FE) method to the study of HTV exposure[14–16]. Significant progress has also been reported in the evaluation of anti-vibration gloves and the measurement of hand forces. Furthermore, new experimental technologies such as laser vibrometer, thin pressure sensors, and new instrumented handles have also been increasingly applied in biodynamics studies in recent years. The applications of general biodynamics knowledge and experimental data have also been expanded to a wider range. It is anticipated that future studies of biodynamics with the new concepts, strategies, and methodologies may lead to the establishment of a robust HTV exposure theory.

In order to help accelerate the progress in the biodynamics of the system, the specific aims of this review are (a) to further clarify the fundamental concepts of the biodynamics of the fingers-hand-arm system, (b) to provide general knowledge of the biodynamic responses, (c) to highlight the major problems for biodynamic measurements and their means of solution, (d) to summarize the new developments of biodynamics and its applications, and (e) to identify the major issues and topics for future studies.

Fundamental Concepts

The precise mechanisms of hand-arm vibration syndrome are not sufficiently understood[7]. Contradictory attitudes on the mechanisms of hand-arm vibration syndrome have dominated—from hyperactivity of the sympathetic nervous system and 'local defects' to statements of primary central nervous system mechanisms[17]. To understand the true mechanisms, it is very important to clearly identify and understand the real mechanical stimuli directly acting on the tissues and cells in the vibration exposure.

Vibration is oscillating motion. The same motion on different systems may not have the same effect. For example, vibration of 9.8 m/s^2 at 5 Hz is unlikely to cause any significant disorder in the fingers, but it could cause severe problems over time in the seated whole body vibration exposure[8]. This is principally because a seated body exhibits resonance of the spinal column near 5 Hz[8], and thus yields high stresses due to considerable response motion of upper

body and the internal organs; however, the dynamic force on the fingers generated at such a vibration magnitude is unlikely to be very significant. This example suggests that the input vibration itself is only half of the story. The other half is the system response. Both aspects can be automatically taken into account if the internal force or deformation is used to quantify the vibration exposure; hence, they are the best theoretical vibration measures.

In engineering, the internal force and deformation are termed 'stress' (force per unit area) and 'strain' (deformation per unit dimension), respectively. The stress can be divided into 'normal stress' and 'shear stress'. While normal stress corresponds to 'normal strain' (compression or tension) of a tissue element, the shear stress distorts the shape of the element that is termed 'shear strain'.

The stresses and strains are essential factors that control the growth, remodeling, morphogenesis of biological systems[18]. It is also common knowledge that the musculoskeletal injuries caused in many manual working tasks are directly related to static and dynamic stresses and deformations in the hand-arm systems[19, 20]. A few studies suggested that shear stress is responsible for vibration-induced disorders[21, 22]. Necking *et al.*[23] reported that vibration exposure could cause hand muscle and nerve damage. Their other study concluded that the level of tissue displacement (or strain) is a crucial factor for the development of vibration-induced muscle injury[24]. The dynamic strains may distort the shapes of the blood vessels and capillaries, which may be one of the reasons that vibration exposure could reduce blood flow[25, 26]. Because nerve sensors sense the stress and strain environment[18], the hyperactivity of the sympathetic nervous system and the release of adverse biological agents are also likely stimulated by the stress and strain. Based on these observations, Dong *et al.*[27] proposed that vibration-induced stress and strain are among the essential mechanical stimuli that directly act on the tissues and cells of the system and cause the vibration-induced disorders. They also suggested that the understanding of these essential vibration stimuli could provide significant insight into the impact of HTV exposure upon various medical effects[1].

It has been well-known that the tissues, especially the soft tissues of the hand-arm system, have significant damping characteristics. As a result of the cyclic stress and deformation processes, vibration energy/power can usually be absorbed or dissipated by the system. Hence, the power absorption is actually an output of the stress and strain stimulations. More than 40 yr ago, it was hypothesized that the energy/power absorption was associated with the etiology of the vibration-induced disorders[28–30]. Whereas the total power absorption of the entire hand-arm system measured at the hand-tool interface was traditionally used to implement the energy concept for studying the HTV exposure and health effects[29], Dong *et al.*[12] recently suggested that the best theoretical parameter for quantifying the power absorption is the vibration power absorption density (VPAD: power absorption per unit volume of tissue).

The tissues at different anatomical locations may have various strengths, adaptations to mechanical stress and deformation, and injury or disorder recovering capabilities. Hence, the same stress, strain or power absorption density at these different locations may not result in the same medical effects. While some types of disorders or injuries may depend on the overall stress and strain, the others may depend primarily on the stress and strain values at a few critical points. Hence, it is also important and useful to identify and understand the distributions of the stress and strain.

It is also common knowledge that the dynamic force acting on the hand-tool interface is associated with the stress and strain inside the system. Therefore, it may be used as an alternative vibration measure. The biodynamic force is an essential factor for evaluating the driving-point biodynamic parameters such as apparent mass, mechanical impedance, and total power absorption[1]. In an earlier conceptual model[8], these biodynamic responses were directly linked to the signs and symptoms of hand-arm vibration syndrome. Although their associations may exist, it may be difficult to understand their exact relationships without establishing the linkages between the physiological and pathological effects and the stresses and strains.

In the operation of a powered hand tool, workers must apply forces on the tool to control, guide, and/or lift the tool, and to achieve desired productivity. The applied forces not only result in quasi-static stress and strain, but they may also directly affect tool vibration[31], vibration transmission[32], and biodynamic responses[13]. The excessive static stress and strain may directly cause injuries and disorders, as observed for some manual tool workers[18, 19]. The static stress and strain may enhance the effects of the dynamic stress and strain. Therefore, the applied forces and their related stresses and strains are also factors for risk assessment[7] and important components in the studies of biodynamics.

Based on the above-described concepts and observations, the authors propose a new conceptual model relating factors influencing cause-effect relationships for the HTV exposure, which is shown in Fig. 1. The model is a revision of the model proposed by Griffin[8]. The major revisions are that the internal biodynamic responses (stresses and deformations) and the physiological and pathological effects are considered

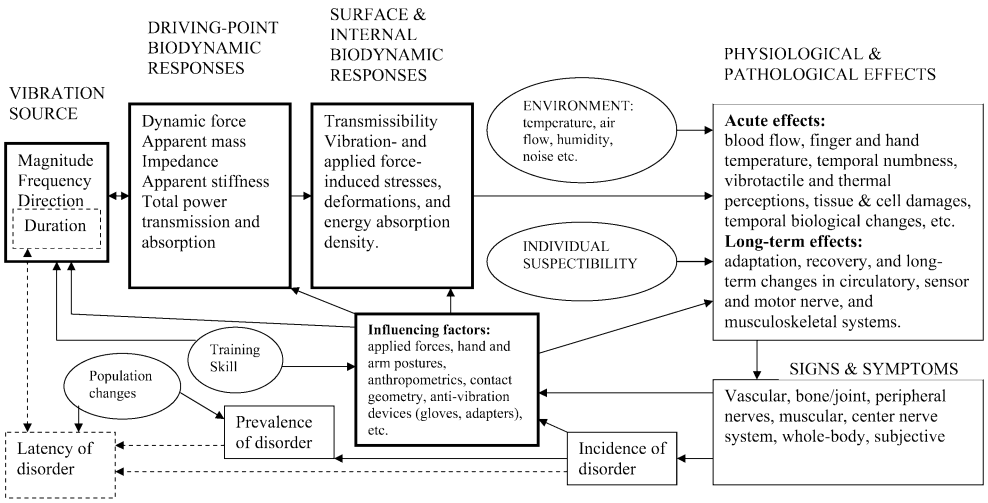

Fig. 1. A conceptual model of factors influencing cause-effect relationships for hand-transmitted vibration exposure.

among the essential blocks in the flow chart in the new model. The factors in the four blocks with the bold-line frame are of major interest for biodynamic studies.

Theoretical Modeling

Traditionally, the theoretical modeling of the hand-arm system for studying its biodynamics has been performed using mechanical models with lumped mass, spring, and damping elements[1]. The lumped parameters are identified upon the curve fitting of the measured data such as the vibration transmissibility values at several anatomical locations, and the mechanical impedance measured at the hand driving point[1]. The models, therefore, do not adequately represent the biomechanical properties of the system. More critically, it is impossible to use such models to understand the local dynamic behaviors in terms of stress, strain, and power absorption density. In recent years, the modeling primarily focused on these detailed local biodynamic responses. Whereas a reliable experimental method has not been developed to measure these responses, finite element and other theoretical models have been developed to simulate the biodynamic interactions between fingers and tools and to predict these essential mechanical stimuli that the soft tissues in fingers receive during the operation of power tools.

The human fingertip is a complex mechanical structure. Macroscopically, a fingertip is composed of skin layers (epidermis and dermis), subcutaneous tissue, arterial bone, and nail. The epidermis, the outermost layer of the skin, consists of primarily protective horny structures, such as stratum corneum. The dermis, a fibrous layer supporting the epidermis, contains numerous mechanoreceptors[33]. The subcutaneous tissue is a fat layer, which primarily consists of lipocytes. The matrix of the subcutaneous tissue contains approximately 60–72% fluid in volume[34]. The biomechanical properties of the skin and the subcutaneous tissues influence the transmission of mechanical stimuli (i.e., stress and strain) through the tissues, and thus, play an important role in the biodynamic responses and tactile sensation. Conceptually, there are two types of models of fingertips in the literature: physical models and structural models. In the physical models, the force responses of a finger are modeled mostly using a combination of linear or nonlinear lumped elements, such as springs and dashpots. Since anatomical structures of the fingertip are not considered, the stress/strain properties within the soft tissues of fingertips can not be simulated. The structural models consider simplified anatomical structures of the fingertip and can predict the stress/strain in the tissues as well as the force responses.

Physical model

Pawluk and Howe[35] proposed a lumped element model to simulate dynamic contact of fingerpad with a flat surface. Using Boltzmann's Superposition Integral, they derived the time-dependent relationship of force and displacement. They found that the time-dependent contact force and the dynamic contact pressure on fingerpad can be well simulated using their models for dynamic loading conditions. The lumped element model has been refined and applied to simulate the dynamic force responses of fingerpad for slow loading rates and in force relaxations[14]. Jindrich *et al.*[36] applied the lumped

element model to simulate the force-displacement characteristics of fingertip for rapid tapping tasks. They reproduced the force response of fingertip during the dynamic impact of tapping for a range of different impact conditions using a lumped-parameter non-linear viscoelastic model.

Structural model

Technically, it is difficult to include all the anatomical structures of the fingertip in a structural fingertip model. Therefore, two types of structural models of fingertips—analytical and finite element (FE) models—have been proposed in the literature to mitigate the difficulties associated with the complex of the substructures of fingertips.

1) Analytical model

The analytical model was developed by using certain simplified assumption of the anatomical structures, such as the "waterbed" model proposed by Srinivasan[37]. In his model, a fingertip is represented by an incompressible fluid representing the subcutaneous tissue enclosed by an elastic membrane representing the skin. Srinivasan's "waterbed" model has been used to predict the deflection of fingertip surface under a static, linear load. Serina *et al.*[38] has proposed an improved model using nonlinear elastic skin membrane and finite deformation theory. Their model has been applied to predict the force/displacement relationship and the force/contact area for static loading conditions. Although the "waterbed" fingertip models are capable of predicting some experimentally observed phenomena, they are not capable of analyzing the variations in the stress and strain within the tissues due to the considerations of uniform tension in the membrane and uniform fluid pressure. They also cannot be used for dynamic loading conditions.

2) Finite element modeling

Srinivasan and Dandekar[39] proposed a two-dimensional FE fingertip model which was composed of soft tissue, bone and nail. The soft tissue was represented by homogeneous, isotropic, and incompressible elastic media, the bone was considered as linearly elastic, and the nail was represented using constrained boundaries. The cross-section of the fingertip was considered as cylindrical with a bone at the center. They applied their model to simulate the stress/strain distributions in the fingertip indented by rectangular gratings. The model predictions on the maximum compressive strain and strain energy density at typical receptor locations were consistent with the electrophysiologically recorded response rate of slowly adapting type I (SAI) mechanoreceptors. However, the predicted surface profile did not agree with the experimental data. Dandekar *et al.*[40] developed three-dimensional fingertip models that include realistic external geometries of the fingertips. In their improved model, the soft tissues were considered as multi-layered with different elastic moduli. The geometries of the FE models were obtained by digitizing the fingertip replicas of human and monkey. The material properties of the soft tissues were optimized by fitting the computed surface deformations to match experimental data. They found that the predictions of their multi-layered FE model agree well with the experimental observations. The FE model was applied to analyze the responses of the slowly adapting type I (SA-I) mechanoreceptors to indentations by complex object shapes. The soft tissues were considered linearly elastic and time-independent in all the FE models mentioned above, therefore, these FE models are not capable of simulating the time-dependent force and deformation responses of fingertip for vibration loadings.

Wu *et al.*[14, 15] proposed nonlinear, two-dimensional FE models of fingertips, which included the most important anatomical structures: soft tissue, nail, and bone. The cross section of the fingertip and the bone are assumed to be elliptical and the tissue thickness is considered to be asymmetric about the bone, as sketched in Fig. 2. The dimensions of the fingertip model were considered to be representative of a male index finger. The tissue thickness between the bone and the skin surface contacting the steel plate is assumed to be larger than that between the bone and the nail. In their earlier models, the soft tissues, which contain skin and subcutaneous tissues, were considered as hyperelastic and viscoelastic, while the bone and the nail were considered as elastic. The dynamic stress/strain distributions in the soft tissues and the dynamic deformation and force responses of the fingertip when it is compressed with a flat plate have also been simulated[14]. The time- and frequency-dependent deformation behaviors of the soft tissue were investigated by imposing different magnitudes of ramp-like loading of the fingertip with different ramping periods and sinusoidal vibrations of the contacting plate at two discrete frequencies (1 Hz and 10 Hz). Figure 3 shows the distributions of the soft tissue strains in the horizontal (Fig. 3, left) and vertical (Fig. 3, right) directions when the fingertip is compressed. The model predictions on the time-histories of displacement at different depths within the fingertip subjected to cyclic loading are shown in Fig. 4.

The two-dimensional FE model has since been refined to include the effects of the material variations in the soft tissue[41]. The improved model is multi-layered and incorporates more detailed anatomical structures of a finger

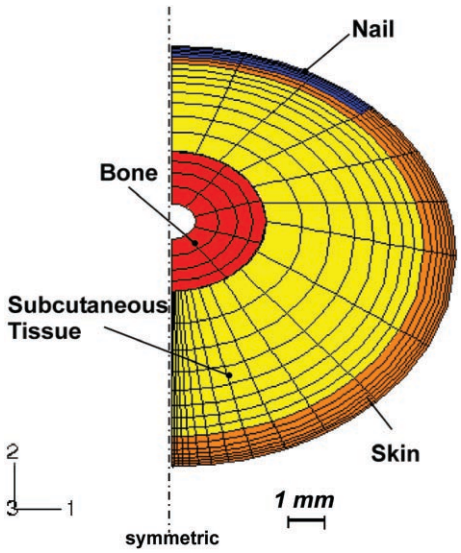

Fig. 2. The two-dimensional finite element model of a human fingertip proposed by Wu *et al.*[14, 15]. The model is composed of skin, subcutaneous tissue, bone, and nail.

(Fig. 2): skin, subcutaneous tissue, bone, and nail. The skin was considered as hyperelastic and viscous, while the subcutaneous tissue was modeled using a sponge-like media: a biphasic material composed of a hyperelastic solid and an inviscid fluid phase[35, 42]. The blood flows through the permeable tissue and the couples with the tissue deformation in the biphasic material model. The subcutaneous tissue was considered to have a deformation-dependent hydraulic permeability that decreases with increasing volumetric compression of the tissue. The model predictions on the surface profile of a fingertip subjected to static indentation and the time-histories of force/deformation responses of the fingertip to a single keystroke agree with published experimental data. The improved FE model has been applied to analyze the biomechanics of two-point discrimination threshold and vibration perception threshold tests.

The stress/strain distributions in the soft tissues in the two-point discrimination threshold tests have been predicted as in Fig. 5[16]. The mechanoreceptors within the soft tissues were assumed to sense the mechanical stimuli during the tests. The mechanical states (stress/strain) of the tissue at a depth of 0.75 mm from the undeformed skin surface, where the Merkel cell receptors are located, were analyzed in the study. The simulation results revealed the variations in horizontal and vertical strains and strain energy density that developed in the skin at the contact points and at the geometric center of the fingertip when the indentor spacing was changed. Assuming mechanoreceptors in the dermis sense the stimuli associated with normal strains and strain energy density rather than those associated with shear strain, the theoretical analysis indicated that the threshold of two-point discrimination test for the fingertip might lie between 2.0 and 3.0 mm, which is consistent with the experimental observations by Perez *et al.*[43] who reported an average two point discrimination distance of 2.1 mm during tactile sensation threshold tests of the index finger.

The vibration perception threshold is believed to be influenced by many factors, especially contact force and vibration frequency. The interaction between fingertips and

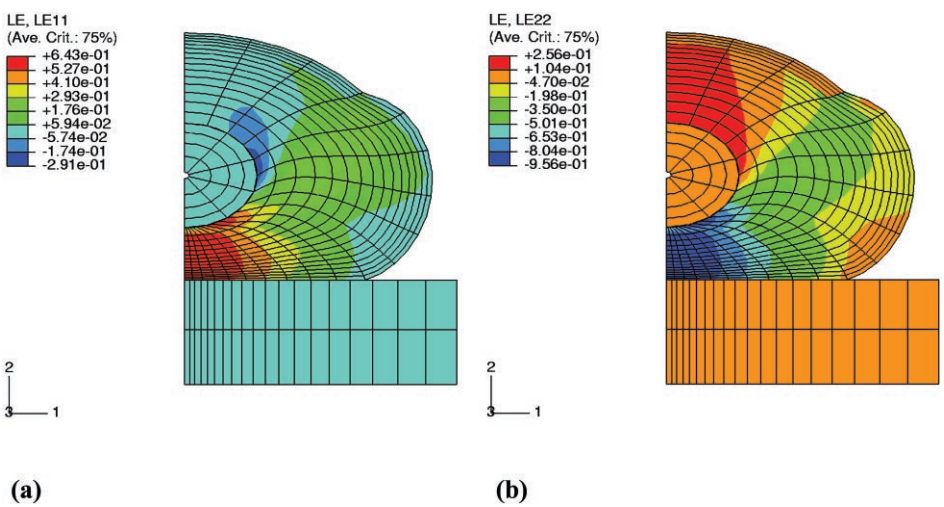

Fig. 3. The predicted distributions of the strain in the fingertip at the compressed state[14]. (a): Horizontal (logarithmic) strain; (b): Vertical (logarithmic) strain.

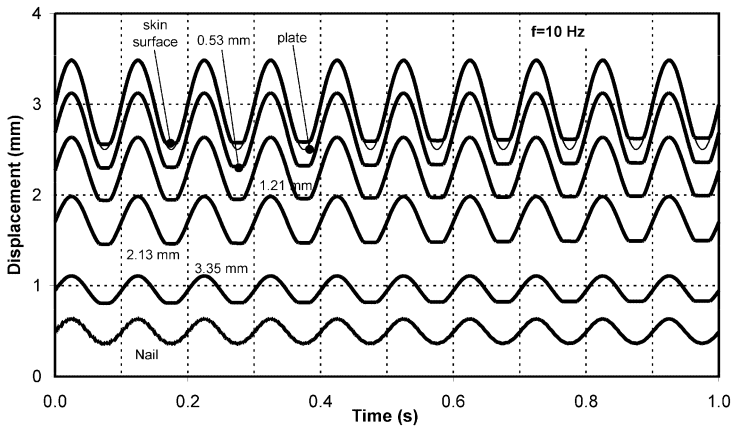

Fig. 4. The predicted time-histories of displacements at different depths within the fingertip during vibration[14].

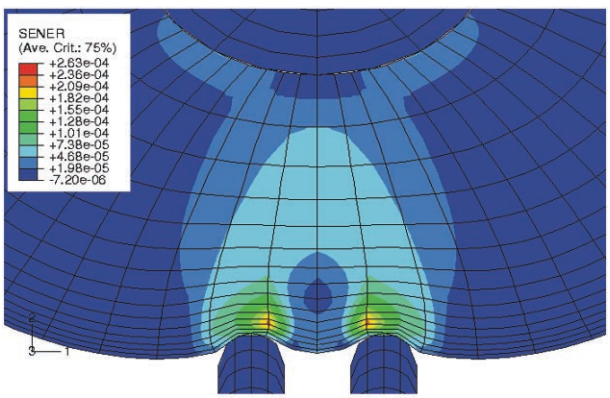

Fig. 5. Finite element (FE) simulation of two-point discrimination threshold tests[16].

(a): FE model. (b) The predicted distributions of the strain energy within the soft tissues of the fingertip indented by the pins.

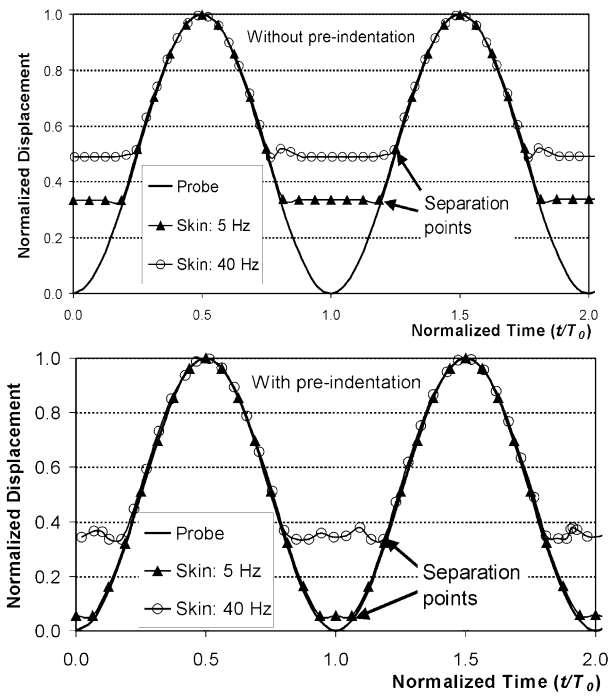

Fig. 6. The predicted time-histories of deformations at the center of skin surface of a fingertip subjected to vibratory indentation of a vibrotactile probe[41].

The model predictions indicated that the skin surface separates from the probe during a portion of the vibration period.

probe during vibrotactile perception threshold tests was analyzed using the FE model[41]. The time-dependent deformation profile of skin surface, strain distributions within soft tissue, and response force of a fingertip, when the fingertip was stimulated using a probe that was vibrating with a sinusoidal movement, were analyzed. The model predicted the separation between the probe and skin surface during the vibrotactile tests (see Fig. 6), which is consistent in trend with reported experimental data[44]. The simulation results suggest that the fraction of time over which the skin separates from the probe during vibration increases with increasing vibration frequency and amplitude, and decreases with increased pre-indentation of the probe. The pre-indentation of the probe has been found to significantly reduce the trend of skin/probe decoupling. The spatial summation of the vertical deformation and the strains in the horizontal and vertical directions in the soft tissue around the location of mechanoreceptors were predicted. The analysis showed that the mechanical stimuli of the fingertip were reduced when the skin/probe separation occurs. The predicted variations of the skin profile as a function of indentation and vibration frequencies compared well with the

experimental data[44].

The analyses of the mechanical behavior of the fingertip have also been performed in the frequency-domain[15]. The modal analysis of the deformed fingertip model was performed using the tangential stiffness of the tissue. The free-vibration analysis of the fingertip model resulted in a large number of natural modes. Considering that most power tools generate dominant vibration in a frequency range of 25–250 Hz[45], the first ten eigen-frequencies of the fingertip model were extracted corresponding to each level of static deformation. The natural frequencies corresponding to the extracted modes were observed to lie in a frequency range from 40 Hz to 320 Hz. The eigen-frequencies of the fingertip were found to increase with increasing amounts of compression or pre-load of the fingertip. The results also show that the eigen-frequency corresponding to a specific mode increased almost linearly with the magnitude of the static deformation, irrespective of the mode of vibration. The simulations are consistent in their trends with the experimental observations by many investigators[13, 46–49], who reported that the resonant frequencies of the fingers and hand increased with increases in the applied forces.

Vibration Transmissibility

Vibration transmissibility is defined as the ratio of the vibration measured on the hand-arm system and the input vibration on the hand-tool interface. Hence, it determines the frequency dependence of the transmitted vibration at an anatomical location on the hand-arm system. So far, it has not been feasible to directly measure the vibration transmitted to anatomical locations internal to the hand-arm system. The transmitted vibration measured on the surface of the system is used to study the transmissibility. The major transducers used for the measurement are accelerometers and laser vibrometers[50, 51]. Ksiazek and Tarnowski[52, 53] reported the use of a high speed camera for the measurement, which showed reasonable results up to 150 Hz.

The transmitted acceleration reflects the inertial force on the system. Hence, it has a relationship to the biodynamic stresses and strains. Several investigators proposed using the transmissibility at an anatomical location as a frequency weighting for assessing the risk of the vibration-induced disorders at that location[27, 54, 55]. Several examples of the transmitted acceleration-based (TAB) weightings are shown in Fig. 7. Dong *et al.*[55] reported that the accelerations on the arm calculated using the TAB weightings were highly correlated to those calculated using the ISO weighting[7]. Another study[56] reported that the wrist sensorineural

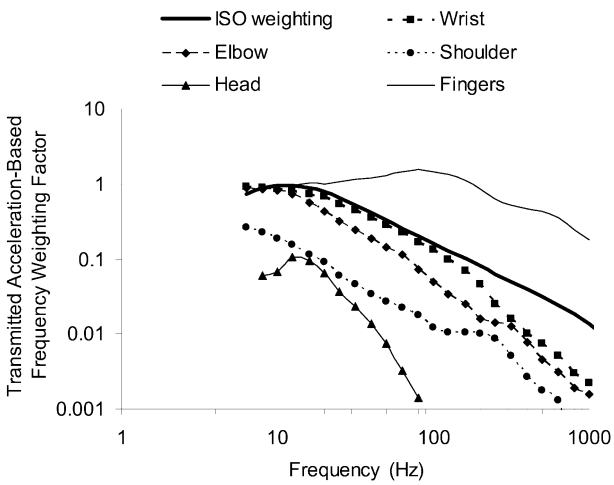

Fig. 7. Frequency weighting factors derived from transmitted accelerations on fingers and at wrist, elbow, shoulder, and head[55].

disorders were reasonably correlated to the ISO-weighted acceleration. Hence, the TAB weighting method may have some value for assessing the risk of the disorders of the wrist-arm system.

At high frequencies (≥100 Hz), the vibration cannot be effectively transmitted beyond the hand[32, 57, 58]. Hence, the inertial force due to the transmitted acceleration on the fingers should be directly correlated to the interface dynamic force. This hypothesis was supported from the study by Dong *et al.*[55]. They also found that at lower frequencies, the transmissibility on the fingers was not correlated to the interface biodynamic force. This is because the biodynamic response at such frequencies is generally affected by the overall response of the entire hand-arm system but the transmissibility on the fingers only represents the finger inertial force[12, 13].

As also shown in Fig. 7, the finger transmissibility is near unity up to 200 Hz. Because the vibration spectra measured on most vibrating tools have dominant frequencies at equal to or less than 250 Hz[45], Dong et al's study also found that the tool accelerations calculated using the finger TAB weighting is highly correlated to unweighted (or unit weighting method) accelerations on these tools[28]. Hence, the finger TAB weighting method is consistent with the unweighted acceleration method, which is recommended by NIOSH as an alternative method for finger risk assessment[59]. A recent epidemiological study also reported that the unweighted acceleration was better than ISO-weighted acceleration for predicting VWF[60].

Another recent application of the transmitted vibration is to check the dc-shift of the acceleration signal[61]. Since the

human hand is a good absorber of high frequency vibration, the acceleration measured on the hand usually has no dc-shift problem.

Driving-Point Biodynamic Responses

The study of the driving-point biodynamic response was very active the last few years. Not only have the study methodology and the measurement technique been improved, but the applications of the response have also been significantly expanded.

Definitions

The driving-point biodynamic response (BR) parameters are conventionally defined as

$$AM = \frac{F_d}{A}, MI = \frac{F_d}{V}, AS = \frac{F_d}{D},$$
$$\text{and } PT = F_d \cdot V \quad (1)$$

where AM, MI, AS, and PT are apparent mass, mechanical impedance, apparent stiffness, and power transmission, respectively, and F_d, A, V, and D are the dynamic force, acceleration, velocity, and displacement at the hand-tool interface or the vibrating surface, respectively.

The dynamic force may have a different phase from those of the motion parameters. Therefore, in the frequency domain, all of these biodynamic response parameters are generally complex, that is, each of them possess real and imaginary components, and they can be generally expressed as

$$Z(\omega) = Z_R(\omega) + Z_I(\omega)j \quad (2)$$

where ω is vibration frequency in rad/s, Z(ω) represents any of the biodynamic response parameters, $Z_R(\omega)$ and $Z_I(\omega)$ are its real and imaginary components, respectively, and $j = \sqrt{-1}$.

The four response parameters in Eq.(1) are not independent. Each of the parameters can be derived from another. For example, if the apparent mass is directly measured, the other parameters can be calculated using the following formulas:

$$MI(\omega) = AM(\omega) \cdot j\omega, AS(\omega) = AM(\omega) \cdot (j\omega)^2,$$
$$PT(\omega) = AM(\omega) \cdot j\omega(|V|)^2 \quad (3)$$

The vibration power absorption (VPA) is the real component of the vibration power transmission (PT), which can be expressed as follows:

$$VPA = Re(MI) \cdot (|V|)^2 = Re(MI) \cdot \left(\frac{A}{\omega}\right)^2 \quad (4)$$

Major problems and improvements of measurement method

Although the driving-point response has been studied for many years, the measurement method has not been standardized. A variety of instrumented handles, test systems, and calculating algorithms have been used[1]. There are considerable differences among reported data[1, 62]. Some of them may be caused from the multitudes of vibration excitations, vibration magnitudes, applied forces, hand and arm postures, handle shapes and dimensions, and individual differences[12, 13, 47, 63–70]. However, the data measured under similar experimental conditions also show significant differences not only in magnitude but also in trend[1, 62].

In the last few years, some fundamental characteristics of the driving point responses have been clarified. A study suggested that the palm soft tissues actually function like a natural cushion for the hand-arm system[49]. Hence, they can be modeled as a spring-damping system and the remaining structures of the palm-wrist-arm system as a mass-spring-damping system that is connected to the palm model. Both the driving-point response data[13, 47, 67, 70] and the vibration transmissibility data[53, 54, 71] indicate that the resonance of the system in the z_h-direction[7] (along the forearm direction) is usually in the range of 16 to 63 Hz, depending the applied force and hand and arm postures. This resonant feature supports the proposed palm theoretical model[49]. It, however, contradicts the flat response phenomenon shown in some previously reported data[63].

Rakheja *et al.*[11] evaluated the biodynamic response characteristics of various mechanical models of the human hand and arm system in terms of their driving-point mechanical impedance modulus and phase responses. It was concluded that a vast majority of these models could not be applied for the development of a mechanical hand-arm simulator or the assessment of dynamic behavior of the coupled hand-tool system. Higher order models, with three and four degrees of freedom, in general, yield impedance characteristics within the range of the values recommended in ISO 10068 (1998)[6], but exhibit excessive static deflections. Moreover, these models involve very light masses (in the 1–8 gram range). It is not practical to use such models to construct any test rig for testing tools and anti-vibration devices. The majority of the lower order models yield reasonable magnitudes of static deflections but relatively poor agreement with recommended impedance values. However, the poor agreement may not necessarily mean that these lower order models are not valid. This is because another study indicated that the recommended data in ISO 10068 was questionable. Two of the seven sets of data[62, 63] used for the synthesis of the recommended data

have no signs of resonance in the z_h-direction (along the forearm direction) at frequencies less than 100 Hz, which is a very unusual feature[10]. These problems suggest that both the impedance data and computer models recommended in ISO 10068 require major revisions[10].

The possible errors in some sets of data might result from instrumentation problems and/or the errors in the algorithms used in the calculation. Dong *et al.*[66] found that the damping of their instrumented handle generally increases with the increase in frequency, and usually becomes non-negligible at frequencies higher than 100 Hz. To resolve the problem, they developed a frequency domain method to cancel the effect. They also found that their instrumented handle didn't demonstrate uniform mass response in the entire frequency range (5 to 1,500 Hz) for the study of the hand-transmitted vibration exposure[72, 73]. This also makes it very difficult to accurately cancel the handle mass effect using the time-domain method that was widely used several years ago. The frequency domain method can not only resolve this issue, but it can also simplify the measurement system and reduce the cost. Hence, they further refined this method and used it in their other studies[12, 13, 48, 49]. This method has also been adopted by several other investigators[70, 74].

In the low frequency range (<40 Hz), some accelerometers may have a large phase difference from some force sensors[10]. The signal filter may also cause a phase shift. Such a problem may have affected some of the reported data. A few investigators[65] reported that the power absorption of the hand-arm system exposed to a constant-velocity (14 mm/s) vibration on the z_h-axis dramatically increased with the reduction in frequency at less than 12.5 Hz. This trend is opposite to those reported from many other studies[12, 13, 47, 70]. Their data also showed that power absorption at less than 5 Hz could be more than ten times higher than that at 31.5 to 50 Hz. This implies that the hand exposed to less than 1 m/s^2 vibration at the low frequencies that could occur on some vehicles could absorb more power than the hand exposed to 20 m/s^2 (comparable with the dominant vibration value on many chipping hammers[31, 75]) in the resonant frequency range of the hand-arm system. This seems unrealistic. The phase difference between the signals of the accelerometer and force sensor could increase with the reduction of frequency[10], which could artificially make the power absorption increase with the reduction of the frequency. This may provide an explanation of the problem in this set of data. Another possible reason for the error may be because the acceleration (e.g. 0.44 m/s^2 at 5 Hz) and force under the low constant-velocity excitation at the low frequencies are small and the motion and/or force signals may be close to the noise level such that the measured data may not be reliable. The noise could be from the electronic system. It may also be from the involuntary motions or actions of the hand and arm. Furthermore, the sinusoidal waveform generated on some shakers at the low frequencies may also be substantially distorted, which could also result in some errors. These observations suggest that: (I) it may not be appropriate to use the low constant-velocity excitation in the low frequency range; (II) some special cautions and/or instruments are required if it is necessary to measure the low frequency response; and (III) it is important to select the appropriate accelerometer and force sensor such that their signals do not have a significant phase difference.

At high frequencies (>100 Hz), it is difficult to accurately cancel the mass effect because the amount of tissues effectively involved in the response is usually much smaller than the mass of the instrumented handle or measuring cap. The effective mass of a handle may also be different with and without the hand coupled on the handle[72]. Although the absolute error in the estimation of the handle mass could be small, it could result in a large percentage of error. The impedance phase angles reported by a few investigators[64, 76] were close to 90° at high frequencies (>100 Hz), which implies that the hand and fingers could respond almost rigidly in the high frequency range. Dong *et al.*[10] pointed out that this is not a natural phenomenon because the vibration at such frequencies can only be effectively transmitted to the soft tissues of the hand which can effectively absorb or isolate high frequency vibration; otherwise, the high frequency vibration would be effectively transmitted to the arm. The possible errors in these data were likely because the mass of the probe or the instrumented handle was not sufficiently cancelled. Besides using the frequency domain method for the mass and damping cancellation, the handle or measuring cap should be as light as possible but the entire handle structure should be as rigid as possible. The vibration on the handle should be distributed as uniformly as possible. Initially used for the power absorption study[66], Welcome *et al.*[73] has developed an instrumented handle that can be used to measure biodynamic response up to 1,500 Hz. They have also proposed a set of methods for systematically evaluating the measurement system. Their handle design concepts have also been adopted by another group of investigators[70], who added the measurements of applied push force and total biodynamic force to the handle fixture.

Distribution of driving-point biodynamic response on the hand

The vibration-induced stresses and strains on the fingers

are very different from those on the palm-wrist-arm system because their biodynamic responses are generally very different[12, 13, 48, 49]. Because of the variations in exposure and the differences in biological structures, the physiological and pathological mechanisms of the disorders in the fingers may also be quite different from those of the bones, joints, and muscles in the wrist-arm system. While the vibration power transmission measured at the fingers may be more closely associated with vibration-induced finger disorders such as vibration white finger, the vibration power transmission measured at the palm may have a better correlation with the disorders in the wrist-arm system. Furthermore, due to the biodynamic response differences, an anti-vibration device that is effective at protecting the wrist and arm may not be effective at protecting the fingers. Therefore, it is useful to determine the *distribution* of the biodynamic response (BR) on the fingers and the palm of the hand.

In recent years, the BR distribution in the z_h-direction has been initially investigated using a method developed by Dong *et al.*[12, 13, 48, 49]. As shown in Fig. 8, these studies found that, at low frequencies (≤ 40 Hz), the mechanical impedance (MI) and vibration power absorption (VPA) on the palm are substantially higher than those on the fingers; the majority of the hand MI and VPA remain distributed at the palm up to 100 Hz; at frequencies higher than 160 Hz, the finger MI and VPA are comparable to or higher than those on the palm; among the three coupling actions (pull-only, grip-only, and combined grip and push) used in these studies, the finger MI and VPA take the lowest value in the combined grip and push action at low frequencies (<40 Hz); however, at frequencies equal to or above 100 Hz, the finger MI and VPA are practically independent of the palm-handle coupling conditions.

A more detailed distribution of the biodynamic response can be determined using a point measurement device such as an impedance head and a button force sensor. Several studies on the development of the measurement devices have been reported[77, 78]. However, further information on the distribution of the biodynamic response is currently not available.

Vibration power/energy absorption (VPA)

As previously mentioned the total VPA is a special parameter of the driving-point response. Several researchers believed that the damage done to the hand was more likely to depend upon the rate with which energy is dissipated in the hand-arm system than upon the acceleration alone, and that the total power absorption of the entire hand-arm system

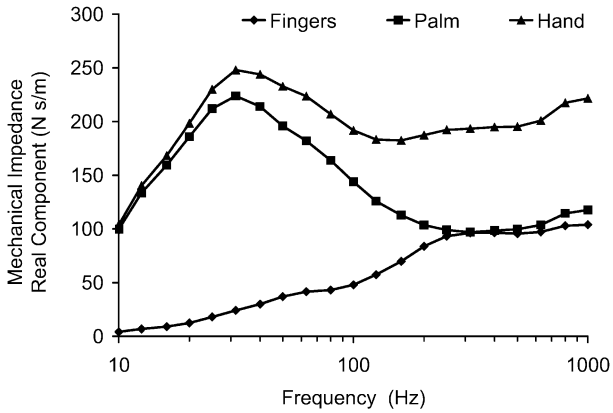

Fig. 8. Distribution of mechanical impedance at the fingers and the palm of the hand under a combined grip (50 N) and push (50 N) action[13].

encompassed a greater complexity of the biological effects of vibration than acceleration does and this method was thus better than the acceleration for the risk assessment[79, 80]. A part of these hypotheses was challenged in recent years.

Dong *et al.* pointed out that although the energy concept may still have some value, the total energy method that had been almost exclusively used in the past has several fundamental deficiencies[12, 48]. Specifically, it ignores the power absorption concentration effect and the frequency dependence of the power absorption distribution in the system. The power absorption in the operation of a low frequency tool such as a sand tamper is likely higher than that of a high frequency tool such as a high speed grinder[27] but few signs of vibration-induced white finger (VWF) were found among tamper users while a large prevalence was found among grinder users[81]. Tominaga[82] recently proposed a new frequency weighting based his epidemiological study on VWF. This weighting suggests the ISO weighting greatly overestimates the low frequency vibration effect but substantially underestimates the high frequency vibration exposure. Many physiological and pathological data also suggest that the most substantial medical effects of the HTV exposure are in the middle frequency range (30–500 Hz)[8, 9], which also disagrees with the ISO weighting method. Because the total energy method emphasizes the lower frequencies similarly to the ISO method, it likely cannot provide a good prediction of VWF[27].

However, the total power absorption is correlated to the ISO-weighted acceleration in a non-linear manner[27]. It may have some association with the subjective sensation[83]. The frequency characteristic of the total power absorption suggests that it may be related to the disorders in the palm-

wrist-arm system[27].

To overcome the deficiencies of the total energy method, Dong *et al.* has proposed the study of the vibration power absorption density (VPAD) and its distribution[12]. While the FE modeling approach can be used for quantifying the VPAD, an experimental approach has also been explored. As the first step of the experimental investigation, the power absorption in the fingers was investigated[12, 48]. Then, an approximate method for quantifying the average VPAD in the fingers was developed[84]. Their studies found that the VPAD depends on both the 'vibration source power density' (acceleration × velocity) and the 'power absorption coefficient' that depends on the dynamic response of the finger-hand-arm system and the soft tissue mass effectively involved in the response[84].

Frequency weightings derived from driving-point biodynamic response parameters

Since the power absorption is proportional to the square of acceleration, as shown in Eq.(4), the square root of the absorption can be considered as an alternative vibration measure so that the derived weighting has a linear relationship with the acceleration. Whereas the VPA-based weighting (W_{VPA}) has been derived directly using the power absorption data[85], it can also be determined using the impedance data as follows:

$$W_{VPA}(\omega_i) = \frac{\sqrt{\mathrm{Re}[\mathrm{MI}(\omega_i)]}}{\omega_i} \Bigg/ \frac{\sqrt{\mathrm{Re}[\mathrm{MI}(\omega_{REF})]}}{\omega_{REF}} \qquad (5)$$

where ω_{REF} is the frequency of the reference impedance, which can be selected based on the convenience for the weighting comparisons or the purpose of a study.

Because the total power absorption in z_h-direction is highly correlated to the square of the ISO-weighted acceleration[27], the VPA-based weighting factors derived from Eq.(5) using the data reported by Dong *et al.*[13] and Kihlberg[47] are very similar to the ISO weighting, as shown in Fig. 9. This suggests that the ISO weighting method is approximately equivalent to the total energy method in z_h-direction. This further suggests that the ISO weighting has the same fundamental deficiencies as the total energy method. Hence, the ISO weighting is unlikely to be suitable for assessing the risk of the fingers and hand exposed to vibration.

Similar to the VPA approach, a frequency weighting based on the power absorption density can be derived by considering the square root of the VPAD as an alternative vibration measure. As shown in Fig. 10, the VPAD-based weighting is much higher that the ISO weighing at frequencies greater than 20 Hz. This supports the assertion that the ISO weighting greatly underestimates the high frequency effect.

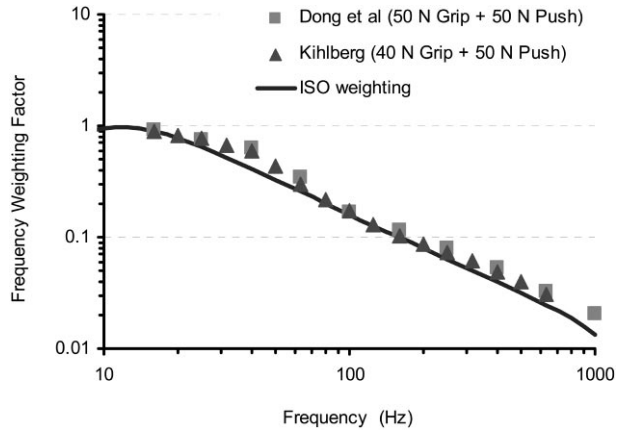

Fig. 9. Comparison of the ISO frequency weighting and the weighting derived from the total vibration power absorption (VPA) of hand-arm system using the data reported by Dong *et al.*[13] and Kihlberg[47].

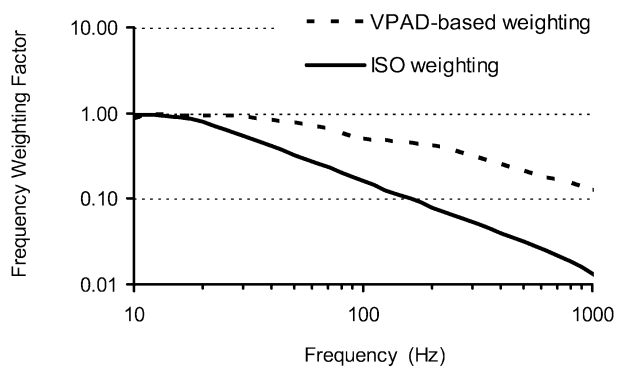

Fig. 10. Comparison of the ISO frequency weighting and the weighting derived from finger average vibration power absorption density (VPAD) using the data reported by Dong *et al.*[84].

In addition to using the power absorption, biodynamic force (BFB) can also be used to derive the frequency weighting[55]. Since the biodynamic force acting on the fingers is directly related to the stress and strains in the fingers and the force can be estimated using the apparent mass measured on the fingers and tool vibration acceleration, the apparent mass is used to represent the frequency dependencies of the stress and strain in the fingers[55]. Based on the same concept, the apparent mass measured on the palm is also used to determine the frequency weighting for assessing the risk of the disorders in the wrist-arm system[55]. Examples of these weightings are shown in Fig. 11.

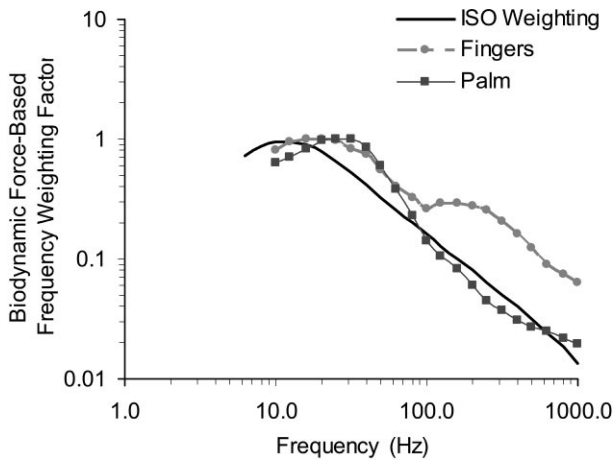

Fig. 11. Comparison of the ISO frequency weighting and the weightings derived from biodynamic forces measured at the fingers and the palm of the hand[55].

Applications of biodynamic response to the design of vibrating tools

Although the model recommended in ISO 10068 was found questionable and impractical for the construction of a test rig[10, 11, 86], it has been used for the theoretical analysis of a vibrating tool[87]. If the dominant frequency of the tool is in the neighborhood of 40 Hz or less, a single degree-of-freedom (1D) model may provide a reasonable approximation because the system response can be approximately modeled as a 1D system in this frequency region[10]. Furthermore, the apparent mass at frequencies higher than 100 Hz is usually less than 300 g[13, 48, 49]. Such a mass may not significantly affect the behaviors of many large tools such as rock drills, road breakers, and big chipping hammers. These observations justify the use of a 1D model for the design and analysis of some tools, which has been done by several investigators[88–90]. However, for the evaluations of an anti-vibration handle or adapter that has a relatively small mass, it is anticipated that a more sophisticated model may be required to simulate the higher frequency responses.

Evaluation of Anti-Vibration Gloves

As shown in Fig. 1, anti-vibration devices can be considered as special influencing factors in the biodynamics of the hand-arm system. In recent years, anti-vibration gloves have been increasingly used and studied. In addition to the traditional transmissibility method[91], the other overall biodynamic responses including the biodynamic force and the force-motion relationship have been proposed to evaluate the effectiveness of anti-vibration gloves[92].

Because the human hand is a very flexible structure, the effectiveness of an anti-vibration glove is location-specific. The glove may significantly reduce the vibration transmitted to the palm but it may provide little reduction of the vibration transmitted to the fingers in a large frequency range, because the apparent mass at the palm is much larger than that at the fingers at the relatively low frequency range[13]. This requires that the effectiveness of the glove for finger protection and the effectiveness for palm protection be examined separately. The test method specified in ISO 10819 (1998)[91] only requires measuring the transmissibility at the palm of the hand. While it may be acceptable for screening the gloves, it cannot provide sufficient information on how effectively a glove can reduce the transmitted vibration when the glove is used with a specific tool[93].

The results of a recent Round-Robin glove testing reveal that the data from different laboratories remain highly variable[94]. Many reasons could cause the differences. The instrumented handle and a palm held adapter recommended in ISO 10819[91] were evaluated by several investigators in order to identify their potential contributions to the overall measurement errors[72]. The results revealed a non-uniform distribution of vibration along the handle surface. The results also revealed the presence of considerable magnitudes of non-axial source vibration caused by the non-axial nature of the feed force imparted by the human hand. Three alternative methods have been proposed to minimize the contributions due to adapter misalignment and the non-axial source vibration[72, 95]. Although the adapter position in the glove can also be reasonably controlled without using the proposed methods by well-experienced investigators[96], these methods provide a more objective control of the reliability of the experiment[97]. The new instrumented handle developed by NIOSH investigators can overcome the deficiencies of the ISO-recommended handle and it has been successfully used in several glove studies[92, 98, 99].

Several studies have been conducted to identify major individual factors that are directly associated with the effectiveness of anti-vibration gloves[98, 100]. These studies didn't find a reliable association between the anthropometrics and the transmissibility of the anti-vibration gloves. In another study, however, Dong *et al.*[99] found that the vibration transmissibility of an air-bladder anti-vibration glove was reliably correlated with the biodynamic response (apparent mass or impedance) in the frequency range of 40 to 200 Hz; and that the glove became more effective when the apparent mass was increased. These findings suggest that an effective approach to increase the effectiveness of the glove is to find a way to increase the apparent mass of the

hand.

The effects of the applied force and hand-handle action on the transmissibility of the gloves have been investigated[98, 101]. These studies revealed that the effects are glove-specific. The applied force could significantly increase the stiffness of some gloves so that the transmissibility can be increased with the increase in the force[101]. On the other hand, increasing the force can increase the apparent mass[13], which can reduce the transmissibility[99]. This effect plays a dominant role in determining transmissibility of the air bladder gloves in a certain force range but the glove-stiffening effect apparently dominates the transmissibility of many other types of gloves[101]. These studies also found that the force influence is frequency-specific, which also depends on the type of glove[98, 101].

While the standardized glove test utilizes a palm adapter method to measure the vibration transmissibility for the evaluation of the gloves, an alternative method has also been developed by Dong *et al.*[92] to assess the gloves using the biodynamic responses of the bare- and gloved-hand-arm system exposed to vibration. A distinct advantage of the newly developed method is that it eliminates the use of an adapter in assessing the vibration isolation effectiveness of the glove. The adapter may change the glove-hand coupling relationship and result in overestimations of the effectiveness of the gloves in the middle- and high-frequency ranges. However, the results also suggest that the presence of the palm adapter between the subject's palm and the glove would not alter the basic trends in the transmissibility response. This suggests that it is acceptable to use the palm adapter method for rough screening of the gloves. While the biodynamic method has proven applicable for air bladder gloves, its application to other types of anti-vibration gloves may need further evaluation. Wasserman *et al.*[102] proposed the use of a flexible force sensor to measure the biodynamic force for the glove evaluation.

The effectiveness of gloves can also be evaluated using vibration transmitted to the fingers, the back of the hand, and the wrist[51, 103, 104]. While this method also eliminates the use of the adapter, its use may not be suitable to measure the transmissibility in the full frequency range (5–1, 500 Hz) of concern. This is because the fingers and hand can effectively absorb the high frequency vibration components. The glove test at workplaces is usually difficult and the experimental data can be very scattered[105]. The reliability and accuracy of the experimental data can be improved if the tool acceleration can also be measured, together with the transmitted vibration[51].

The effectiveness of the antivibration gloves is tool-specific[93, 106–108]. A few studies have demonstrated that it is acceptable to use the transmissibility measured in a laboratory to predict the frequency-weighted transmissibility of the anti-vibration gloves[106]. A study also showed that a broad-band white noise spectrum can be used to replace the M- and H-spectra specified in the glove test standard[109], which can simplify the test procedures. Another study demonstrated that when the ISO 10819 is used, it is not necessary to conduct the measurement up to 30 s as required in the standard[110]. Some specific revisions on ISO 10819 have been proposed[111].

Similar to ISO 10819, ISO 13753 (1999)[112] is mainly designed for screening glove materials. The impedance data in ISO 10068 are for the entire hand-arm system, which is the summation of the finger and palm mechanical impedance[13]. With this method, the effectiveness of the glove material for finger protection may be substantially overestimated. Furthermore, the transmissibility of the glove is measured at the palm in ISO 10819, in which only the palm-wrist-arm system is effectively involved in the response that determines the glove performance. Hence, there is an inconsistency in the use of mechanical impedance between ISO 13753 and ISO 10819. Such an inconsistency may not be clearly reflected in the weighted transmissibility values but it is likely detectable in the transmissibility spectra of the unweighted accelerations. Based on these observations, it has been suggested to use the finger and palm impedance data separately for the estimation[49], which can not only resolve such an inconsistency but may also provide a more realistic estimation.

Applied Forces

The total hand-tool coupling force is generally composed of the biodynamic force and the applied force[113]. While the biodynamic force can be considered as a passive component imposed to the hand-arm system, the applied force is a voluntary force from the tool operator[114]. They may play different roles in the initiation and development of vibration-induced injuries and disorders and they should be separately quantified and considered in the risk assessment. While the biodynamic force is a driving-point response parameter, this section reviews the studies of the applied force.

ISO 5349-1 (2001)[7] recommends the consideration of the applied force in the risk assessment. However, a specific method has not been developed for implementation. From the point of view of biodynamics, the effects of the applied force on the vibration-induced disorders can be taken into account by quantifying its influence on the static and dynamic stresses and deformations. Since the dynamic stress and

deformation should be somehow related to the biodynamic force and transmissibility, the effects of the applied force may also be taken into account by determining its influences on the biodynamic force-based (BFB) and transmitted acceleration-based (TAB) frequency weightings[55].

The development of convenient, reliable, and affordable hand force measurement methods for field application remains a formidable research task. In order to help develop effective methods, a draft ISO standard (ISO 15730/CD, 2004)[115] on the definition and general guidelines for the measurement of the hand coupling forces for operators exposed to hand-arm vibration has been proposed. A few investigators indicated that this draft standard has several fundamental deficiencies and technical problems[113]. Hopefully, it may be significantly improved when it is formally published.

Depending on the requirements of the accuracy and reliability in a study, different measurement methods have been used in the recent studies. A few new instrumented handles have been developed[13, 115–120]. They are suitable for laboratory studies. Some of them may also be used to measure hand forces during work tasks by incorporating the handles into vibrating tools. However, it is difficult to do so without changing the vibration characteristics on some of the tools. Furthermore, this approach may be inconvenient and expensive, especially when used in a large scale field study. Gillmeister and Schenk[121] reported a new instrumented palm adapter, which can provide convenient acceleration and force measurements. The measured force is the local force acting on the palm. It may also be possible to use similar adapters to measure the force at the fingers. The major limitations of this method are that the adapter may change the hand-tool coupling relation, and that the pressure distribution cannot be measured. Wafer-thin, light, and flexible force pressure sensors can be wrapped around the tool handle[50, 116, 122], incorporated into a work glove[77], or distributed on the palm[78, 123]. Electromyography (EMG) has been widely used for measuring hand forces in manual tasks[124, 125]. Several studies have also applied this technique to measure the hand force on workers using powered hand tools[126–128]. A few investigators have also started to examine and improve a psychophysical technique known as force matching for the force measurement[129]. A visual observation method for force estimation has also been evaluated in recent years[130].

The relationships among the total contact force, peak contact pressure, and the hand grip and push forces have been investigated[116, 122]. The results suggest that the hand-handle contact force and peak pressure are strongly dependent upon not only the grip and push forces but also the handle diameter. The total and peak contact forces for a given handle size can be expressed as a linear combination of grip and push forces, where the contribution of the grip force is considerably larger than that of the push force. The results further suggest that a linear relationship can characterize the dependence of the contact force and peak pressure on the handle diameter. The results show that the contact force developed in the vicinity of proximal phalanges of the digits and the palm is generally attributed to the push force, while forces at the fingers surface are caused by the gripping action. Owing to the difficulties associated with the measurement of interface pressures, the proposed relationships could be conveniently applied to obtain an estimate of the mean values of peak pressures on the basis of directly measurable grip and push forces.

The relationship between the applied forces (grip, push, contact forces) and the interface biodynamic response in the z_h-direction (along the forearm) has been studied[70]. This study found that the contact force was better correlated to the response at frequencies higher than 200 Hz while the lower frequency response was more closely correlated to the summation of the grip and push forces. This may be explained from the fact that the response at the lower frequencies is mainly distributed on the palm and that it heavily depends on the palm effective force (grip + push) but the response distributed on the fingers and palm are equally important at higher frequencies such that the force acting on the palm alone should not be sufficient to determine the overall response[12, 13].

Edgren *et al.*[131] recently studied the relationships between two orthogonal force measurements relative to the third metacarpal under a maximal voluntary power grip on cylindrical handles. The two force components were resolved into a magnitude and corresponding angle. They found that, on average, magnitude increased 34.8 N as handle diameter increased from 2.54 cm to 3.81 cm, and then monotonically declined 103.8 N as the handle diameter increased to 7.62 cm. When the diameter was smallest (2.54 cm), the greatest force component was in the direction where the fingertips opposed the palm. Conversely, when the diameter was largest (7.62 cm), the smallest component was in the same direction. The angle for the largest diameter increased with increasing hand size.

Studies reported in recent years also showed that the grip force shared among the fingertips is independent to the magnitude of the grip force and the diameter of the handle[119]; wearing glove or using tool with handles wrapped with vibration absorption material can reduce the contact pressure[123], triggering force, and muscular exertion[127].

Major Remaining Issues and Topics for Further Studies

The advanced biodynamics of the hand-arm system based on the biodynamic stress and strain concept is still at its initial stage. There are many issues and technical problems that have not been resolved. On the other hand, there are many opportunities and interesting topics for future studies.

Characterization and reduction of the vibration at the source

Effective reductions or controls of the vibration transmitted to hand and the exposure duration are probably the most effective approach for preventing hand-arm vibration syndrome. This requires developing tools that vibrate less harshly, antivibration handles and devices, and effective exposure monitoring devices.

The major role of the biodynamics in these developments is to provide reliable biodynamic response data and practical computer models. Further studies are required to collect more reliable data for improving ISO 10068[6]. It may be more useful to provide a standardized measurement method than to have a standard that only provides several sets of impedance data and computer models for some specific working conditions. Simply doubling the impedance data measured using a single hand-arm system may not be accurately representative of the true response in the tool operation using two hands[86, 132]. This suggests that the impedance or apparent mass in two-hand operations should also be studied.

The methods for evaluating the effectiveness of the antivibration devices such as antivibration handles, adapters, and gloves remain major issues for future studies. The standard method is based on the transmissibility of the ISO-weighted acceleration at the palm of the hand[91]. While the frequency weighting remains a critical issue for more studies, future studies on antivibration devices should report the transmissibility spectra of both weighted and unweighted accelerations. Another important aspect in the future studies is to determine the reduction distribution, especially that on the fingers.

It is currently recommended that the impedance data presented in ISO 10068[6] are used for estimating the transmissibility of anti-vibration glove material in ISO 13753[112]. A study reported that this method was acceptable when the loading mass in the material test was taken as 5 kg and the frequency-weighted accelerations were used in the calculation of the transmissibility[109]. If the impedance data in ISO 10068 are revised, the loading mass may need to be reevaluated.

It may be useful to investigate the characteristics of vibration in time-history. The relationship between impact vibration and the dynamic stresses and deformations inside the fingers-hand-arm system should be established, which may be correlated to some types of vibration-induced injuries and disorders.

A recent study has further confirmed that the vibration exposure duration is probably the most important parameter in the risk assessment[60]. Experiments have shown that the operators cannot be trusted to evaluate their exposure durations[133–135]. They tend to significantly overestimate the duration of the exposure. The detailed work-rest pattern may also be an important parameter for the risk assessment. Accurately quantifying the exposure duration and pattern may help establish more reliable dose-response relationship. Several new approaches for the measurements have been proposed[136–138]. Knowledge of hand-arm biodynamics should be further used to assist in the developments of more convenient and reliable portable vibration measurement systems such as instrumented watches and finger adapters for measuring both vibration magnitude and exposure duration.

System modeling

A single model may not be universally applicable to all the problems. Depending on the study objectives, appropriate models of the fingers, hand, arm, and the entire system with different complicities may be further developed and validated.

It may not be feasible for the current FE models to simulate the very detailed tissue structures. It may also be difficult for the FE models to precisely predict the dynamic stresses and deformations under every possible working condition. The major purposes of the FE modeling should be as follows:

- to understand the basic characteristics of the applied force-induced stresses and deformations under representative handle curvatures, geometries, textures *et al.*;
- to understand the basic distribution patterns of the dynamic stresses and deformations under different vibration magnitudes, directions, frequencies, and applied forces.
- to establish the basic relationships among the driving-point response parameters, the stresses and deformations, the accelerations transmitted to the surface of the system;
- to interpret the phenomena observed in the physiological and pathological studies and to explore the mechanisms of the vibration-induced injuries and disorders.
- and to assist in the design and/or improvements of diagnosis test methods and devices.

Driving-point biodynamic responses and vibration transmissibility

The biodynamic response distribution has been far from sufficiently studied. More experimental data are required to investigate the major factors that could influence the responses and transmissibility.

In addition to their use for the evaluations of tools and anti-vibration devices, a major objective of the studies on the driving-point response and vibration transmissibility is to help develop more optimum frequency weightings. There are large differences among the weightings derived from the transmitted acceleration, biodynamic force, and power absorption density. Each of the methods has unique features but none of them is perfect. Further studies are required to overcome the deficiencies of these biodynamic methods so that a better biodynamics-based frequency weighting methodology can be developed.

It should be emphasized that any significant change from the current ISO frequency weighting will likely have a profound impact not only on academic research and many national and international standards but also on the manufacturers of vibrating tools, anti-vibration devices, and some vibration measurement instruments. Hence, such a change must be based on a robust theory and reliable experimental data. Furthermore, the biodynamic studies may not take into account all the influencing factors that could significantly affect the development of hand-arm vibration syndrome. Any new frequency weighting derived from a biodynamic study must be sufficiently tested and evaluated using physiological, pathological, and epidemiological data before recommending it for any field application.

Applied force and pressure

Further developments of the force measurement methods and devices, especially for field studies, are required. The incorporation of the applied forces into the risk assessment will require not only more biodynamic studies but also studies in the other three foundations of hand-transmitted vibration.

Summary

The biodynamics of the hand-arm system is an essential foundation not only for the future standardization of the measurement, evaluation, and assessment of hand-transmitted vibration exposure, but also for the developments of better tools and anti-vibration devices. The advanced biodynamics based on the biodynamic stresses and deformations has been initiated and many studies can be conducted in this direction. The new biodynamic concept and the newly developed methodologies also provide many opportunities for studying the driving-point biodynamic responses distributed on the hand. It is anticipated that the further studies of the biodynamics of the system will eventually lead to establishment of a robust vibration exposure theory.

References

1) Dong RG, Rakheja S, Schopper AW, Han B, Smutz WP (2001) Hand-transmitted vibration and biodynamic response of the human hand-arm: a critical review. Crit Rev Biomed Eng **29**, 391–441.
2) Griffin MJ (1994) Foundations of hand-transmitted vibration standards. Nagoya J Med Sci **57** (Suppl), 147–64.
3) Curry BD, Govindaraju S, Brain JLW, Zhang LL, Yan J-G, Matloub HS, Riley DA (2003) Evidence for frequency-dependent arterial damage in vibrated rat tails. In: Proceeding of the 38th UK Conference on Human Response to Vibration. Alverstoke, Gosport, England.
4) Krajnak K, Welcome D, Lindsley WG, Dong RG (2005) The biodynamic and physiological responses of the rat tail to a single bout of vibration exposure. In: Proceedings of XXth Congress of the International Society of Biomechanics and 29th Annual Meeting of the American Society Biomechanics, Cleveland, Ohio, USA.
5) Burström L (1990) Measurement of the impedance of the hand and arm. Int Arch Occup Environ Health **62**, 431–9.
6) ISO 10068 (1998) Mechanical vibration and shock—free, mechanical impedance of the human hand-arm system at the driving point. International Organization for Standardization, Geneva, Switzerland.
7) ISO 5349-1 (2001) Mechanical vibration—measurement and evaluation of human exposure to hand-transmitted vibration—part 1: General requirements. Geneva, Switzerland: International Organization for Standardization.
8) Griffin MJ (1990) Handbook of human vibration. Academic Press, London.
9) Pelmear PL, Wasserman DE (1998) Hand-arm vibration: A comprehensive guide for occupational health professionals. OEM Press, Beverly Farms, MA, USA.
10) Dong RG, Warren C, Welcome DE, McDowell TW, JZ Wu (2004) A comparison and evaluation of the reported mechanical impedance data of the human hand-

arm system. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
11) Rakheja S, Wu JZ, Dong RG, Schopper AW (2002) A comparison of biodynamic models of the human hand-arm system for applications to hand-held power tools. J Sound Vib **249**, 55–82.
12) Dong RG, Schopper AW, McDowell TW, Welcome DE, Wu JZ, Smutz WP, Warren C, Rakheja S (2004) Vibration energy absorption (VEA) in human fingers-hand-arm system. Med Eng Physics **26**, 483–92.
13) Dong RG, Wu JZ, McDowell TW, Welcome DE, Schopper AW (2005) Distribution of mechanical impedance at the fingers and the palm of human hand. J Biomech **38**, 1165–75.
14) Wu JZ, Dong RG, Rakheja S, Schopper AW (2002) Simulation of mechanical responses of fingertip to dynamic loading. Med Eng Physics **24**, 253–64.
15) Wu JZ, Rakheja S, Dong RG, Schopper AW, Smutz WP (2002) Effects of static compression on the vibration modes of a fingertip. J Low Freq Sound, Vib Control **21**, 229–43.
16) Wu JZ, Dong RG, Schopper AW, Smutz WP (2004) A structural fingertip model for simulating of the biomechanics of tactile sensation. Med Eng Physics **26**, 165–75.
17) Stoyneva Z, Lyapina M, Tzvetkov D, Vodenicharov E (2003) Current pathophysiological views on vibration-induced Raynaud's phenomenon. Cardiovas Res **57**, 615–24.
18) Taber LA (1995) Biomechanics of growth, remodeling, and morphogenesis. Appl Mech Rev **48**, 487–545.
19) Chaffin DB, Andersson GB, Martin B (1999) Occupational biomechanics. John Wiley & Sons, Inc., New York.
20) Karwowski W, Marras WS (1999) Occupational ergonomics. CRC Press, New York, USA.
21) Greenstein D, Parkin A, Maughan J, Kester RC (1994) Perfusion defects in vibration white finger: a clinical assessment using isotope limb blood flow. Cardiovasc Surg **2**, 354–8.
22) Jen CJ, McIntire LV (1984) Characteristics of shear-induced aggregation in whole blood. J Lab Clin Med **103**, 115–24.
23) Necking LE, Lundborg G, Lundstrom R, Thornell LE, Friden J (2004) Hand muscle pathology after long-term vibration exposure. J Hand Surgery-British Europ **29B**, 431–7.
24) Necking LE, Lundstrom R, Dahlin LB, Lundborg G, Thornell LE, Friden J (1996) Tissue displacement is a causative factor in vibration-induced muscle injury. J Hand Sur-British Europ **21B**, 753–7.
25) Bovenzi M, Lindsell CJ, Griffin MJ (2001) Response of finger circulation to energy equivalent combinations of magnitude and duration of vibration. Occup Environ Med **58**, 185–93.
26) Welsh AJL, Griffin MJ (2004) Effect of vibration magnitude and push force on finger blood flow. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
27) Dong RG, McDowell TW, Welcome DE, Wu JZ (2004) An investigation of the relationship between vibration-induced white finger and power absorption. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
28) Lidström IM (1973) Measurement of energy dissipation by the body when using a vibrating tool. Nordisk Hygenisk Tidskrift **2**, 41–5.
29) Pradko F, Lee RA, Greene JD (1965) Human vibration-response theory. Am Soc Mech Eng No. 65-WA/HUF-19.
30) Cundiff JS (1976) Energy dissipation in human hand-arm exposed to random vibration. J Acous Soc Am **59**, 212–4.
31) Dong RG, McDowell TW, Welcome DE, Warren C, Schopper AW (2004) An evaluation of the standardized chipping hammer test specified in ISO 8662-2. The Ann Occup Hyg **48**, 39–49.
32) Pyykkö I, Färkkilä M, Toivanen J, Korhonen O, Hyvärinen J (1976) Transmission of vibration in the hand-arm system with special reference to changes in compression force and acceleration. Scand J Work Environ Health **2**, 87–95.
33) Gray H (1973) Anatomy of the human body. 29th ed., ed. by Gross C, Lea and Febider, Philadelphia.
34) Fawcett D (1986) Text book of histology. 11th ed., W.B. Saunders Co, Philadelphia.
35) Pawluk D, Howe R (1999) Dynamic lumped element response of the human fingerpad. J Biomech Eng **121**, 178–83.
36) Jindrich DL, Zhou Y, Becker T, Dennerlein JT (2003) Non-linear viscoelastic models predict fingertip pulp force-displacement characteristics during voluntary tapping. J Biomech **36**, 497–503.
37) Srinivasan M (1989) Surface deflection of primate fingertip under line load. J Biomech **22**, 343–9.
38) Serina E, Mockensturm E, Mote CJ, Rempel D (1998) A structural model of the forced compression of the fingertip pulp. J Biomech **31**, 639–46.

39) Srinivasan M, Dandekar K (1996) An investigation of the mechanics of tactile sense using two-dimensional models of the primate fingertip. J Biomech Eng **118**, 48–55.
40) Dandekar K, Raju BI, Srinivasan MA (2003) 3-D finite-element models of human and monkey fingertips to investigate the mechanics of tactile sense. J Biomech Eng **125**, 682–91.
41) Wu JZ, Dong RG, Schopper AW, Smutz WP (2003) Analysis of skin deformation profiles during sinusoidal vibration of fingerpad. Ann Biomed Eng **31**, 867–78.
42) Mow VC, Kuei SC, Lai WM, Armstrong CG (1980) Biphasic creep and stress relaxation of articular cartilage: theory and experiment. ASME J, Biomech Eng **102**, 73–84.
43) Perez C, Holzmann C, Jaeschke H (2000) Two-point vibrotactile discrimination related to parameters of pulse burst stimulus. Med Biol Eng Comput **38**, 74–9.
44) Goodwin A, John K, Darian-Smith I (1989) Skin profiles during sinusoidal vibration of the fingerpad. Exp Brain Res **77**, 79–86.
45) Griffin MJ (1997) Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. Occup Environ Medicine **54**, 73–89.
46) Gurram R, Rakheja S, Gouw GJ (1994) Biodynamic response of the human hand-arm system subject to sinusoidal and stochastic excitations. In: Advances in Industrial Ergonomics and Safety VI. 239–46 Taylor & Francis, London.
47) Kihlberg S (1995) Biodynamic response of the hand-arm system to vibration from an impact hammer and a grinder. Int J Ind Ergonomics **16**, 1–8.
48) Dong RG, McDowell TW, Welcome DE, Wu JZ (2004) Biodynamic response of human fingers in a power grip subjected to a random vibration. J Biomech Eng (Transactions of the ASME), **126**, 446–56.
49) Dong RG, Welcome DE, McDowell TW (2005) Biodynamic response at the palm of the human hand subjected to a random vibration. Ind Health **43**, 242–55.
50) Valentino M, Rapisarda V, Scalise L, Paone N, Santarelli L, Fenga C, Ross LG (2004) A new method for the experimental assessment of finger haemodynamic effects induced by a hydraulic breaker in operative conditions. J Occup Health **46**, 253–9.
51) Dong RG, McDowell TW, Welcome DE, Smutz WP, Schopper AW, Warren C, Wu JZ, Rakheja S (2003) On-the-hand measurement methods for assessing effectiveness of anti-vibration gloves. Int J Ind Ergon **32**, 283–98.
52) Ksiazek MA, Tarnowski J (2001) Measurements of hand-tool vibrations by non-contact methods. In: Proceeding of the 9th Conference on Hand-arm Vibration. Nancy, France.
53) Ksiazek MA, Tarnowski J (2002) Measurements and modeling of hand-handle system. In: Proceeding of the 37th UK Conference on Human Responses to Vibration. 370–81, Dept. of Human Science, Loughborough University, UK.
54) Thomas M, Beauchamp Y (1998) Development of a new frequency weighting filter for the assessment of grinder exposure to wrist transmitted vibration. Computers Ind Eng **35**, 651–4.
55) Dong RG, Welcome DW, Wu JZ (2005) Frequency weightings based on biodynamics of fingers-hand-arm system. Ind Health **43**, 516–26.
56) Malchaire J, Piette A, Cock N (2001) Associations between hand-wrist musculoskeletal and sensorineural complaints and biomechanical and vibration work constraints. Ann Occup Hyg **45**, 479–91.
57) Sörensson A, Lundström R (1992) Transmission of vibration to the hand. J Low Freq Noise Vibrat **11**, 14–22.
58) Reynolds DD (1977) Hand-arm vibration: A review of 3 years research. In: Proceeding of the 2nd International Conference on Hand-arm Vibration. 99–128 Cincinnati, OH, USA.
59) NIOSH (1989) Criteria for a recommended standard: Occupational exposure to hand-arm vibration. U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, Cincinnati, OH, USA.
60) Griffin M, Bovenzi M, Nelson CM (2003) Dose-response patterns for vibration-induced white finger. Occup Environ Med **60**, 16–26.
61) Maeda S, Dong RG (2004) Measurement of hand-transmitted vibration exposure. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
62) Gurram R, Rakheja S, Brammer AJ (1995) Driving-point mechanical impedance of the human hand-arm system: Synthesis and model development. J Sound Vib **180**, 437–58.
63) Gurram R, Rakheja S, Gouw GJ (1995) Mechanical impedance of the human hand-arm system subject to sinusoidal and stochastic excitations. Int J Ind Ergon **16**, 135–45.

64) Burström L (1997) The influence of biodynamic factors on the mechanical impedance of the hand and arm. Int Arch Occup Environ Health **69**, 437–46.
65) Burström L, Lundström R (1994) Absorption of vibration energy in the human hand and arm. Ergonomics **37**, 879–90.
66) Dong RG, McDowell TW, Welcome D, Wu JZ, Warren C, Smutz WP, Schopper AW (2002) Mechanical energy absorption in human fingers exposed to hand-transmitted vibration. In: Biomedical engineering: Recent developments. ed. by Vossoughi J, 159–60, Medical and Engineering Publishers, Inc.
67) Bylund SH, Burstrom L (2003) Power absorption in women and men exposed to hand-arm vibration. Int Arch Occup Environ Health **76**, 313–7.
68) Burstrom L, Sorensson A (1999) The influence of shock-type vibrations on the absorption of mechanical energy in the hand and arm. Int J Ind Ergonom **23**, 585–94.
69) Sorensson A, Burstrom L (1996) Energy absorption of vibration in the hand for higher frequencies. J Low Freq Noise Vib **15**, 71–9.
70) Marcotte P, Aldien Y, Boileau PE, Rakheja S, Boutin J (2005) Effect of handle size and hand-handle contact force on the biodynamic response of the hand-arm system under zh-axis vibration. J Sound Vib **283**, 1071–91.
71) Gurram R, Rakheja S, Gouw GJ (1994) Vibration transmission characteristics of the huan hand-arm system and gloves. Int J Ind Ergonom **13**, 217–34.
72) Dong RG, Rakheja S, Smutz WP, Schopper AW, Caporali S (2003) Dynamic characterization of the simulated tool handle and palm-adapter used for assessment of vibration performance of gloves. J Testing Evaluat **31**, 234–46.
73) Welcome DE, Dong RG, McDowell TW, Wu JZ (2004) Evaluations of instrumentation for measuring biodynamic response of hand-arm system. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
74) Moustafa AK, Reynold D (2004) Mechanical impedance characteristics of the hand and arm. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
75) Griffin MJ (1997) Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. Occup Environ Med **54**, 73–89.
76) Lundström R (1984) Local vibration—Mechanical impedance of the human hand's glabrous skin. J Biomech **17**, 137–44.
77) Feutry D, Lemerte P, Claudon L (2004) Design of a new instrumented glove for the measurement of the contact pressure distribution at the hand/handle interface. In: Proceeding of the 10th International Conference on Hand-arm Vibration. 85–6, Las Vegas, USA.
78) Nikonovas A, Harrison AJL, Hoult S, Sammut D (2004) The application of force-sensing resistor sensors for measuring forces developed by the human hand. J Eng Med (IMechE Part H) **218**, 121–6.
79) Lidström IM (1977) Vibration injury in rock drillers, chiselers, and grinders. Some views on the relationship between the quantity of energy absorbed and the risk of occurrence of vibration injury. In: Proceeding of the 2nd International Conference on Hand-arm Vibration. 77–83, Cincinnati, OH, USA.
80) Burstrom L (1990) Absorption of vibration energy in the human hand and arm. Doctorial thesis, Lulea University of Technology.
81) Tominaga Y (1993) The relationship between vibration exposure and symptoms of vibration syndrome. J Sci Labor **69**, 1–14.
82) Tominaga Y (2004) Frequency weighting of hand-arm vibration. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
83) Reynolds DD, Standlee KG, Angevine EN (1977) Hand-arm vibration. Part III: Subjective response characteristics of individuals to hand-induced vibration. J Sound Vib **51**, 267–82.
84) Dong RG, Wu JZ, Welcome DE, McDowell TW (2005) Estimation of vibration power absorption density in human fingers. J Biomech Eng (in press).
85) Donati P (2001) Evaluation of occupational exposure to hand-transmitted vibration: frequency weighting and exposure time (a preliminary survey) Vibration Injury Network, Appendix H4A (http://www.humanvibration.com/EU/VINET/).
86) Schenk Th, Kinne J, Gillmeister F (2001) A real hand-arm model for use in hand-held too test stands for vibration studies. In: Proceeding of the 9th International Conference on Hand-arm Vibration. 121–7, Nancy, France.
87) Oddo R, Loyau T, Boileau PE, Champoux Y (2004) Design of a suspended handle to attenuate rock drill hand-arm vibration: model development and validation. J Sound Vib **275**, 623–40.
88) Golycheva EV, Babitsky VI, Veprik AM (2004) Vibration protection for an operator of a hand-held percussion machine. J Sound Vib **274**, 351–67.
89) Golycheva EV, Babitsky VI, Veprik AM (2003)

Dynamic correlation of excitation in hand-held electro-pneumatic percussive machines. J Sound Vib **259**, 829–43.

90) Lin JH, Radwin RG, Richard TG (2003) A single-degree-of-freedom dynamic model predicts the range of human responses to impulsive forces produced by power hand tools. J Biomech **36**, 1845–52.

91) ISO 10819 (1996) Mechanical vibration and shock—Hand-arm vibration—Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. International Organization for Standardization, Geneva, Switzerland.

92) Dong RG, Subhash R, McDowell TW, Welcome DE, Wu JZ, Warren C, Barkley J, Washington B, Schopper AW (2004) A method for determining the transmissibility of antivibration gloves using biodynamic responses of hand-arm system. J Sound Vib **282**, 1101–18.

93) Griffin MJ (1998) Evaluating the effectiveness of gloves in reducing hazards hand-transmitted vibration. Occup Environ Med **55**, 340–8.

94) Hewitt S (2002) Round robin testing of anti-vibration gloves towards a revision of ISO 10819:1996. In: Proceeding of the 37th UK Conference on Human Responses to Vibration. 118–29, Dept. of Human Sciences, Loughborough University, UK.

95) Smutz WP, Dong, RG, Han B, Schopper AW, Welcome D, Kashon M (2002) A method for reducing adaptor misalignment when testing gloves using ISO 10819. Ann Occup Hyg **46**, 1–7.

96) Boileau PE, Boutin J, Rakheja S, Dong RG (2002) Critical evaluation of a laboratory test procedure for measuring the vibration transmissibility of gloves. In: Proceeding of the 37th UK Conference on Human Responses to Vibration. 106–17, Dept. of Human Sciences, Loughborough University, UK.

97) Dong RG, Rakheja S, Smutz WP, Schopper AW, Wu JZ (2002) Evaluating anti-vibration performance of a glove using total effective transmissibility. International J Ind Ergon **30**, 33–48.

98) Dong RG, McDowell TW, Welcome DE, Barkley J, Warren C, Washington B (2004) Effects of hand-tool coupling conditions on the isolation effectiveness of air bladder anti-vibration gloves. J Low Freq Noise, Vibrat Active Control **23**, 231–48.

99) Dong RG, McDowell TW, Welcome DE, Smutz PW, Schopper AW (2005) The correlation between biodynamic characteristics of human hand-arm system and the isolation effectiveness of anti-vibration gloves. Int J Ind Ergonom **35**, 205–16.

100) O'Boyle MJ (2001) The effect of hand and arm volume on the vibration transmissibility of gloves according to current standards. In: Proceeding of the 36th UK Conference on Human Response to Vibration. 359–67, Farnborough, UK.

101) O'Boyle MJ, Griffin MJ (2004) Transmissibility and dynamic stiffness of glove materials and the apparent mass of the hand. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.

102) Wasserman J, Logston D, Wasserman D (2004) The use of a resistive pressure sensor to assess glove effects on tool transmitted vibration. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.

103) ANSI S3.40 (1989) Guide for the measurement and evaluation of gloves which are used to reduce exposure to vibration transmitted to the hand. American National Standards Institute (ANSI), New York.

104) Paddan GS, Griffin MJ (2001) Measurement of glove and hand dynamics using knuckle vibration. In: Proceedings of the 9th International Conference on Hand-arm Vibration, Section 15. Nancy, France.

105) Pinto I, Stacchint N, Bovenzi M, Paddan GS, Griffin MJ (2001) Protection effectiveness of anti-vibration gloves: Field evaluation and laboratory performance assessment. In: Proceedings of the 9th International Conference on Hand-arm Vibration. 387–96, Nancy, France.

106) Rakheja S, Dong R, Welcome D, Schopper AW (2002) Estimation of tool-specific isolation performance of anti-vibration gloves. Int J Ind Ergon **30**, 71–87.

107) Dong RG, McDowell T, Welcome D, Rakheja S, Caporali SA, Schopper AW (2002) Effectiveness of a transfer function method for evaluating vibration isolation performance of gloves when used with chipping hammers. J Low Freq Sound, Vibrat, Control **21**, 141–56.

108) Nataletti P, Lenzuni P, Lunghi A, Pieroni A, Marchetti E (2004) Antivibration gloves effectiveness: in field and laboratory tests and proposal for a new standard. In: Proceeding of the 10th international conference on hand-arm vibration. Las Vegas, USA.

109) Boileau PE, Boutin J (2001) Investigating the relationship in vibration transmissibility characteristics of resilient materials and gloves using standardized test methods. In: Proceeding of the 9th International

Conference on Hand-arm Vibration. 397–405, Nancy, France.

110) Paddan G (2001) Effect of measurement period on the testing of antivibraiton gloves. In: Proceeding of the 36th Conference on Human Responses to Vibration. 345–57, Centre for Human Science, QinetiQ, Farnborough, UK.

111) Voss P (2004) The revision of the glove vibration isolation standard: ISO 10819. In: Proceeding of the 10th International Conference on Hand-arm Vibration. 177, Las Vegas, USA.

112) ISO 13753 (1999) Mechanical vibration and shock—hand-arm vibration—method for measuring the vibration transmissibility of resilient materials when loaded by the hand-arm system. International Organization for Standardization, Geneva, Switzerland.

113) Dong RG, Welcome DW, Wu JZ (2005) Estimation of the biodynamic force acting at the interface between hand and vibrating surface. Ind Health **43**, 485–94.

114) Dennis A, Nowak DA (2004) Different modes of grip force control: voluntary and externally guided arm movements with a hand-held load. Clin Neurophysiol **115**, 839–48.

115) ISO/CD 15230 (2004) Definition and guidelines for the measurement of the coupling forces for operators exposed to hand-arm vibration. International Organization for Standardization, Geneva, Switzerland.

116) Welcome DE, Rakheja S, Dong RG, Wu JZ, Schopper AW (2004) Relationship between the grip, push and contact forces between the hand and a tool handle. Int J Ind Ergon **34**, 507–18.

117) McGorry RW (2001) A system for the measurement of grip forces and applied moments during hand tool use. Appl Ergon **32**, 271–9.

118) Chadwick EKJ, Nicol AC (2001) A novel force transducer for the measurement of grip force. J Biomech **34**, 125–8.

119) Freund J, Toivonen R, Takala EP (2002) Grip forces of the fingertips. Clin Biomech **17**, 515–20.

120) Zatsiorsky VM, Gao F, Latash ML (2003) Finger force vectors in multi-finger prehension. J Biomech **36**, 1745–9.

121) Gillmeister F, Schenk T (2001) Hand-arm vibration and coupling force measurement with a new adapter. In: Proceeding of the 9th International Conference on Hand-arm Vibration. 9–18, Nancy, France.

122) Aldien Y, Welcome DE, Rakheja S, Dong RG, Boileau PE (2005) Contact pressure distribution at hand-handle interface: role of hand forces and handle size. Int J Ind Ergon **35**, 267–86.

123) Björing G, Johansson L, Hägg GM (2002) Surface pressure in the hand when holding a drilling machine under different drilling conditions. Int J Ind Ergon **29**, 255–61.

124) Spielholz P, Silverstein B, Morgan M, Checkoway H, Kaufman J (2001) Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors. Ergonomics **44**, 588–613.

125) Hoozemans MJM, van Dieën JH (2004) Prediction of handgrip forces using surface EMG of forearm muscles. J Electromyogr Kinesiol **15**, 358–66.

126) Armstrong TJ, Marshall MM, Martin BJ, Foulke JA, Grieshaber DC, Malone G (2002) Exposure to forceful exertion and vibration in a foundry. Int J Ind Ergon **30**, 163–79.

127) Chang CH, Wang MJJ, Lin SC (1999) Evaluating the effects of wearing gloves and wrist support on hand-arm response while operating an in-line pneumatic screwdriver. Int J Ind Ergon **24**, 473–81.

128) Lin JH, Radwin R, Fronczak F, Richard T (2003) Forces associated with pneumatic power screwdriver operation: statics and dynamics. Ergonomics **46**, 1161–77.

129) McDowell TW, Dong RG, Welcome DE (2004) A pilot study of glove effects on a force matching method. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.

130) Marshall MM, Armstrong TJ (2004) Observational assessment of forceful exertion and the perceived force demands of daily activities. J Occup Rehabil **14**, 281–94.

131) Edgren CS, Radwin RG, Irwin CB (2004) Grip force vectors for varying handle diameters and hand sizes. Hum Factors **46**, 244–51.

132) Kinne J, Latzel K, Schenk T (2001) Application of two-hand impedance as basis for mechanical modeling. In: Proceedings of the 9th International Conference on Hand-arm Vibration. 113–20, Nancy, France.

133) Palmear KT, Coggon DN, Bednall HE, Kellingray SD, Pannett B, Griffin MJ, Haward B (1999) Hand-transmitted vibration: occupational exposures and their health effects in Great Britain. HSE, UK.

134) Gerhardsson L, Balogh I, Hambert PA, Hjortsberg U, Karlsson JE (2005) Vascular and nerve damage in workers exposed to vibrating tools. The importance

of objective measurements of exposure time. Appl Ergon **36**, 55–60.

135) Akesson I, Balogh I, Skerfving S (2001) Self-reported and measured time of vibration exposure at ultrasonic scaling in dental hygienists. Appl Ergon **32**, 47–51.

136) Gillmeister F, Schenk T, Melzig-Thiel R (2001) A personal dosimeter for daily vibration exposure. In: Proceeding of the 9th International Conference on Hand-arm Vibration. 55–62, Nancy, France.

137) Dong RG, Bader J, Welcome D, Rakheja S, Schopper AW (2001) An accurate method for measuring the exposure duration of hand-transmitted vibration. In: Proceedings of the 36th United Kingdom Group Meeting on Human Responses to Vibration. 416–24, Centre for Human Sciences, QinetiQ, Farnborough, UK.

138) Maeda S (2004) Work computer for prevention of over exposure to hand-transmitted vibration. In: Proceeding of the 10th International Conference on Hand-arm Vibration. 123–4, Las Vegas, USA.