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An examination of the vibration transmissibility of the hand-arm system in three orthogonal directions

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ABSTRACT

The objective of this study is to enhance the understanding of the vibration transmission in the hand-arm system in three orthogonal directions (*X*, *Y*, and *Z*). For the first time, the transmitted vibrations distributed on the entire hand-arm system exposed in the three orthogonal directions via a 3-D vibration test system were measured using a 3-D laser vibrometer. Seven adult male subjects participated in the experiment. This study confirms that the vibration transmissibility generally decreased with the increase in distance from the hand and it varied with the vibration direction. Specifically, to the upper arm and shoulder, only moderate vibration transmission was measured in the test frequency range (16 to 500 Hz), and virtually no transmission was measured in the frequency range higher than 50 Hz. The resonance vibration on the forearm was primarily in the range of 16–30 Hz with the peak amplitude of approximately 1.5 times of the input vibration amplitude. The major resonance on the dorsal surfaces of the hand and wrist occurred at around 30–40 Hz and, in the *Y* direction, with peak amplitude of more than 2.5 times of the input amplitude. At higher than 50 Hz, vibration transmission was effectively limited to the hand and fingers. A major finger resonance was observed at around 100 Hz in the *X* and *Y* directions and around 200 Hz in the *Z* direction. In the fingers, the resonance magnitude in the *Z* direction was generally the lowest, and the resonance magnitude in the *Y* direction was generally the highest with the resonance amplitude of 3 times the input vibration, which was similar to the transmissibility at the wrist and hand dorsum. The implications of the results are discussed.

Relevance to industry: Prolonged, intensive exposure to hand-transmitted vibration could result in hand-arm vibration syndrome. While the syndrome's precise mechanisms remain unclear, the characterization of the vibration transmissibility of the system in the three orthogonal dimensions performed in this study can help understand the syndrome and help develop improved frequency weightings for assessing the risk of the exposure for developing various components of the syndrome.

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1. Introduction

Hand-transmitted vibration exposure is associated with hand-arm vibration syndrome (HAVS) (NIOSH, 1997; Griffin, 1990). Although many studies on this subject have been reported, the syndrome's precise mechanisms remain unclear (ISO 5349-1, 2001). One of the essential foundations for further understanding their mechanisms is the biodynamic responses of the hand-arm system to vibration (Griffin, 1994; Dong et al., 2005a, b). Because the transmissibility on the human body is directly measurable, it can be used to represent the distributed features of the system responses, and it has a certain relationship with the driving-point response function (Dong et al., 2013), the examination of the vibration transmissibility has been used as one of the major approaches to quantify and understand the biodynamic responses.

It remains a challenging task to accurately measure the transmitted vibration on the hand-arm system of a subject. While no feasible non-invasive method has been developed to measure the vibration inside the system of a human subject, the measurement has been most frequently performed at the surface of the hand-arm system using miniature accelerometers (Pyykkö et al., 1976; Reynolds 1977; Griffin et al., 1982; Gurram et al., 1994; Cherian et al., 1996; Thomas and Beauchamp, 1998; Adewusi et al., 2012).

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The attachment of an accelerometer to the skin usually introduces some artificial constraints to the local structure where the vibration is measured. The mass of the accelerometer could also significantly affect the measurement results. This is primarily because the resonant frequency of the mass-skin assembly is likely to be within the frequency range of concern for hand-transmitted vibration exposure. A tight fixation may increase the attachment stiffness so that the useful measurement frequency range can be increased; however, this may further alter the biodynamic properties of the local structure. These effects also make it impractical to attach a sufficient number of accelerometers on the system to characterize the vibration distribution with reasonable spatial resolution. Furthermore, it is very difficult to fix and determine the global orientation of the accelerometer at each measurement location, because the orientation of the accelerometer fixed on the deformable contact surface may vary with the applied force and pressure distribution, which may also vary with subject and measurement location.

These problems can be largely overcome by using a three-dimensional (3-D) laser vibrometer. While a 1-D laser vibrometer has been used for the measurement of the transmitted vibration in the direction approximately vertical to the surface of the hand-arm system (Sörensson and Lundström, 1992; Rossi and Tomasini, 1995; Deboli et al., 1999; Nataletti et al., 2005; Scalise et al., 2007; Concettoni and Griffin, 2009; Xu et al., 2011), the feasibility of applying a 3-D laser vibrometer to reliably measure multi-axial vibrations of the hand-arm system has not been proven. Except for a preliminary introduction of the current study (Welcome et al., 2011), the application of a 3-D laser vibrometer for the measurement of 3-D vibrations on the entire hand-arm system was not found during the literature review for this study.

The reported transmissibility data, together with the driving-point response functions, have provided a general understanding of the vibration transmission in the hand-arm system, especially along the forearm direction. Specifically, the vibration can be effectively transmitted to the head, neck, shoulder, and/or arms below 25 Hz (Pyykkö et al., 1976; Sakakibara et al., 1986; Reynolds, 1977). This explains why the low-frequency vibration is predominantly perceived in these substructures (McDowell et al., 2007). This also partially explains why the most highly weighted frequencies for subjective sensation or discomfort for the hand-transmitted vibration exposure are in the low frequency range (Miwa, 1968; Giacomin et al., 2004; Morioka and Griffin, 2006). While the major resonance of the shoulder and upper arm is likely to be in the range of 8–12 Hz (Kinne et al., 2001; Dong et al., 2007; Adewusi et al., 2012), the major wrist-forearm resonance is usually in the range of 16–40 Hz (Thomas and Beauchamp, 1998; Kihlberg et al., 1995; Dong et al., 2007, 2012). Above 100 Hz, the vibration transmission is largely limited to the hand and fingers (Pyykkö et al., 1976; Reynolds, 1977). The major finger resonance can vary from 80 to more than 300 Hz (Sörensson and Lundström, 1992; Dong et al., 2007), depending on the specific locations on the fingers and the applied finger forces.

There are large differences among the impedance data measured in different directions (Dong et al., 2012). This suggests that the vibration transmission in the hand-arm system should also vary significantly with the vibration directions. However, their specific differences have not been clearly identified. It is common knowledge that the stiffness of the human skin in the shear or tangential direction under pressure is usually much less than that in the compression direction. The low stiffness could significantly reduce the useful measurement frequency range in the directions tangential to the skin using conventional accelerometers, casting some doubt on the reported data. However, little information on the vibration transmissibility in the tangential directions was available from the reported studies that used the 1-D laser vibrometer in the measurement. Furthermore, the vast majority of the reported studies did not measure or report the phase angle of the transmissibility, which often proves useful, for example to determine the phase relationships among the vibration motions at different locations or the vibration mode shapes of the system. Simultaneous measurement of 3-D vibration transmissibility will also provide coupled 3-D vibration transfer functions of the system, which will be essential to develop a more realistic 3-D model of the hand-arm system but this has not been yet attempted.

Based on this background, the specific aims of this study are twofold: (a) to examine the feasibility of using a 3-D laser vibrometer for the measurement of the 3-D transfer functions on the hand-arm system; and (b) to characterize the vibration transfer functions distributed on the entire hand-arm system in three orthogonal directions. The implications of the results for developing improved biodynamic models of the system are also discussed.

2. Method

2.1. Experimental setup

Seven healthy male adults participated in this study. Their anthropometric measurements are listed in Table 1. The study protocol was reviewed and approved by the NIOSH Human Subjects Review Board.

Fig. 1 shows the basic instrumentation setup and the subject posture. A pictorial view of the setup is shown in Fig. 2. A 3-D vibration test system (MB Dynamics, 3-D Hand-Arm Vibration Test System) was employed to generate the required vibration spectra in three directions: *Z* - along the forearm; *Y* - along the centerline of the instrumented handle in the vertical direction; and *X* - in the horizontal plane normal to the *Y*-*Z* plane. An instrumented handle equipped with a tri-axial accelerometer (ENDEVCO 65–100) and a pair of 3-D force sensors (Kistler 9017B and 9018B) was used to measure the accelerations and applied grip force in three directions. A force plate (Kistler 9286AA) was used to measure the push force applied to the handle. Each subject was also instructed to grip the handle with the forearm parallel to the floor and aligned with the *Z* axis, the elbow angled between 90° and 120°, and shoulder abducted between 0° and 30°; these parameters are similar to those recommended in the standardized glove test (ISO 10819, 1996) and those used for the reference values in ISO-10068 (1998). As also used in these standards, 30 N grip and 50 N push are generally considered as the average hand forces applied in many tool operations. Therefore, the grip and push forces were also controlled as 30 ± 5 N and 50 ± 8 N, respectively, in the current study. The measured forces were displayed on two virtual dial gauges on a computer monitor in front of the subject, as also shown

Table 1
Subject anthropometry (hand length = tip of middle finger to crease at wrist; hand breadth = the width measured at metacarpal).

Subject	Height (cm)	Weight (kg)	Hand length (mm)	Hand breadth (mm)
1	180.8	80.70	200	90
2	185.4	69.10	192	86
3	182.9	68.95	192	84
4	176.5	79.83	193	83
5	180.3	88.45	192	89
6	179.1	87.00	190	89
7	181.6	99.79	200	94
Mean	180.9	81.97	194	88
SD	2.8	11.00	4	4