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Vibrations transmitted from human hands to upper arm, shoulder, back, neck, and head

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Some powered hand tools can generate significant vibration at frequencies below 25 Hz. It is not clear whether such vibration can be effectively transmitted to the upper arm, shoulder, neck, and head and cause adverse effects in these substructures. The objective of this study is to investigate the vibration transmission from the human hands to these substructures. Eight human subjects participated in the experiment, which was conducted on a 1-D vibration test system. Unlike many vibration transmission studies, both the right and left hand-arm systems were simultaneously exposed to the vibration to simulate a working posture in the experiment. A laser vibrometer and three accelerometers were used to measure the vibration transmitted to the substructures. The apparent mass at the palm of each hand was also measured to help in understanding the transmitted vibration and biodynamic response. This study found that the upper arm resonance frequency was 7–12 Hz, the shoulder resonance was 7–9 Hz, and the back and neck resonances were 6–7 Hz. The responses were affected by the hand-arm posture, applied hand force, and vibration magnitude. The transmissibility measured on the upper arm had a trend similar to that of the apparent mass measured at the palm in their major resonant frequency ranges. The implications of the results are discussed.

Relevance to industry: Musculoskeletal disorders (MSDs) of the shoulder and neck are important issues among many workers. Many of these workers use heavy-duty powered hand tools. The combined mechanical loads and vibration exposures are among the major factors contributing to the development of MSDs. The vibration characteristics of the body segments examined in this study can be used to help understand MSDs and to help develop more effective intervention methods.

1. Introduction

Wrist, elbow, shoulder, and neck disorders are among the major components of upper extremity musculoskeletal disorders (MSDs) (Bernard, 1997; NRC, 2001). They remain major occupational diseases for further studies (Linaker and Walker-Bone, 2015). The use of vibrating hand tools or vibration exposure is one of the primary work-related factors of these disorders (Bovenzi et al., 1987; Gemne and Saraste, 1987; Van der Windt et al., 2000; Ariens et al., 2000; Miranda et al., 2008). This may be because the vibration exposure can affect joint mechanical stability and muscle activities (Rohmert et al., 1989; Romaiguère et al., 1993). Large vibrations or shocks may also cause injuries of the hard tissues and soft tissues of these joint structures. While the exact roles of vibration in the development of these MSDs remain unclear, a reliable dose-response relationship between the disorders and the vibration exposure has not been established (Bovenzi et al., 1987; Gemne and Saraste, 1987; Bovenzi, 1998). Further studies are also required to develop more effective methods for preventing these disorders.

Biomechanical stimuli such as stresses and strains of biological tissues are essential factors that control the growth, remodeling, and morphogenesis of a biological system (Taber, 1995). Vibration-induced stresses, strains, and power absorptions of the tissues are part of the biomechanical stimuli. While it is very difficult to directly measure these vibration stimuli, they are usually estimated using biodynamic models developed based on measurable response functions such as vibration transmissibility and driving-point response functions (apparent mass and mechanical impedance) of the hand-arm system (Wu et al., 2010). Therefore, the

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measurements and analyses of these biodynamic response functions are important steps towards understanding vibration-induced MSDs. These response functions are also very important for designing, analyzing, and testing tools and vibration-reducing devices.

Many studies have investigated the driving-point response functions of the hand-arm system (Gurram et al., 1995; Marcotte et al., 2005; Kihlberg, 1995; Dong et al., 2008, 2013a). Other studies have also measured the vibration transmissibility at the wrist, elbow, forearm, and upper arm (Pyykko et al., 1976; Reynolds and Angevine, 1977; Aatola, 1989; Gurram et al., 1994; Adewusi et al., 2010; Thomas and Beauchamp, 1998; Xu et al., 2009, 2015; Welcome et al., 2015; Marchetti et al., 2015). The theoretical relationship between the transmissibility and the driving-point response functions have also been described (Dong et al., 2013b). These studies have provided some useful knowledge of the responses of the hand-arm system to vibration. For example, while the palm-wrist-forearm-elbow-upper arm-shoulder subsystem theoretically has an infinite number of natural frequencies, only a few major resonances can be consistently observed in the reported experimental data. Unlike the resonances of many metal structures, the transmissibility resonances of the hand-arm system are not sharp and the peak transmissibility value is usually less than 3.0. These phenomena indicate that the hand-arm system exhibits large damping properties that effectively suppress the vast majority of the resonances. These natural properties can help protect the hand-arm system from damage or injuries. However, it is still desired to avoid the remaining hand-arm resonances to protect the system from potentially-harmful vibration exposures. One of the major remaining resonances usually occurs in the range of 20–40 Hz. It can be clearly identified from the vibration transmissibility measured at the wrist, forearm, and elbow (Thomas and Beauchamp, 1998; Xu et al., 2009, 2015; Welcome et al., 2015; Marchetti et al., 2015). It can also be clearly observed in the impedance data, but the impedance resonant frequency is higher than the transmissibility or apparent mass resonant frequency; the impedance is equal to the apparent mass multiplied by the frequency. This resonant frequency depends primarily on the palm contact stiffness and the effective mass of the palm-wrist-forearm substructures (Dong et al., 2008). This explains why the specific resonant frequency is primarily affected by the palm contact force, hand and arm postures, handle geometry, vibration direction, and dynamic properties of the individual. A vibration-reducing glove basically reduces the palm contact stiffness and the related resonant frequency (Dong et al., 2009). This explains why the vibration-reducing effectiveness of such gloves is usually limited to vibration frequencies above 25 Hz, as observed in the transmissibility spectra of gloves (Welcome et al., 2012; McDowell et al., 2013). Another important resonant frequency is usually observed in the range of 8–12.5 Hz (Marchetti et al., 2015; Adewusi et al., 2010; Xu et al., 2015), the specific value of which also depends primarily on the above-mentioned influencing factors. It can be clearly identified from the vibration transmissibility spectra measured at the upper arm, elbow, and wrist, as well as the apparent mass measured at the palm of the hand (Adewusi et al., 2010; Marchetti et al., 2015; Xu et al., 2015). The independence from the measurement location indicates that this resonance is a global resonance of the entire hand-arm system, although the resonance is most obvious in the upper arm (Adewusi et al., 2010; Xu et al., 2015). Coincidently, the highest frequency weighting defined in the current standard for risk assessments of hand-transmitted vibration exposures occurs at 12.5 Hz (ISO 5349-1, 2001), which is at the upper boundary of this frequency range. This suggests that the vibration perception of the entire hand-arm system is largely influenced by the overall biodynamic response of the system, as the frequency weighting function is derived primarily based on the equal sensation contours of the vibration perception of the entire hand-arm system (Miwa, 1967; Brammer, 1986). It is hypothesized that the resonances of the shoulder, back, neck, and head to hand-transmitted vibration occur at lower magnitudes at lower frequencies, as these locations are farther from the vibration excitation location, and these substructures have larger effective masses and constraints than the hand-arm system. However, very limited data of the transmissibility at these locations have been reported (Sakakibara et al., 1986; Odenwalda and Krumma, 2014). The specific vibration response characteristics at these locations remain either unclear or unknown.

As the first step to enhance the understanding of the vibration effects on the shoulder and neck MSDs, the objective of this study is to investigate the vibration transmission from both hands to the upper arms, shoulders, back, neck, and head. The apparent mass at the palm of the hand, which should be closely related to the transmissibility on these substructures according to the relationship theorem (Dong et al., 2013b), are also measured. The implications of the experimental results are discussed.

2. Method

2.1. Experimental instrumentation

The experiment was conducted on a 1-D Hand-Arm Vibration Test System (MB Dynamics). The vibration was delivered to the hands along the forearm direction (Z axis) through symmetrical, dual instrumented handles. A pictorial view of the instrumentation setup and subject posture during the experiment is shown in Fig. 1 (a). The left and right instrumented handles were equipped with tri-axial accelerometers (PCB 356A12 and Endevco 65–100, respectively) for measuring input acceleration. A pair of force sensors (Kistler 9212) were attached in each handle to measure the grip force from each hand. A force plate (Kistler, 9286AA) was used to measure the push force applied to the handles. The applied and target grip and push forces were displayed on two virtual dial gauges on a monitor to guide the subject in controlling the hand forces. A 3-D scanning laser vibrometer (Polytec, PSV-500) was used to measure vibration on the subject's skin at five locations distributed on the upper arm, shoulder, back, and neck. To enhance the signal quality, retro-reflective tape was applied on the skin at each of the measurement locations. In order to measure the vibration transmitted to three locations not accessible to the laser vibrometer (i.e., both wrists and the forehead), three accelerometer instrumented adapters were also used. These three adapters were fabricated using different materials based on the geometric design recommended in the standardized glove test (ISO 10819, 1998) and evaluated in a previous study (Xu et al., 2015). As shown in Fig. 1(b), Adapter A was made of magnesium; Adapter B was made of wood; and Adapter C was made of polylactic acid (PLA) using a 3-D printer. The adapters A, B, and C were equipped with tri-axial accelerometers (Endevco, M35A) and weighed 13 g, 15 g, and 7 g, respectively. The same adapters were attached to the same locations for all the subjects and trials.

Broadband random vibrations from 4 to 100 Hz were used as the excitations. Vibration at frequencies above 100 Hz cannot be effectively transmitted to the human arms and upper body. In addition, powered hand tools do not usually generate substantial vibrations below 5 Hz, and the standard method for hand-transmitted vibration exposure risk assessment focuses on frequencies above 5 Hz (ISO 5349-1, 2001). Therefore, this study investigated the vibration transmissibility in the frequency range between 4 and 100 Hz. The vibration signals measured with the 3-D laser vibrometer were acquired, analyzed, and stored using the

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