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Evaluation of psychometric estimates of vibratory hand-tool grip and push forces

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Abstract

Tool grip and push forces are important determinants of health risk associated with operation of powered hand tools. In the field, use of sophisticated hand-force instrumentation can be impractical. This study investigated the potential for using psychophysical force recall methods to estimate grip and push forces when operating vibratory hand tools. This study examined various combinations of handle vibration and grip and push force exposures upon one's ability to recall those forces using psychophysical methods. Twelve male subjects grasped and pushed an instrumented handle for 45 s at one of three levels of force while it vibrated sinusoidally at one of five frequencies (0, 12.5, 40, 125, or 250 Hz). We examined the effects of post-exertion rest periods of 10 and 20 s upon force recall performance, and day-to-day test-retest reliability. Results showed vibration frequency and force level differentially influenced grip and push force recall accuracy. Subjects characteristically overestimated grip and push forces; especially during vibration exposures of 40 and 125 Hz. The magnitude of the overestimations increased as target force levels decreased. Test–retest correlations were reasonably strong.

Relevance to industry

Operators of powered hand tools are at risk of developing health problems associated with repeated forceful actions and exposure to intense hand-transmitted vibration. To better assess health risks, hand-tool coupling forces should be quantified. Psychophysical force recall techniques may permit assessment of these forces without the need for expensive or fragile instrumentation. An understanding of the effects of vibration and force level upon force recall accuracy and reliability must first be explored before such methods are proposed for research or field assessments.

Keywords: Force matching; Force recall; Coupling force; Hand-arm vibration; Psychophysics

1. Introduction

The operation of powered hand tools such as grinders, chain saws, chipping hammers, and drills exposes workers to hand-arm vibration. A tight hand-tool coupling not only imposes higher stresses on the anatomical structures of the hand-arm system and impedes peripheral circulation, but it also increases the transmissibility of vibration to the hand and arm (Riedel, 1995; Kaulbars, 1996; Wasserman, 1998). The use of vibratory tools in combination with forceful and repetitive hand motions may also result in a greater incidence of other forms of cumulative trauma disorders such as carpal tunnel syndrome (see Chapter 5 of NIOSH, 1997; Armstrong et al., 2002).

The need for hand-force measurement has been widely recognized (ISO, 2001), and an ISO standard addressing coupling-force measurement has been drafted (ISO, 2004). However, consensus as to how to best measure those forces has yet to be achieved.

Several methods have been used to measure the hand forces applied to tool handles. One is to instrument the tool

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grip surfaces with strain gauges or force transducers (Radwin, 1999; McGorry, 2001 are examples). However, the application of instrumentation to tool handles must inevitably be customized for each tool's unique hand grip geometry and other properties. This approach is expensive, time consuming, and could alter the true grip posture and dynamics when operating the tool if not properly configured. Some instrumentation manufacturers have dealt with these problems by developing wafer-thin, flexible force sensors that can be applied to tool handles or incorporated into a work glove (Wasserman et al., 2001; Nikonovas et al., 2004; Welcome et al., 2004). So far, such instrumentation methods have been expensive and are often too fragile for many hand-tool exposure assessments in field environments.

An alternative to direct force measurement is the use of psychophysical force magnitude estimation methods. Psychophysical methods are well-documented to demonstrate lawful behaviors (Stevens and Mack, 1959; Stevens, 1960; Eisler, 1962). Psychophysical methods are widely used in ergonomics for a variety of applications including exertion ratings (Borg, 1982), lifting task evaluations (Garg et al., 1980), posture studies (Wiker et al., 1989a), and for cross-modal matching of a wide variety of perceptual phenomena (Stevens, 1957). Perception of exertion levels has demonstrated repeatability within a variety of work postures (Wangenheim et al., 1986) and in post-exertion force-recall protocols (Hammarskjöld et al., 1990). Subjects have also shown remarkable abilities to correctly rank weights and forces (Karwowski et al., 1992; Kumar and Simmonds, 1994; Wiktorin et al., 1996).

Several investigators have studied the reliability and accuracy of psychophysical force recall techniques (Lowe, 1995; Wiktorin et al., 1996; Bao and Silverstein, 2005). This type of measurement is carried out by asking a test subject to reproduce his/her hand force with a similar type of hand-handle coupling action (e.g. push, power grip, or pinch grip) on a dynamometer, grip strength meter, or pinching strength meter. These studies demonstrated that the subjects could reproduce familiar forces reasonably well; and the force recall method could be considered reliable within certain force ranges. However, these studies were performed with manual tasks or simulated labor in the absence of hand-transmitted vibration exposure. The accuracy and reliability of the force recall method under exposure to hand-transmitted vibration have not been reported.

Force-recall accuracy may degrade during or immediately following exposure to vibrating tools. Several factors may contribute to force-recall degradation. First, several investigators have found motor-sensory illusions and loss of position sense with exposure to muscle or tendon vibration (Goodwin et al., 1972; Feldman and Latash, 1982; Miall et al., 2000). Nowak et al. (2004) suggested that vibration may impair a subject's memory of forces used in lifting tasks causing them to overestimate forces during task replication. Second, vibration-induced involuntary muscle contraction, known as the tonic vibration reflex (TVR), has been associated with over-gripping of tools (Goodwin et al., 1972; Radwin et al., 1987). Third, cutaneous perception of pressure and vibratory stimuli is differentially affected by various vibration frequencies and acceleration characteristics and is susceptible to vibration-induced paraesthesia (Verrillo, 1975).

The human hand-arm system has been regarded as a biomechanical system consisting of rigid elements that are coupled to springs and viscous damping elements. This system responds differently to various vibration exposures and with different levels of hand-tool coupling stiffness (i.e., grip force) for any given vibration frequency. Common terms used to describe these biodynamic responses to vibration include dissipated power, vibration transmissibility (expressed as a transfer function), and apparent mass. However, the biodynamic response has usually been expressed in terms of mechanical impedance (Lundström, 1984; ISO, 1998; Dong et al., 2004b). A high mechanical impedance value indicates that the system is more responsive to vibration stimuli. Mechanical systems, including the hand-arm system, exhibit particularly high impedance values at certain vibration frequencies. The frequency at which the system exhibits its highest mechanical impedance is referred to as the system's natural frequency or resonance point. It is speculated that vibration-induced disruptions in force perception may be particularly pronounced at the resonance frequency.

While there are several findings that indicate that subjects can reliably recall and reproduce forces over a wide range of postures and force levels (Wiktorin et al., 1996), the accuracy of force-recall data may be affected by changes in the force level. In his book, Stevens (1986, pp. 271–279) described a phenomenon that commonly occurs in psychophysical matching experiments. This phenomenon exhibits itself as a tendency for the subject to shorten the range of his/her responses. In other words, the subject tends to err in the direction of the center of the scale. Stevens referred to this consequence as the "regression effect" where subjects tend to regress towards the mean. This phenomenon appeared in several studies where subjects tended to over-force low-force targets and under-force high-force targets (e.g., Kumar and Simmonds, 1994). Likewise, in Wiker et al.'s (1989b) study, psychophysical functions for grip and pinch force pivoted; producing over-forcing of low-force grips; under-forcing high-force grips; and maintaining accuracy at the midpoint at 50% maximum voluntary effort grips.

There is likely an interaction between force level and the biodynamic response to vibration. Studies have shown that increased muscle force increases the biodynamic system stiffness which, in turn, increases its mechanical impedance and its resonance frequency (Lundström, 1984; Kihlberg, 1995; Dong et al., 2004b). Thus, increased or decreased grip and push forces might influence the resonance effect and the vibration-induced sensorineural disturbances at certain frequencies. Increased force levels may also