International Journal of Industrial Ergonomics 59 (2017) 64–79

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Measuring dynamic stiffnesses of preloaded distal phalanges in vibration - Test bench validation and parameter study

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ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form
16 December 2016
Accepted 5 March 2017
Available online 19 March 2017

Keywords:
Hand–arm vibration
Energy dissipation
Raynaud's phenomenon
Phalanx dynamic stiffness
Soft tissue damping

ABSTRACT

An experimental vibration test bench was built for measuring the dynamic stiffnesses and dissipated power densities of preloaded distal phalanges undergoing vibration. The aim of this test bench was to analyse the effects of vibration frequency, static preloading, and vibration excitation amplitude on local biodynamic response. Prior to implementation, the test bench was validated by comparison with a tension–compression testing machine and a reference dynamic mechanical analyser. A measurement study was then conducted on a group of 20 subjects. The mean dynamic stiffness showed that the mechanical behaviour of the index finger distal phalanx is similar to that of a complex amorphous polymer: it exhibits frequency-related stiffening with a rubbery plateau, a glassy transition zone, and a glassy state. The static preloading condition considerably modifies the dynamic response of the phalanx, as well as the dissipated power, which is significantly greater when the preloading is high. An amplitude-related softening phenomenon, similar to the Payne effect for rubber, was also revealed. This can be explained by the thixotropic character of the extracellular matrix of the distal phalanx soft tissues.

Relevance for industry: Extensive exposure of the hand–arm system to regular vibration may lead to various disorders and injuries, due in part to changes in mechanical quantities, such as dynamic stress, strain, or dissipated power density, arising from the propagation of such vibration. Nowadays, the direct measurement of this biodynamic response inside soft tissues is still extremely challenging. A way to assess the overall mechanical effects of these local quantities on the human finger is to measure and analyse both the macroscopic stiffness and the dissipated power of fingers.

1. Introduction

Sustained exposure to excessive vibration levels may cause a number of pathological disorders of a vascular, osteo-articular, or musculo-tendinic order (Bovenzi, 1990; Griffin, 1996; Matoba, 1994). These pathologies are generically referred to as vibration syndrome or hand–arm vibration syndrome (HAVS).

Multiple epidemiological studies (Åström et al., 2006; Chetter et al., 1997; Kattel and Fernandez, 1999; Narini et al., 1993) supported by physiological and histological observations of the acute effects of hand–arm vibration (Griffin, 2012; Krajnak et al., 2012) have shown that these disorders are partly related to the frequencies emitted by the machine held by a worker and to other cofactors, such as working posture and pushing and gripping forces.

Measurements of the biodynamic responses of the hand–arm system enable the analysis of the influence of such factors, with the aim of better understanding the mechanisms that induce these vibration disorders. For several years, multiple research studies have focused on estimating the biodynamic responses of the upper limb; most of these have involved selecting mechanical impedance (Driving Point Mechanical Impedance, DPMI) as the biodynamic response of subjects gripping a vibrating handle (Aldien et al., 2006; Burström and Lundstrom, 1998; Gurram et al., 1995; Marcotte et al., 2005). These types of measurement very often provide overall information on the hand–arm system. They are better suited to the study of bone-joint or muscle-tendon pathologies than to that of vascular disorders situated in the finger (digital) blood vessels. Therefore, in order to focus more specifically on vascular pathologies, such as Vibration White Finger or Raynaud's syndrome, it is necessary to collect accurate knowledge of the biodynamic response of finger-transmitted vibration (Griffin, 1996). There have been several attempts to obtain more local experimental data with the help of an instrumented handle by measuring, for example, the distributed impedance in the palm-fingers system

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http://dx.doi.org/10.1016/j.ergon.2017.03.006
0169-8141/

(Dong et al., 2006, 2005a), or by plotting vibration transmissibility diagrams on the dorsal face of hands (Noel, 2011). These methods are likely to accurately provide overall information on the actual use of hand-held rotary machines. However, it has proven difficult to fully determine the relative contribution of each influencing factor (contact area, push/grip forces, posture, input vibration amplitude, etc.) for a high frequency condition, and some findings even contradicted each other (Burström, 1997; Gurram et al., 1995; Marcotte et al., 2005). However, a number of studies (Adewusi et al., 2008; Dong et al., 2008a) concluded that the biodynamic responses of the hand–arm–finger system measured from instrumented handles are often subject to errors at high frequencies (>300 Hz). Alternatively, the results are not reproducible between laboratories owing to the measuring bias introduced by the vibrating handle itself at a high frequency (producing problems of mass cancellation at high frequencies, loss of signal coherence, vibration noise related to the handle assembly, etc.). To potentially overcome the previous drawbacks, an alternative might consist of directly measuring the local biodynamic responses at the fingertips by using specific devices. For a number of years, the assessment of the local mechanical impedance of the fingers has been the objective of a number of different research fields, such as of course the pathological effects of finger-transmitted vibration (Lundström, 1984; Mann and Griffin, 1996), but also the field of human tactile sensitivity (Moore and Mundie, 1972; Moore, 1970; Wiertlewski and Hayward, 2012), the design of haptic systems (Chai-Yu and Oliver, 2005; Kern and Werthschützky, 2008), and determining mathematical models of the skin dynamic response (Gulati and Srinivasan, 1997; Hajian and Howe, 1997). The common procedure was to locally vibrate the fingertip with a small-sized probe in contact with the skin for two main phalanx boundary conditions: i) clamped fingernail (Gulati and Srinivasan, 1997; Lundström, 1984; Moore and Mundie, 1972), and ii) free fingernail (Hajian and Howe, 1997; Mann and Griffin, 1996; Wiertlewski and Hayward, 2012). When measuring the local finger biodynamic response, it was easier to carefully control the influencing parameters, such as the probe surface contact and the static-preload, than when assessing the distributed hand-finger system with an instrumented handle. The disadvantage of this method is that it does not reproduce the use of hand-held rotary machines accurately. However, at a high-frequency condition, it is reasonable to expect the trends of the biodynamic responses to be comparable for whichever test method used, because these trends reflect the mechanical behaviour of the local soft tissues, which may be weakly dependent on those of the entire hand-finger system (Wu et al., 2006). Several studies have been carried out to determine in a nearly comprehensive way the influence of a number of parameters on the local finger biodynamic response, but some of these studies have produced contradictory findings, especially regarding the preloading effect (Lundström, 1984; Moore and Mundie, 1972). Moreover, some researchers pointed out certain potential measurement inconsistencies leading to an overestimation of the inertial effects (Dong et al., 2004b; Wu et al., 2006).

The purpose of our study was to describe, validate, and use in parameter analysis form a new experimental vibration test bench for measuring the local biodynamic responses of the distal phalanx. This test bench was designed to provide accurate, reliable, reproducible results at frequencies between 20 Hz and 500 Hz. We aimed at characterizing the mechanical dynamic behaviour of fingertip soft tissues at a high-frequency (>50 Hz) condition by reducing the effects of other disturbing factors, such as muscle activity and inertial forces produced by the bones or fingernail, as much as possible. Inertial effects were minimized by clamping the fingernail (Wu et al., 2006). To avoid muscle activity as much as possible, the static preloading was performed in a passive way by compressing the fingertip between its support and the probe instead of actively pressing the indenter by using the muscles and tendons of the finger. We first describe the experimental setup, its related metrological equipment, and the signal processing parameters. The deconvolution method for driving the electrodynamic shaker in acceleration is presented. A phase calibration procedure was applied to cancel phase mismatch due to electronic devices. The phase angle accuracy was quantified. Then, the measurement bench was validated by comparison with the results obtained from a tension–compression machine and a reference dynamic mechanical analyser. Finally, a measurement study was performed on 20 subjects. The study parameters were the vibration amplitude and quasi-static preloading. The influence of the vibration frequency on the dynamic stiffness or the mechanical power dissipated by the distal phalanx was analysed before focusing on the effects of the preloading and level of excitation vibration. These results were then examined from a rheological standpoint in an attempt to provide a number of additional physiological explanations.

2. Method

2.1. Apparatus

The experimental setup for measuring the static and dynamic stiffnesses of preloaded distal phalanges is shown in Fig. 1.

The seated subjects place their right forearm on an aluminium platform (Fig. 1 item k). This holder of adjustable height is fitted with four lateral stops with adjustable positions at the elbow and wrist. The purpose of these stops is to ensure appropriate positioning of the subject's forearm and prevent intentional or unintentional movements that could potentially disrupt the measurement. The middle, ring, and little fingers grip a 30 mm diameter plastic cylinder screwed to the holder and adjustable to the subject's morphology. The index finger distal phalanx is adhered (using double sided tape) to the inside face of a curved steel support (Fig. 1 item i). This support is screwed to a piezoelectric force sensor (model B&K 8200) (Fig. 1 item c) rigidly fixed to a steel block. The force sensor is used to estimate the output effort between the fingernail and its support. A piezoelectric accelerometer (model B&K 4705B002) (Fig. 1 item b) with a low measurement range (70 m.s^{-2} sine wave peak) is positioned near the force sensor to check that the vibration level is sufficiently low so as not to disturb the output force measurement. The distal phalanx is vibrated using an electrodynamic shaker system (model B&K 4809) (Fig. 1 item e) generating a 10–20 kHz bandwidth signal and sustaining sine wave peak dynamic forces of a maximum of 45 N. The electrodynamic shaker is fixed to a support micrometer that is controlled manually (Fig. 1 item h). This allows the quasi-static preloading of the distal phalanx by moving the 7 mm diameter cylindrical indenter (Fig. 1 item j). The indenter is screwed to an impedance head (model B&K 8001) rigidly mounted to the vibratory shaker shaft (Fig. 1 item d). The impedance head sensor enables the measurement of both the input force applied by the cylindrical probe to the skin and the input acceleration. The compression distances used to estimate the static stiffnesses from the force/displacement curves were measured using a laser telemeter (model ILD 1700-200 from Micro-Epsilon) with a high resolution of 12 μm (Fig. 1 item a). The telemeter laser beam impacted a 4 mm thick aluminium disk (Fig. 1 item f) fixed to the shaker moving shaft.

The data acquisition, control, and computing operations were performed using MATLAB software with specific modules. A conceptual diagram of the metrological equipment with the different