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The development of a new artificial model of a finger for assessing transmitted vibrations

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ABSTRACT

Prolonged exposure of the hand to tool-induced vibrations is associated with the occurrence of conditions such as vibration white finger. This study involves the development of a new artificial model that approximates both loading and vibration behaviour of the human finger. The layered system uses polypropylene "bones", encased in a cylinder of low modulus, room-temperature curing silicone gel (to replicate subcutaneous tissues), with an outer layer of latex (to replicate the dermis and epidermis). A protocol for manufacture was developed and dynamic mechanical analysis was carried out on a range of gels in order to choose a range close to the mechanical properties of the human finger. The load-deflection behaviour under quasi-static loading was obtained using an indenter. The indentation measurements were then compared with a set of validation data obtained from human participant testing under the same conditions. A 2-D FE model of the finger was also used to assess vibration responses using existing parameters for a human finger and those obtained from the tested materials. Vibration analysis was conducted under swept sinusoidal excitations ranging from 10 to 400 Hz whilst the FE finger model was pressed 6 mm toward the handle. Results were found to compare well. This synthetic test-bed and protocol can now be used in future experiments for assessing finger-transmitted vibrations. For instance, it can aid in assessing anti-vibration glove materials without the need for human subjects and provide consistent control of test parameters such as grip force.

1. Introduction

The prolonged usage of vibrating hand-held tools, in an operator's daily work routine is associated with the development of hand-arm vibration syndrome (HAVS). Vibration-induced finger damage and disorders are recognised as a major aspect of HAVS (Griffin, 1990), and the fingers are important substructures within the hand-arm system. The evaluation of anti-vibration (AV) gloves should be partly based on the amount of vibration reduction on the fingers (Paddan and Griffin, 2001). However, mainly due to technical challenges, the measurement of the vibration transmissibility of the AV gloves at the fingers has been very limited (Griffin et al., 1982; Paddan and Griffin, 2001). Possibly for similar reasons, the AV glove evaluation standard uses the vibration transmissibility of the glove on the palm of the hand and in the forearm direction (ISO 10819, 1996; 2013) but not on the fingers. This standard does not directly attempt to resolve the challenge of vibration attenuation at the fingers. However, the original version included criteria which required that any AV glove had to be a full-finger glove with similar materials and thickness at both the palm as well as the fingers (ISO 10819, 1996). Subsequently, the required thickness of the glove material at the fingers has been relaxed from 100% to greater than or equal to 55% of the thickness of the palm in the revised version of the glove standard (ISO 10819, 2013).

The measurement of the vibration transmissibility of gloves can be affected by many factors, such as: variability between and within subjects (Hewitt, 1998; Paddan and Griffin, 2001), controlling feed and grip forces, test rig behaviour, and temperature. One previous study has investigated the effects of several variables on measuring vibration transmissibility of gloves; it has found that misalignment of the palm-adaptor can reduce the measured transmissibility by approximately 20%. Other variables include inter-subject variability (± 10%), temperature variation (± 4%) and controlling feed forces (± 4%) (Hewitt, 1998).

Measurements of glove transmissibility at the fingers are limited and require more research (Paddan and Griffin, 2001). One of the existing methods uses a finger-adaptor (similar to the standard palm-adaptor) method to measure the glove transmissibility at the fingers. Unfortunately, the effectiveness of transmissibility measured using this method can be overestimated for assessing gloves due to a number of factors including: the difficulty of using the adaptor inside the glove;

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and the effective mass of each finger being small compared to that of the palm. Also, the geometry and the mass of the finger is relatively small when compared to the probable geometry and mass of the finger-adaptor. The effectiveness with which gloves reduce the vibration transmission at the finger would be better if the transmissibility was measured reliably (Welcome et al., 2014). Further, the vibration transmissibility measured at the finger can vary depending on the location of the measurement on each of the fingers (Welcome et al., 2011). It is therefore difficult to use the finger-adaptor method to evaluate the transmissibility distribution reliably. Additionally, the glove transmissibility at the fingers can be indirectly estimated by measuring vibrations for gloved and un-gloved fingers (Cheng et al., 1999; Paddan and Griffin, 2001). A modelling study indicated that using a relative method is acceptable for estimating the transmissibility at the finger-glove interface (Dong et al., 2009). However, using the finger-adaptor method may change the geometry of the finger which may affect the dynamic properties of the finger and produce unreliability in measurement (Concettoni and Griffin, 2009).

Several recent studies have used a 3-D laser vibrometer for measuring the transmissibility at the back of the fingers, and using such a technique reduced the unreliability associated with the use of the finger adaptor method (Welcome et al., 2011, 2014, 2015; Dong et al., 2013). However, no in-vivo experimental method has been established that directly measures the vibration responses inside the soft issues of the hand-arm system (ISO 5349-1, 2001; Wu et al., 2010); their evaluation remains dependent on modelling, and the accuracy of the models is based on how accurate the data is which is used. Finite element modelling (FE) is considered to be the best method for providing detailed biodynamic responses inside the soft tissues of the entire system, and several studies have investigated the FE model that replicates the biodynamic responses of the human finger to vibration (Wu et al., 2007, 2008, 2010, 2015).

The mechanical properties of human skin differ and can be influenced by a number of factors including hydration, age and anatomical structure (Derler et al., 2007; Shao et al., 2009). This variability creates a complication when attempting to obtain consistent and reliable results from individuals. To achieve a reliable measurement which produces the mechanical behaviour of human skin, such as the friction and stiffness properties of human skin, synthetic models of a fingertip have been created for experimental use (Derler et al., 2007; Shao et al., 2009), but none of these studies have included vibration transmission.

Several materials have been investigated for replicating human skin and soft tissue structures at the fingertip. In a previous study a synthetic model was created using polyvinylsiloxane (Ramkumar et al., 2003a, 2003b). Another study has used various silicone and polyurethane materials as mechanical friction equivalents to the skin, and a polyurethane-coated polyamide fleece with a surface structure was found which is like that of skin and demonstrated the best friction correspondence to human skin in dry conditions (Derler et al., 2007). A recent study has used 101RF silicone rubber (cured hardness: 30 Shore A) to replicate the mechanical properties of the anatomical construction of the real fingertip. The results show that a synthetic fingertip that utilised only pure silicone showed a difference in friction behaviour when compared to the real fingertip. However, the soft multi-layer synthesis fingertip was found to be closer to the real one (Shao et al., 2009).

This present study was designed to develop and test a new physical model for assessing finger-transmitted vibration that can replicate the mechanical and vibration behaviour of the real human finger at room temperature.

2. Materials

2.1. Materials analysis

Two types of material were selected for analysis. Room-temperature curing silicone gel based on polyorganosiloxanes (Magic Power Gel, from Raytech, see Table 1 for details) was used to replicate subcutaneous tissues while latex (Liquid Latex Rubber, from Polycraft) was used to replicate the outer layer skin (the dermis and epidermis). Two cylindrical specimens of silicone gel were prepared with two different mixing ratios by volume. One cuboid specimen of latex was cut from a cured sheet. A summary of the properties of the specimens is provided in Table 2.

Table 1
The properties of Power Magic Gel.

Components	Colour	Approx. working time	Cross linking time
Part A	transparent	7–10 min	10–15 min
Part B	blue		

Table 2
Properties and dimensions of the specimens used in the study.

Material	No. of specimens	Mixing ratio	Dimensions (mm)
Silicone gel	2	1:1 and 1:2	H = 35.5, Ø = 20
Latex	1	–	H = 29.3, L = 20, W = 1.6

Dynamic Mechanical Analysis (DMA) was conducted to study the mechanical properties (Young's modulus and loss factor) of the selected material specimens and to investigate their sensitivity to temperature and amplitude changes. This information was used to determine the optimum mixing ratio of the silicone gel parts (base and catalyst) to provide a similar stiffness to that of the real human tissues.

DMA was performed using a Metravib Viscoanalyser, as shown in Fig. 1(a). The installation of each specimen varied, depending on the design of the specimen. Each of the silicone gel specimens (1:1 and 1:2) was inserted between compression plates that were located in an analyser chamber as shown in Fig. 1(b), whilst for the latex sheet specimen two clamps were used instead (see Fig. 1(C)). Specimens were subjected to sinusoidal loading and the resulting force and displacement traces used to find the Young's modulus and loss factor.

Each specimen was subjected to a strain sweep test at room temperature followed by a temperature sweep test. For the strain sweep test, each specimen was tested under different dynamic strain amplitudes at room temperature, whilst the temperature test was conducted under a fixed dynamic strain amplitude over a range of temperatures. The temperature of the specimen was measured using a thermocouple located inside the chamber. First, the chamber temperature was cooled down using liquid nitrogen until the target temperature was obtained, and then the specimen was subjected to sinusoidal loading with a selected dynamic strain. A frequency of 10 Hz was selected for all the tests and the specimens. The selection of the frequency was dependent on the calibration of the machine that showed the best dynamic response at 10 Hz and specimen size. The testing parameters are shown in Table 3.

In order to check the consistency of the silicone gel (Power Magic Gel) over time, the specimen of mix ratio 1:2 was retested under the same condition after 30 days. The 1:1 specimen was damaged during removal from DMA machine and this was not suitable for re-testing.

2.2. Geometry and parameters of an artificial finger (AF)

The anatomy and mechanical properties of the human index finger were considered in order to develop a physical model of the finger. The structure of the human finger is shown in Fig. 4. The Young's modulus of tissues in the human finger was previously defined: for a bone ($E = 1.5 \times 10^9$ Pa), subcutaneous tissues ($E = 3.4 \times 10^4$ Pa) and skin, including (epidermis and dermis) ($E = 1.36 \times 10^5$ Pa) (Wagner et al., 2008). In the present study a polypropylene rod (nylon), 8 mm in diameter, provided by Plastic Direct Ltd., UK, was used to make artificial phalanx bones that had a Young's modulus similar to that of human