A new methodology for measuring the vibration transmission from handle to finger whilst gripping

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Abstract

The transmission of vibration from hand-held tools via work gloves and into the operators' hands can be affected by several factors such as glove material properties, tool vibration conditions, grip force, and temperature. The primary aim of this study is to develop a new methodology to measure and evaluate vibration transmissibility for a human finger in contact with different materials, whilst measuring and controlling the grip force. The study presented here used a new bespoke lab-based apparatus for assessing vibration transmissibility that includes a generic handle instrumented for vibration and grip force measurements. The handle is freely suspended and can be excited at a range of real-world vibration conditions whilst being gripped by a human subject. The study conducted a frequency response function (FRF) of the handle using an instrumented hammer to ensure that the handle system was resonance free at the important frequency range for glove research, as outlined in ISO 10819: 1996: 2013, and also investigated how glove material properties and design affect the tool vibration transmission into the index finger (Almagirby et al. 2015). The FRF results obtained at each of six positions shows that the dynamic system of the handle has three resonance frequencies in the low frequency range (2, 11 and 17 Hz) and indicated that no resonances were displayed up to a frequency of about 550 Hz. No significant vibration attenuation was shown at frequencies lower than 150 Hz. The two materials cut from the gloves that were labelled as anti-vibration gloves (AV) indicated resonance at frequencies of 150 and 160 Hz. However, the non-glove material that did not meet the requirements for AV gloves showed resonance at 250 Hz. The attenuation for the three materials was found at frequencies of 315 Hz and 400 Hz. The level and position of the true resonance frequencies were found to vary between samples and individual subjects.

Relevance to industry: Extended exposure to vibration transmitted from some of these tools may cause hand-arm vibration syndrome. Anti-vibration gloves are used as a strategy to reduce the vibration transmitted into operators' hands. Unfortunately, their performance in reducing transmitted vibrations into the fingers is still not clear. The approach presented here allows a better understanding of the effects of gloves on finger-transmitted vibration and can deliver helpful data on the performance of standard AV gloves in reducing finger-transmitted vibration. This new approach can help glove manufacturers to assess the performance of AV glove materials separately, and the results and knowledge obtained can help in selecting suitable gloves for the operation of hand-held vibrating tools, conducting a risk evaluation of the vibration exposure, and the designing of AV gloves

Keywords: finger-transmitted vibration, anti-vibration glove, AV glove materials, hand-arm vibration, index finger, grip force, resonance frequency

1. Introduction

Many types of hand-held vibrating tools, such as chain saws, grinders, drills, and chipping hammers are widely used in several industries. Extended exposure to vibration transmitted from such tools may cause hand-arm vibration syndrome (HAVS) (Griffin, 1990; Xu et al., 2014). The National Institute for Occupational Safety and Health indicated that exposure to hand-transmitted vibration was also reported as being a major component associated with wrist syndrome (NIOSH, 1997). International Standards include guidelines for the measurement and evaluation of human exposure to vibrations in the hand. The standardised daily exposure to hand-transmitted vibration is based on the eight-hour energy-equivalent acceleration value as a reference duration and known as “A(8)”. This value depends on the vibration magnitude and frequency, and exposure duration, while the influence of the hand grip force is ignored (ISO 5349-1, 2001; ISO 5349-2, 2002).

Many studies have suggested that the effect of hand force should be taken into account as a weighting factor in assessing the risk associated with hand-transmitted vibration (Welcome et al., 2004). This requires identification of the relationship between the hand force, the vibration transmission and health effects. Moreover, an accurate definition and a measurement technique for the hand force is needed (Gurram et al., 1995). Different types of anti-vibration (AV) gloves that aim to decrease the hand-transmitted vibration are currently available (Griffin, 1998) and the international standard ISO 10819 outlines the procedure designed for assessing and testing the performance of such gloves. Some research studies have stated that gloves could be useful for protecting operators’ hands from damage due to hand-transmitted vibration, such as the effects on blood circulation in the fingers (Jetzer et al., 2003; Mahbub et al., 2007; Hewitt et al., 2014). However, some doubt remains about the effectiveness of gloves for attenuating vibrations transmitted to the hand and fingers (Griffin, 1990, 1998; Paddan and Griffin, 2001; Dong et al., 2009; Almagirby et al., 2015). Additionally, gloves can impair dexterity whilst increasing the effort of hand grip force and these issues could pose a safety risk (Wimer et al., 2010). The balance between vibration reduction and dexterity impairment will depend on tool specifications and work conditions. In order to help determine this balance, it is important to identify how much vibration a glove can reduce.

Vibration-induced damage to the fingers is the main aspect of HAVS (Griffin, 1990), so the fingers are arguably the most important substructures of the hand-arm system to be considered. Mainly due to technical challenges such as the mounting and alignment of instrumentation, the study of the vibration transmissibility to the fingers has been restricted (Griffin et al., 1982; Paddan and Griffin, 2001). The standardised AV glove evaluation is primarily dependent on the vibration transmissibility into the palm of the hand and along the forearm path (ISO 10819, 1996, 2013).

A previous version of the AV glove standard (ISO 10819, 1996) stated that both the fingers and the palm of the hand should be gloved in the same way, thus ensuring similar material properties and thickness. The key assumption was that the anti-vibration material would reduce vibration transmitted into the fingers in the same was as into the palm; in the worst case, a glove complying with the standard should be significantly better at attenuating finger-transmitted vibration than a glove that does not. However, the validity of this assumption has not been adequately confirmed.

The criteria set in the earlier AV glove standard set a practical challenge: AV gloves that satisfy the criteria are extremely bulky to wear and inconvenient to use. For that reason, there are no glove designs that fully comply with the criteria. However, some commercially available gloves are labelled as having AV capability. To enable these gloves to comply, the previous version of the glove standard has recently been reviewed and modified (ISO 10819, 2013); specifically, the thickness of the AV glove material that covers the fingers is decreased to equal or greater than 55% with respect to that covering the palm area.

Another approach investigated the effect of a covered handle on vibration transmissions into the hand-wrist system (Singh and Khan, 2014). The study used four covered handles and one uncovered, which were attached to a drill machine for measuring. The measurement was taken on the handle surface and the wrist. This study showed that all four covered handles reduced transmitted vibration by about 59 %. Transmitted vibrations in the Z direction (Feed force direction) were found to vary significantly across all the covers used. However, these variations were not significant in the Y direction. Furthermore, vibrations transmitted to the wrist of subjects were found to vary across the five cases and indicated that about 60% of vibrations were transmitted into the fingers and palm of each operator's hand rather than the wrist. However, the study only considered the effect of transmitted vibrations on the wrist, not on the fingers (Singh and Khan, 2014).

In order to study the vibration on gloved fingers, a number of different approaches have been taken. One approach is similar to that used for measuring transmissibility at the palm in the standardised method (ISO 10819, 2013) and involves an adapter instrumented with a tri-axial accelerometer which is inserted at the interface of the glove material and the fingers. As the mass and size of a typical finger adapter and accelerometer are of a similar order to the mass and size of the finger itself, transmissibility measurements can be affected significantly. Additionally, vibration of the fingers could vary significantly at different points on each finger (Welcome et al., 2011). This makes it challenging to apply a finger adapter approach for effectively measuring transmissibility. Transmissibility of the glove at the fingers has also been indirectly identified by measuring the vibrations at the fingers with and without the AV gloves (Cheng et al., 1999; Paddan and Griffin, 2001). Moreover, a 3-D laser vibrometer method has been used in some recent studies to measure hand-arm transmitted vibration (Welcome et al., 2011).

Another study examined the transmissibility of AV gloves using a 3-D laser vibrometer to measure transmitted vibration from the back of the finger (Welcome et al., 2014). It indicated that the AV gloves showed very small attenuation over the full range of frequencies and resonance frequency at 125 Hz when a grip force of 30±5 N was applied with the inter-subject variability of the amplitude and position of the peak.

A more recent study (Welcome et al., 2015) measured vibration transmissibility on the hand-arm system and indicated that the major resonance that occurred on the forearm was in the range of 16-30 Hz, in the Y direction of the wrist. The resonance on the dorsal surface of the hand was at a frequency that ranged between 30-40 Hz. At a frequency beyond 50 Hz, the transmission of vibration was limited to the hand and fingers. In the fingers, the major resonance occurred at about 100 Hz in the X and Y directions and at about 200 Hz in the Z one. In addition, the resonance peak was lowest in the Z direction (Welcome et al., 2015).

No in-vivo technique has been developed that can directly measure the effect of transmitted vibration inside the soft tissues of the hand-arm system (ISO 5349-1, 2001; Wu et al., 2010). Instead, the determination of transmitted vibration often depends on the modelling of the system. The reliability of these models depends on their ability to represent fully the actual hand-tool system and the accuracy of the measurements that are used for calibration and validation (Dong et al., 2007).

The primary aim of this study is to develop a new methodology to measure and evaluate vibration transmission to a human finger in contact with different materials, whilst measuring and controlling the grip force.

2. Methods

2.1. Experiment instrumentation

Figure 1 shows the arrangement of the instrumentation and the subject posture that are used in the approach. As shown in Figures 2 and 3, a generic handle with a 40 mm diameter, and made from aluminium, was developed and instrumented for finger transmitted vibration and grip force measurements.

The handle was freely suspended at the ends and connected by a thin stinger to an electrodynamic shaker (LDS V406) with a maximum force capability of 150 N. The handle was connected to the stinger via a piezoelectric force transducer with a sensitivity of 43208 N/V (PCB Model 208C03) to determine the excitation force.

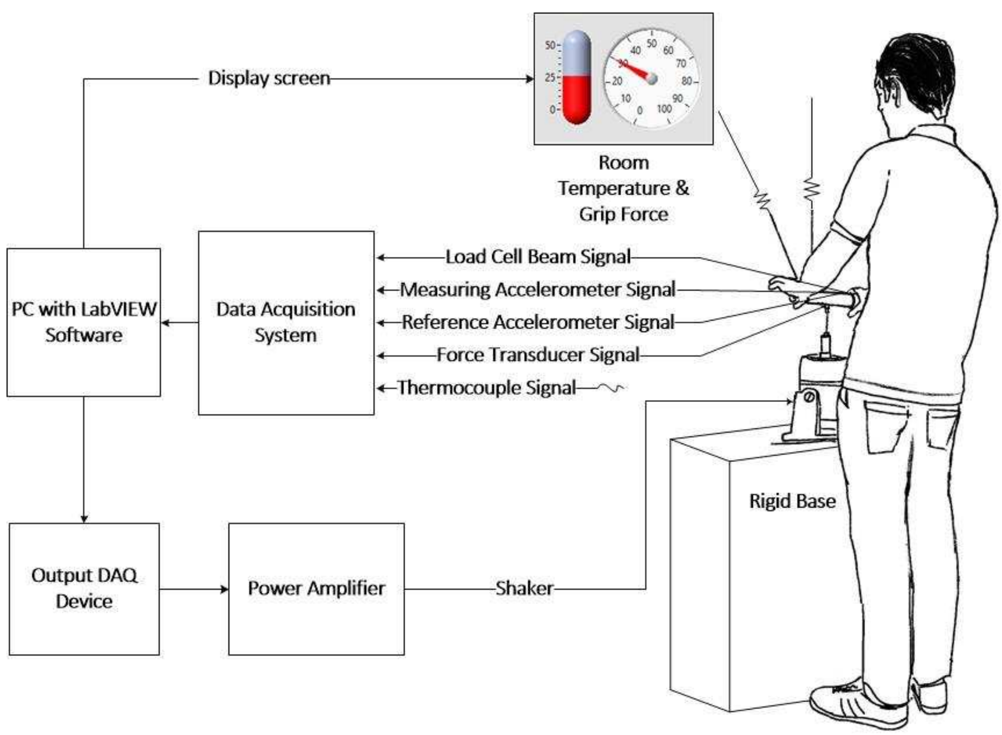


Figure 1: Instrumentation and subject set up including the vibration controlling and response measurement system, grip force and temperature measurement and display system

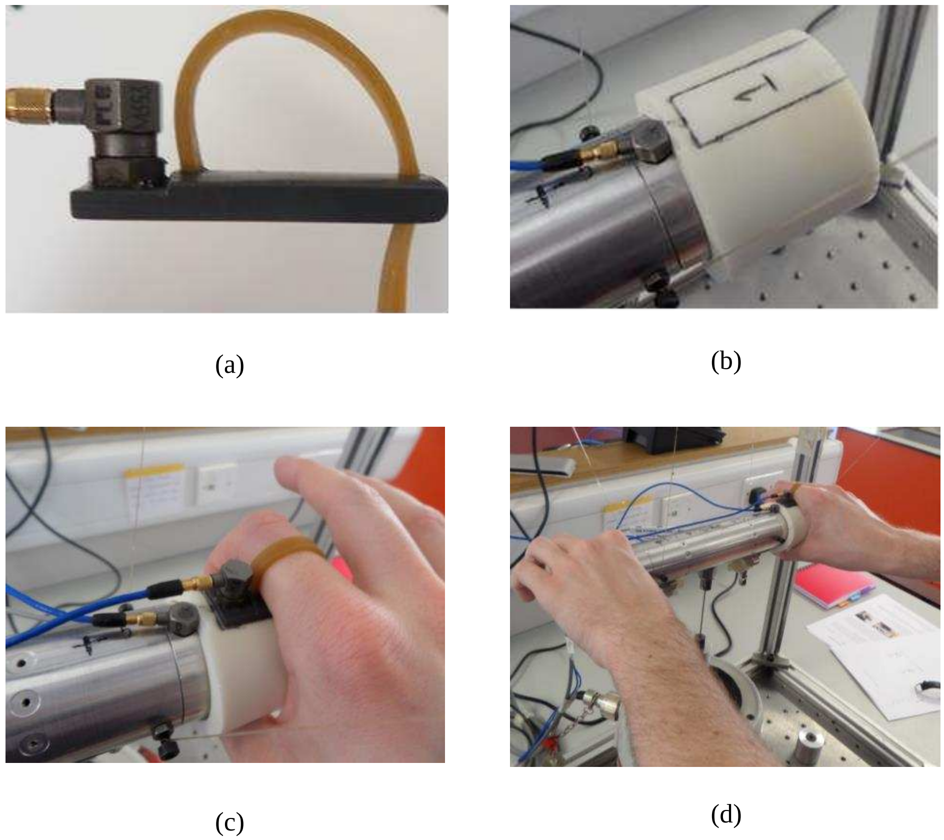


Figure 2: Experimental setup showing: (a) finger mounting adapter, (b) material sample, (c) right end close-up (d) posture for gripping of the handle

The right end of the handle was designed and instrumented to measure a grip force ranging from 10 N to 50 N in order to control the gripping force of the right index finger and the thumb of the human subjects. The design used a split cylinder with a strain gauged beam element (LCL -040), using a design as outlined by ISO 10819 1996 (see Figure 3). The grip force measurement system was calibrated over a range 0 to 100 N. The ambient air temperature was also monitored and recorded during each test using a thermocouple.

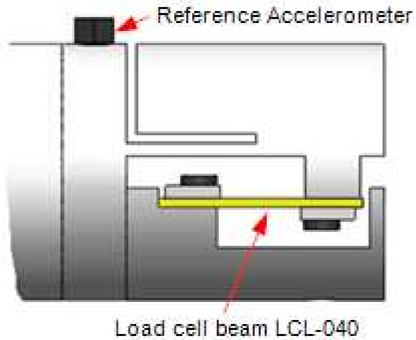


Figure 3: Cross-sectional diagram of the instrumented end of the handle

National Instruments devices (with a maximum sampling rate of 5000 Hz) were used to drive the shaker, capture measurements and continuously display data on the screen using LabVIEW software (version 2014).

2.2. Dynamic response of the system

An ideal test system should have no resonances of its own in or near the frequency range of interest. In order to identify the natural frequencies of the handle, the frequency response functions (FRFs) of the system were collected at six positions along the handle length, using instrumented hammer tests as shown in Figure 4. For accuracy purposes, 10 hammer hits were taken for each position. The FRF test was conducted with and without the handle being gripped. Note that the system is designed to operate in only the vertical direction (parallel to the stinger) so only resonances with significant motion in this direction were considered.

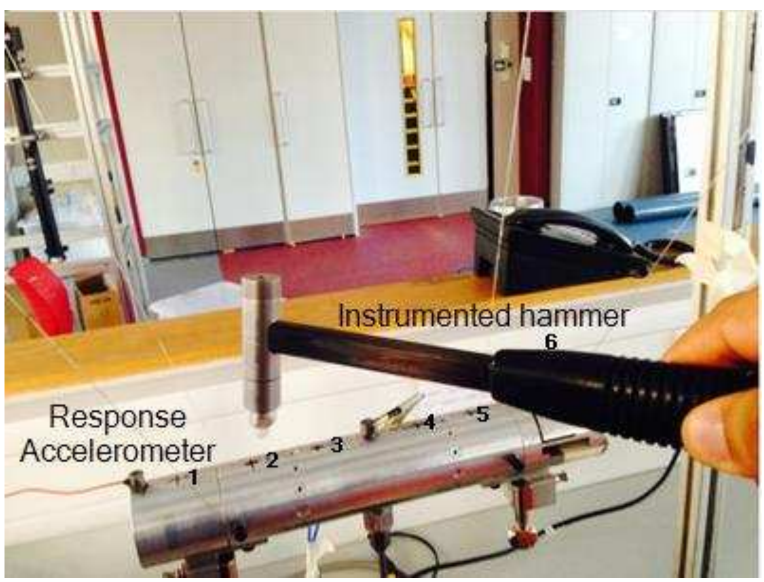


Figure 4: Hammer test setup of the handle

2.3. Glove material measurements

Twelve healthy adults (eleven males and one female) aged from 22 to 48 years old were recruited for the testing (Almagirby et al., 2015). Three glove material samples were tested (latex foam, patterned rubber and foam), as shown in Figure 5, and labelled 1, 2 and 3. Samples 2 and 3 were cut from a commercial AV glove, whilst sample 1 was used for comparision. Each material sample was prepared to be fitted around the right end of the handle, and the adapter was fitted onto the index finger of the right hand of the subject being tested (see Figure 2)

Figure 5: Structure of materials used in the study

Discrete sinusoidal vertical vibration signals were applied to the handle, covering a frequency range from 20 to 400 Hz.

All of the collected data was processed and analysed with DIAdem view software (Version 2014). As the purpose of the testing was to identify the transmissibility of the glove materials while gripped by the index finger, this could be measured indirectly. Alternatively, the result was obtained by two steps. Firstly, the transmissibility of the bare handle (T_{bare}) was defined as:

$$T_{bare} = \frac{A_{Fb}}{A_{Hb}} \tag{1}$$

where: A_{Fb} is the acceleration of the bare index finger (from the "finger-adapter" accelerometer); and A_{Hb} is the acceleration of the handle (from the "reference" accelerometer).

The transmissibility was then calculated for the glove materials (T_{glove}) by the following equation:

$$T_{glove} = \frac{A_{Fg}}{A_{Hg}} \tag{2}$$

where A_{Fg} is the acceleration of the gloved index finger (from the "finger" accelerometer); and A_{Hg} is the acceleration of the handle (from the "reference" accelerometer).

Lastly, the two transmissibilities were used to gain a one corrected transmissibility ($T_{correted}$), which explains the frequency response of the handle-adapter system using the equation below:

$$T_{correted} = \frac{T_{glove}}{T_{bare}} \quad (3)$$

The corrected transmissibilities, $T_{correted}$ for all twelve human subjects and all three glove materials are shown in Figure 8.

3. Results and Discussion

3.1. Test rig dynamic behaviour

The FRF data obtained at each of six positions indicate that the dynamic system of the handle, stinger and suspension has three resonances at low frequencies (2, 11 and 17 Hz), and no other resonances are present up to a frequency of 550 Hz. (see Figure 6).

At low frequency, the most significant resonance is the one at 11 Hz. For this peak, the FRF magnitudes at the ends (positions 1 and 6) are much higher than those in the middle (positions 3 and 4) which indicates rocking behaviour relative to the shaker connection point. The resonance at 17 Hz, on the other hand, shows similar amplitudes at all points, indicating a vertical bouncing mode resulting in extension and compression of the stinger. The high frequency modes above 550 Hz are thought to be flexural modes of the handle dominated by the split-bar section.

When only the right end of the handle was gripped, the peak heights at all the resonances reduced – presumably due to increased damping from the hands (see Figure 7). The frequencies of the low-frequency modes dropped, reflecting the increase in effective mass from the addition of the hand. The shape of the rocking mode (near 17 Hz) also changed somewhat, with the maximum motion occurring at the free end (position 1) and minimum motion at the gripped end (position 6).

Overall, this study has concluded that the new test rig is suitable for measuring vibration transmissibility for HAV research. This is reasonable for testing vibration transmissibility of gloves materials at frequencies ranging from 20 Hz to 400 Hz, which are of importance to this research as outlined in the international standards for AV gloves (ISO 10819, 1996).

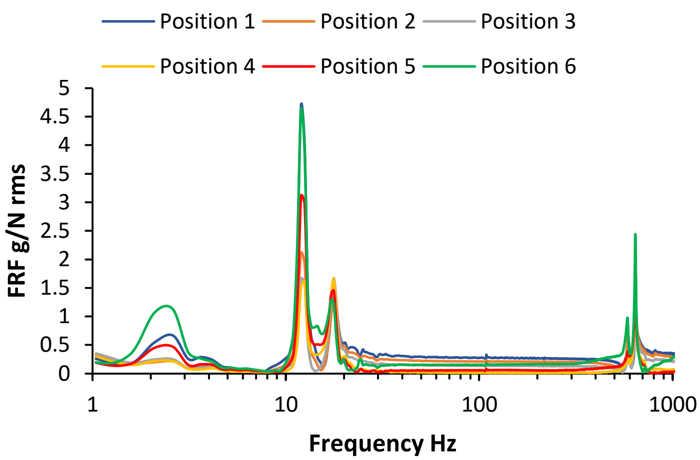


Figure 6: Frequency response function (FRF) for the six positions along the handle

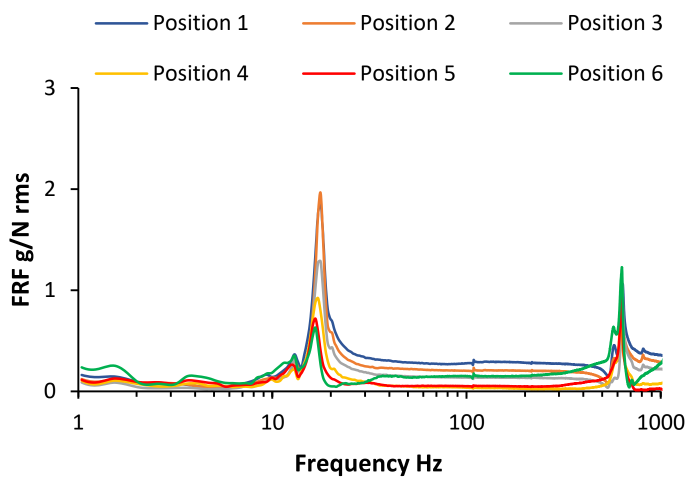


Figure 7: Frequency response function (FRF) for the six positions along the handle when the right end was gripped by index finger and thumb

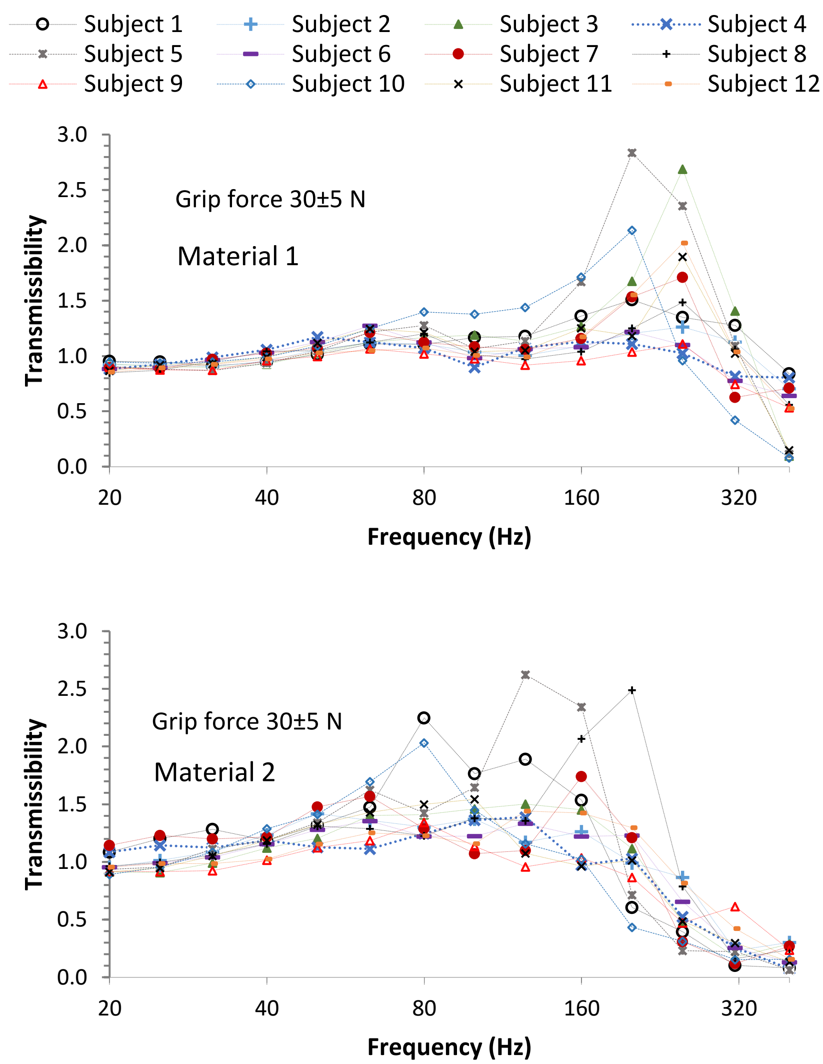
3.2. Transmissibility measurements

The transmissibility measurements of all three glove materials for all human test subjects are shown in Figure 8. None of the materials (1, 2 and 3) showed significant vibration attenuation at frequencies below 150 Hz, but all of them showed significant attenuation at frequencies above 315 Hz. All tests showed that transmissibility to the fingers actually increased in the range 80 to 200 Hz. This indicates that gloves can introduce additional resonance. In some cases, vibration at the fingers was three times higher than that on the handle. Each glove material specimen showed little variation between individual subjects:

Material 1 showed good agreement among subjects at frequencies below 80 Hz. The significant resonance was in the range 200 to 250 Hz and attenuation occurred beyond 315 Hz.

Material 2 showed greater variability between individuals. The main resonance frequencies were found between 80 Hz and 200 Hz. However, generally attenuation began around 250 Hz.

Material 3 showed less variation compared to Material 2, but more than Material 1. The resonance occurred around 160 Hz and attenuation above 250 Hz.



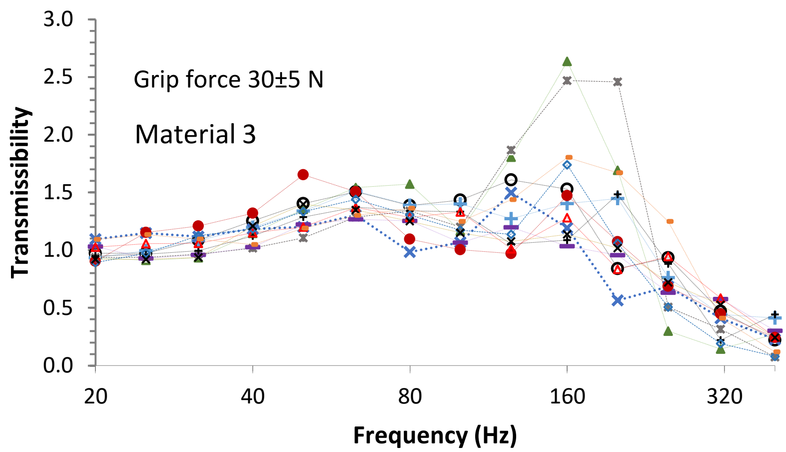


Figure 8: Transmissibility measurements against frequency for all subjects with three materials (Almagirby et al., 2015)

In comparison, previous studies using the palm adapter approach indicated that there were very small attenuation frequencies below 200 Hz (Griffin, 1998; Boyle and Griffin, 2001; Xu et al., 2014). While the design of the gloves (Welcome et al., 2014) and the structure and mechanical properties of glove material (Almagirby et al., 2015) affect results somewhat, the findings from the new test rig are consistent with previous findings.

Previous work has indicated that the glove-hand resonance is approximately 125 Hz when a grip force of 30±5 N is applied (Welcome et al., 2014). The glove-finger resonance measured in this present study varied depending on individuals and materials considered. This is expected, as finger mass would vary. Also, the effective stiffness of the glove-finger system would not be consistent as it is affected by material type and grip force. When gripping a handle, the stiffness associated with the resonance in question arises from a combination of the individual stiffnesses of the glove and the finger tissues. A previous study has stated that the resonance frequency of the fingers increases with the increase of the finger grip force due to increased stiffness of the surface of the fingers and also their joints (Welcome et al., 2014). Additionally, large deformations of the glove materials (which have open cell meso/microstructures) are known to cause stiffening. Thus slight inconsistencies in grip force could alter the combined stiffness (and hence the resonance frequency) significantly.

Findings from this present study also show good agreement with findings obtained from a 3-D laser vibrometer (Welcome et al., 2014), which can be very promising, as that was the only study that measures transmissibility at different positions of the back of the fingers and not on the palm.

Material 1 (non-glove material), seemed to be the one with the worst performance, with less attenuation compared with AV materials, but this was expected because it is the stiffest and not designed for AV gloves.

Materials 2 and 3 did not show enough attenuation across the frequency range 150 Hz to 250 Hz to be classified as AV in accordance with glove standard ISO 10819. As they had passed the ISO standard check, it can also be assumed that they are less effective in reducing vibration on fingers than on the palm (Welcome et al., 2014).

The results of this present study suggest that AV gloves may only be effective at attenuating vibration on the fingers at frequencies above 250 Hz.

The measured grip force data was not significantly different among individuals and all three tested materials when examined under stepped vibration frequencies. Figure 9 shows a typical grip force data for Material 1 and the descriptive statistics of grip force for all tested materials and the 12 subjects are listed in Table 1.

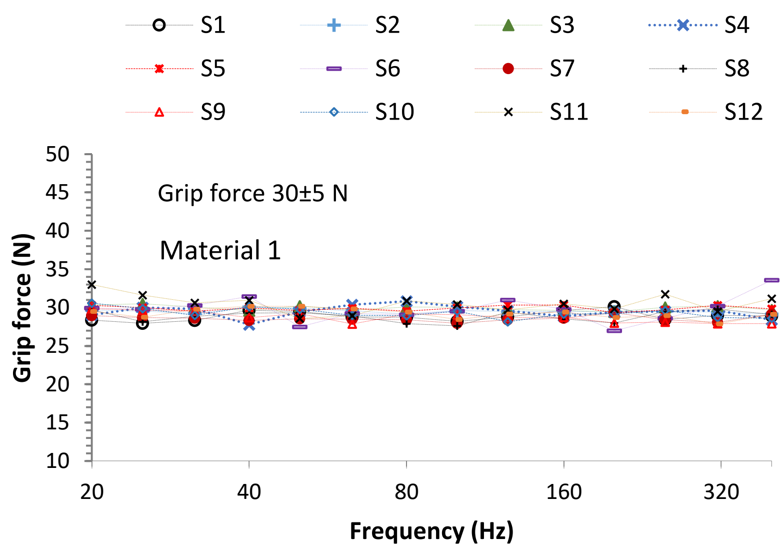


Figure 9: Typical grip forces against frequency measured for all 12 subjects

Table 1: Grip force (N) means and standard deviations (SDs) based on 12 subjects for the three glove materials

Material	Mean	SD	Minimum	Maximum
1	29.47	0.93	28.13	31.76
2	29.88	0.64	28.98	31.28
3	29.72	0.71	28.14	30.80

No statistical correlations were found between transmissibility measurements (including resonance frequency and resonance peak) of all three glove materials and other testing parameters such as grip force and anthropometric measurements of the hand. Hand size was measured according to the method outlined in the British Standard for protective gloves (BS EN 420, 2003). The range of hand size was from 7 to 9 and the mean was 7.75 ± 0.75 SD. The correlations were calculated using SPSS statistical software (IBM SPSS Statistics, version 22). Since the transmissibility was measured using a finger-thumb system, this study suggests that further characteristics of the finger – rather than of the entire hand – are required, in order to gain a better understanding of finger transmitted vibration.

There were certain limitations to the study presented here. The vibration transmissibility measured at the finger could differ depending on adaptor misalignment. It could also be argued that for loose-fitting gloves, the effect of bunching in the material is not well represented by the way in which the test material is mounted on the handle. Moreover, only a small number of glove candidate materials have been studied. These factors will be investigated in future research by the authors, as well as the development of a synthetic finger test-bed which has the potential to replace human subject testing and allow for more material parameters to be investigated in an expanded study.

Conclusions

This paper has introduced a new test rig for measuring finger vibration when gripping a handle. This allows for vibration over a range of different frequencies with different grip levels. Testing has shown that the system is suitable for testing in the frequency range 20 to 400 Hz. There are no system resonances close to this range.

No significant vibration attenuation was shown at frequencies lower than 150 Hz. The two materials cut from the gloves labelled as anti-vibration gloves (AV) indicated resonance at frequencies of 150 and 160 Hz. However, the non-glove material that did not meet the requirements of AV gloves showed resonance at 250 Hz. The attenuation for these three materials was found at frequencies of 315 Hz and 400 Hz.

The test rig was used for testing vibration transmissibility of AV glove materials. Human subject testing, compared with findings from other studies, indicated that AV glove materials are less effective in protecting the fingers from vibration than they are in protecting the palm of the hand.

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