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VIBRATION TRANSMISSIBILITY MEASUREMENT OF GLOVE MATERIALS UNDER DIFFERENT GRIP FORCES

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Abstract

The transmission of vibration from tools, through work gloves and into the hands, is affected by many factors such as glove material properties, tool vibration conditions, temperature, and grip force. This study investigated how glove material properties affect tool vibration transmission into the index finger. Three samples of material (two taken from differently designed anti-vibration gloves and another for comparison that was designed for mounting vibration-sensitive equipment) were assessed using stepped sinusoidal vertical vibration excitations covering the 20 to 400 Hz. Twelve human subjects were used for the testing. For all samples and subjects, measurements were obtained for: (I) dynamic mechanical analysis of the samples; (II) the transmissibility of vibration to the index finger at a grip force of 30 N, across the range of frequencies; and (III) transmissibility of vibration to the index finger at a frequency of 125 Hz for finger grip forces of 15, 30, and 45 N. No significant vibration attenuation was provided at frequencies below 150 Hz. The two materials taken from the gloves that passed the ISO 10819:1996 test showed resonance at frequencies of 150 and 160 Hz, but the material that did not put to the ISO test showed resonance at 250 Hz. The attenuation for all three materials was occurred at 315 Hz and 400 Hz. There was no significant change of transmissibility across the range of finger grip forces for any of the material samples. The level of transmissibility was found to vary between samples and subjects.

1. Introduction

Prolonged, intensive occupational exposure to hand-transmitted vibration is associated with hand-arm vibration syndrome (HAVS), and many types of anti-vibration (AV) gloves have been developed to reduce the vibration transmitted into the hands (Griffin 1998) . The international standard ISO 10819 has defined the procedure for testing and assessing gloves, whilst the standardised daily vibration exposure is determined as A(8) (ISO 5349-12001). Moreover, a glove can only be labelled as an anti-vibration glove if the fingers of the glove have the same material properties and thickness as those that cover the palm of the hand (ISO 108191997). A few studies have indicated that AV gloves could help workers to protect their hands, but there is still some doubt regarding the ability of these gloves to attenuate the vibration transmitted into the fingers (Griffin 1990; Welcome, Dong et al. 2014). These gloves may substantially increase the effort of hand grip and reduce finger dexterity (Wimer, McDowell et al. 2010). As a consequence, some AV gloves might be uncomfortable to wear and perhaps cause hand fatigue. While many studies have carried out the vibration transmissibility of AV gloves with regard to the palm of the hand, the study of the vibration transmissibility of such gloves in relation to the fingers has been limited (Welcome, Dong et al. 2014). As vibration-induced finger injuries and disorders are major components of HAVS (Griffin 1990), the fingers are critical substructures in the

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hand-arm system. Therefore, there is a motivation to measure the transmissibility of the gloves at the fingers.

Vibration transmissibility of gloves can be affected by many factors, such as the type of glove materials and their properties, tool vibration conditions, temperature and grip force. Although the AV gloves fulfil the requirements of vibration transmissibility, their assessment had been performed under controlled conditions such as room temperature and grip force, as stated in ISO 10819.

The present study, however, was designed to carry out a dynamic mechanical analysis of material samples in order to predict the dynamic responses of glove materials against a frequency spectrum and the effects of temperature, followed by an investigation into how the properties of different glove materials affect the tool vibration transmission into the index finger, and how the transmissibility of a glove material can be affected when varying grip forces are applied.

2. Material analysis

2.1. Method

Three different materials were selected for analysis. Materials 2 and 3 were taken from gloves that had passed the ISO 10819:1996 test, while material 1 was used for comparison, being a material designed for mounting vibration sensitive equipment. The summary of the characteristics of the samples are shown in Table 1.

Table 1 Characteristics of the samples used in the study

Material order	Material description	Thickness (mm)
1	Latex foam, new	6.10
2	Rubber, old	6.56
3	Foam, new	6.60

Dynamic Mechanical Analysis (DMA) was conducted for all three materials in order to gain material properties for comparison, and samples were prepared depending on their structures (see Figure 1). DMA involves measuring the mechanical response of a material sample when sinusoidal loading is applied.

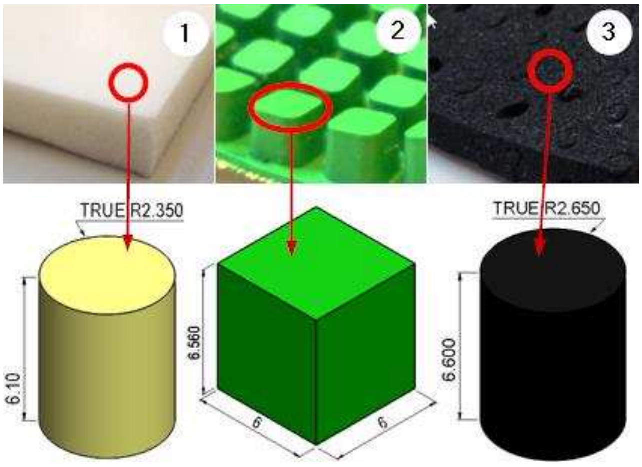
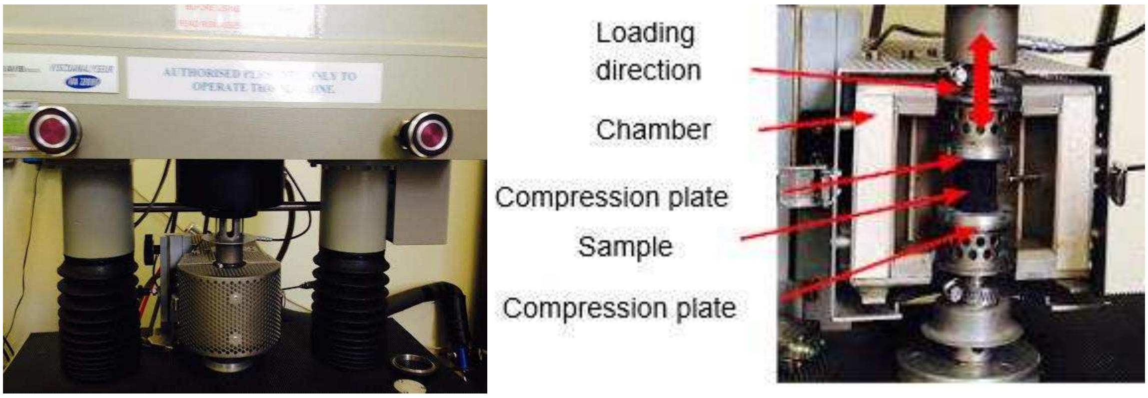


Figure 1 Material structures and dimensions of samples used for DMA testing (in mm)

The DMA was conducted using Metravib Viscoanalyser equipment as shown in Figure 2 (a). Each sample was installed between compression plates located in an analysis chamber, as shown in Figure 2 (b). The sample temperature was measured using a thermocouples probe located in the chamber. At the start of the test, the chamber was cooled using liquid nitrogen to -60 °C. Once the temperature had stabilised, the sample was subjected to sinusoidal vibrations with a dynamic strain amplitude of 10^{-3}. Measurement of the resulting force signal was made at seven different frequencies (values spaced evenly on a logarithmic scale between 1 and 31.5 Hz).The chamber was heated slowly by 5 °C and, after stabilisation, the vibration testing repeated. This process was repeated at 5 °C increments up to 80 °C.



(a) (b)

Figure 2 (a) Metravib Viscoanalyser VA2000 equipment; (b) Chamber and sample holding mode

The results obtained from the DMA equipment were used to produce viscoelastic master curves based on the Temperature-Frequency Superposition principle (Ferry 1980). In this work, the software employed to obtain the master curves was generated in-house and utilised the Differential Evolution Algorithm to find smooth spline curves that provide a best fit to the test data in a least squares sense.

2.2. Results from DMA of material samples

The master curves generated from the DMA data were used to predict the Young's modulus and loss factor for each material at temperatures and loading frequencies of interest in hand-arm vibration studies. This data is shown in Figures 3, 4 and 5.

It can be seen that the Young's modulus of all three materials (1, 2 and 3) increased as frequency of vibration increased and temperature decreased. A significant increase in the Young's modulus for all materials occurred when cooled to 0 °C as at this condition, the materials were closer to their glass transition temperatures. Note that the modulus of Materials 1 and 2 was approximately ten times higher than that of Material 3.

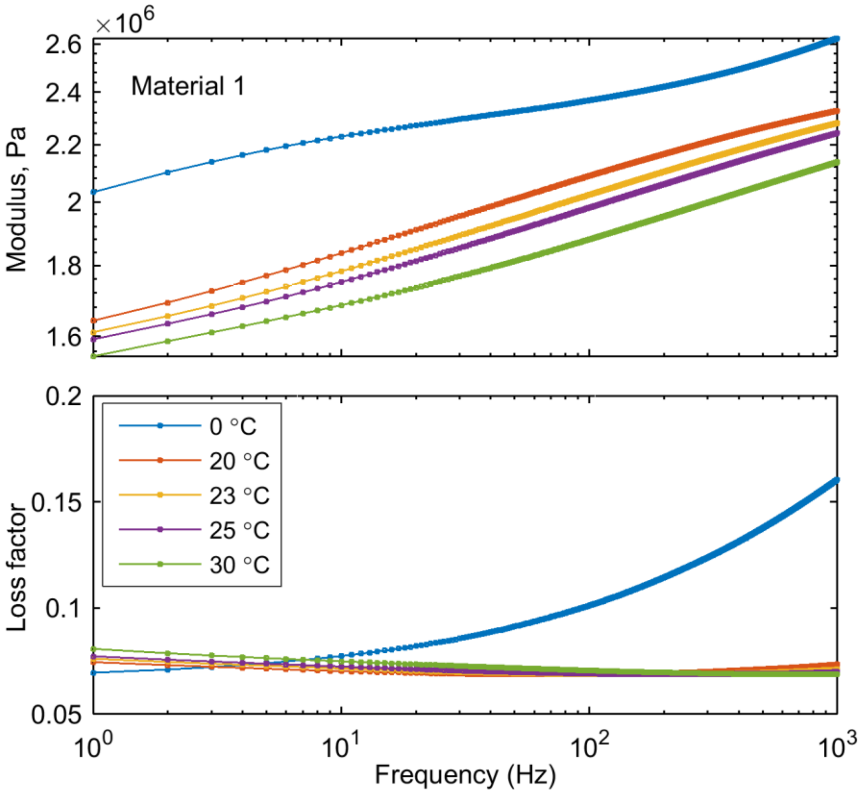


Figure 3 Young's modulus and loss factor against frequency for Material 1, $T_g \approx -35$ °C

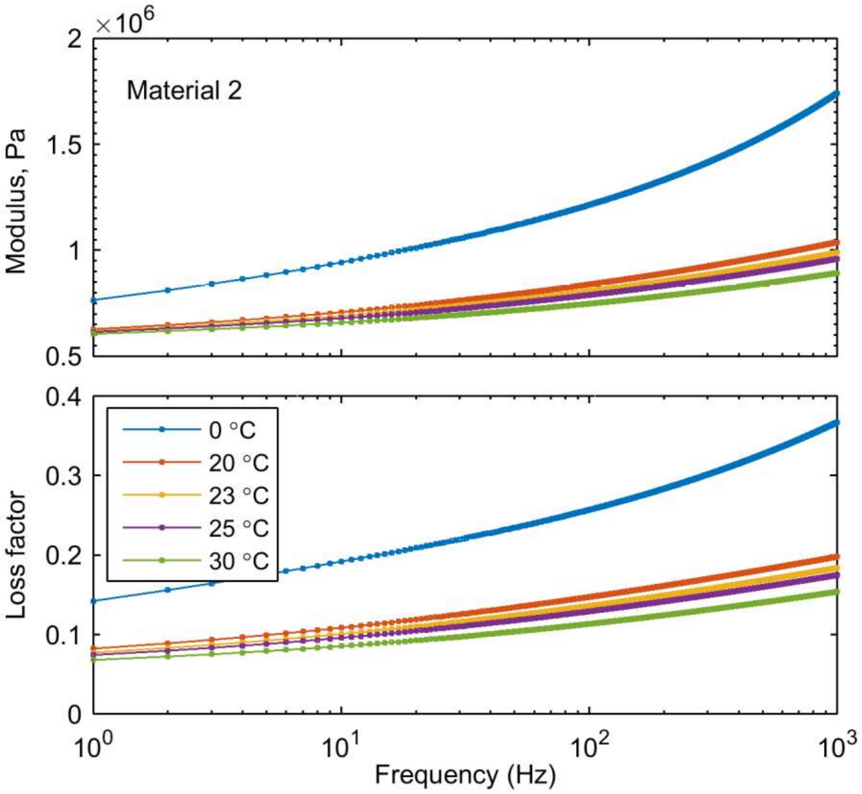


Figure 4 Young's modulus and loss factor against frequency for Material 2, $T_g \approx -35$ °C

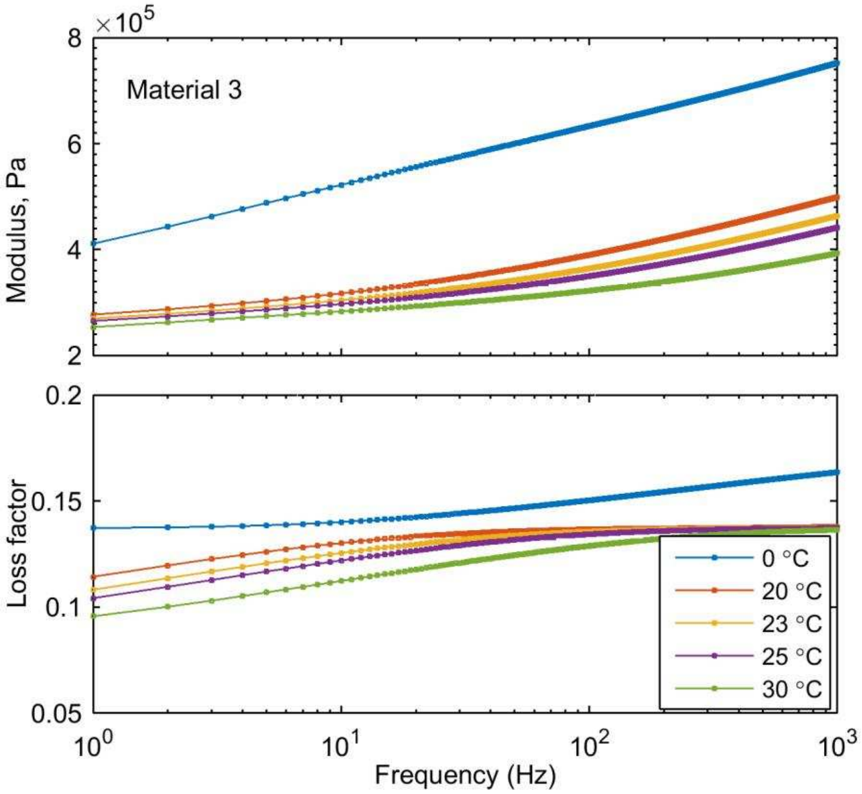


Figure 5 Young's modulus and loss factor against frequency for Material 3, $T_g \approx -50$ °C

The loss factor of Material 1 was not significantly affected by frequency when subjected to a temperature range from 20 to 30 °C, but there was a dramatic increase with frequency when at 0 °C, as shown in Figure 3. The loss factor of Material 2 gradually increased over the frequency range, but this was most significant at 0 °C as shown in Figure 4. Material 3 showed different loss factor behaviour, with a slight change at low frequencies and a tendency to have the same behaviour temperature ranged from 20 to 30 °C at frequencies beyond 100 Hz. However, it had a significantly higher loss factor at 0 °C, as shown as in Figure 5.

3. Human subject testing

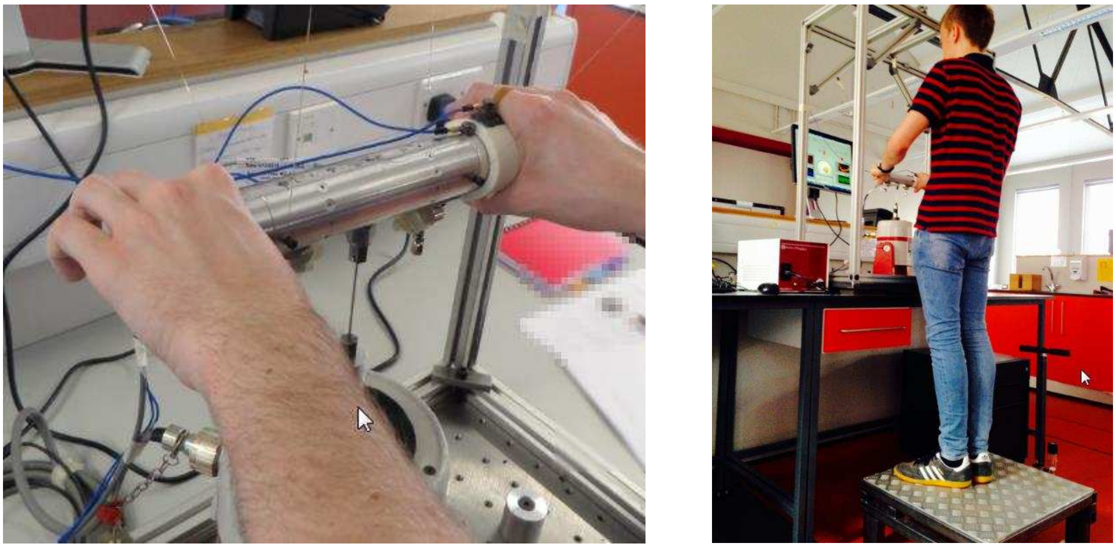
3.1. Method

Twelve human subjects aged 22 to 48 were used for the testing, and their characteristics are provided in Table 2. The design of the experiment was reviewed and approved by the Research Ethics Committee of the Faculty of Engineering at the University of Sheffield.

Table 2 Characteristics of the human subjects

	Range	Average
Age (years)	22 - 48	28.8
Weight (kg)	63 - 88	71.8
Height (cm)	173 - 183	176.4
Hand length (cm)	17 - 20	18.2
Hand circumference (cm)	17 - 22	19.9

A generic handle as shown in Figure 6 was produced and instrumented for vibration and grip force measurements. The handle was connected to a piezoelectric force transducer with sensitivity 43208 N/V (PCB Model 208C03) to measure the excitation force, freely suspended at the ends and attached to an electrodynamic exciter (LDS V406) with peak force capacity of 150 N via a thin stinger to provide the vertical excitation. The right hand end of the handle was designed and instrumented to measure a grip force to control the gripping force of the subjects. The design used a split cylinder with a strain gauged beam element (LCL -040), based on a design in accordance with ISO 10819 1996 (see Figure 7).



(a) (b)

Figure 6 (a): Posture of hands for the measurement of transmissibility of glove material to the Index finger. (b): Posture of subjects for all measurements. The finger grip force is displayed on ascreen was located in front of the subjects.

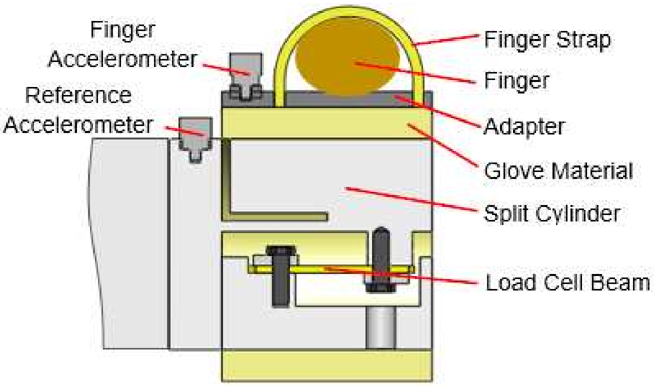


Figure 7 Cross-sectional diagram of the right end of the handle

Two piezoelectric accelerometers with nominal sensitivity 1.02 mV/ (m/s^2) (PCB Models 353B15 and 353A15) were used for measuring the acceleration data: one was attached to the handle and used as a reference accelerometer, whilst the other was mounted on an adapter strapped to the finger (see Figure 7). The material sample was placed around the right hand end of the handle, and the adapter was fitted onto the index finger of the right hand of the subject being tested (see Figures 6 and 7).

The subjects were asked to maintain a grip of 30 N, and once they were comfortable, the handle was excited using discrete sinusoidal vibration excitation signals that covered the range from 20 to 400 Hz software. Once the vibration input sequence had been completed, the subjects were then asked to maintain a grip of 15 N before being subjected to a vibration frequency of 125 Hz for 5 sec, and this was then repeated for a grip force of 45 N.

All experiments were carried out with no glove material in place and with each of the three materials.

The vibration amplitude produced by the rig was 1.47 ms^{-2} rms (frequency weighting W_h in accordance with ISO 5349-1:2001). All vibration measurements were performed at room temperature, which ranged from 22.9 °C to 23.4 °C.

3.2. Analysis of the transmissibility of gloves materials

All the measured data was processed and analysed using DIAdem view software (Version 2014). While the aim of the testing was to identify the transmissibility across the glove material when gripped by the finger, this could not be measured directly. Instead, the result was achieved in two steps. First, the transmissibility of the bare handle was defined as:

$$T_b = \frac{a_{fb}}{a_{Hb}} \tag{1}$$

where: T_b is the transmissibility of the bare handle; a_{fb} is the acceleration of the bare index finger (from the “finger” accelerometer); and a_{Hf} is the acceleration of the handle (from the “reference” accelerometer).

Next, for glove materials, the transmissibility was calculated using the following equation:

$$T_g = \frac{a_{fg}}{a_{Hg}} \tag{2}$$

where: T_g is the transmissibility of the glove material; 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).

Finally, the two transmissibilities measured were used to produce a single corrected transmissibility that describes the response of the handle-adapter system using Equation (3):

$$T_c = \frac{T_g}{T_b} \tag{3}$$

where: T_c is the corrected transmissibility of the glove material.

The corrected transmissibilities, T_c of all three of glove materials for all 12 subjects are shown in Figures 8, 9 and 10. No significant vibration attenuation was found for any of the materials at frequencies below 150 Hz. They all showed significant attenuation at frequencies above 315 Hz. Material 1 showed a good agreement between subjects for frequencies below 80 Hz. The true resonance frequency was found in the range 200-250 (see Figure 8) and generally attenuated at frequencies above 315 Hz.

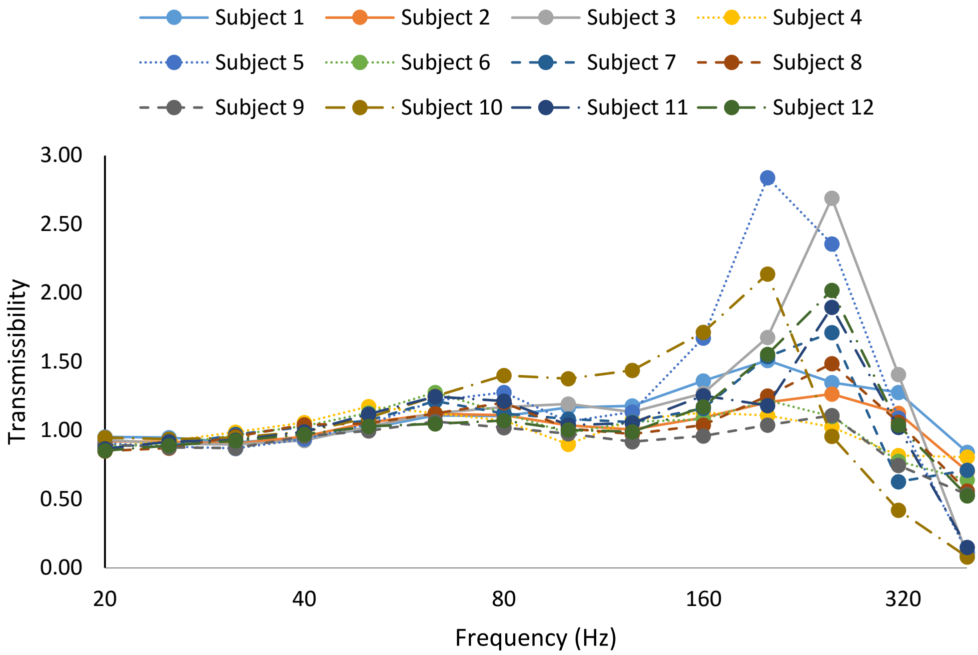


Figure 8 Transmissibility measurements against frequency for all subjects when using Material 1

Material 2 showed variable transmissibility among individuals. A slight variation in the range of resonance frequencies was found at frequencies from 80 Hz to 200 Hz, however, generally attenuation started to occur at a frequency of around 250 Hz (see Figure 9).

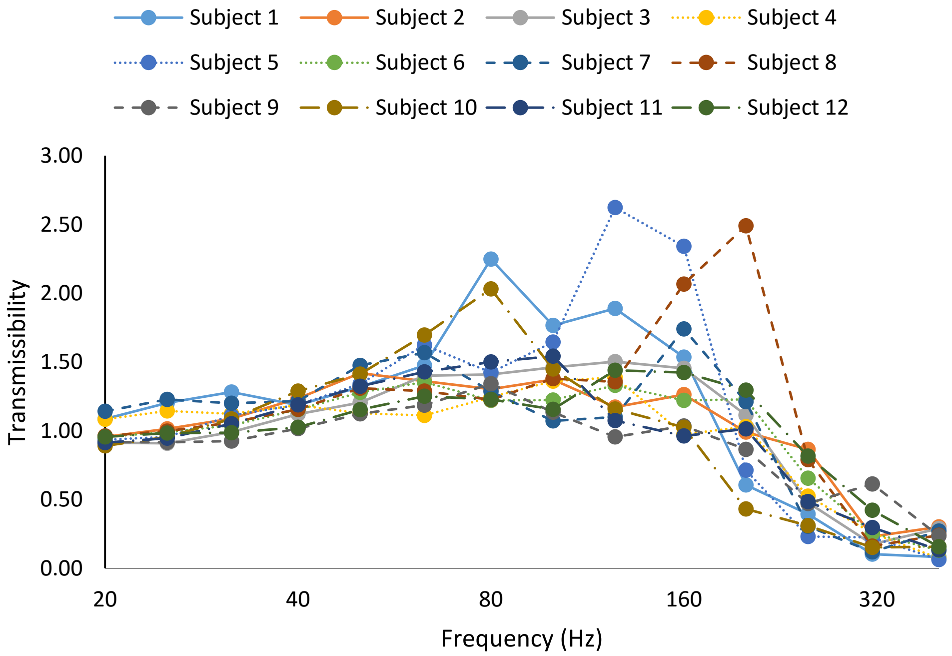


Figure 9 Transmissibility measurement against frequency for all subjects when using Material 2

Material 3 showed less variation in transmissibility when compared with Material 2, but more than Material 1. The resonance response was mostly shown at a frequency of 160 Hz and generally started attenuating at a frequency of 250 Hz (see Figure 10).

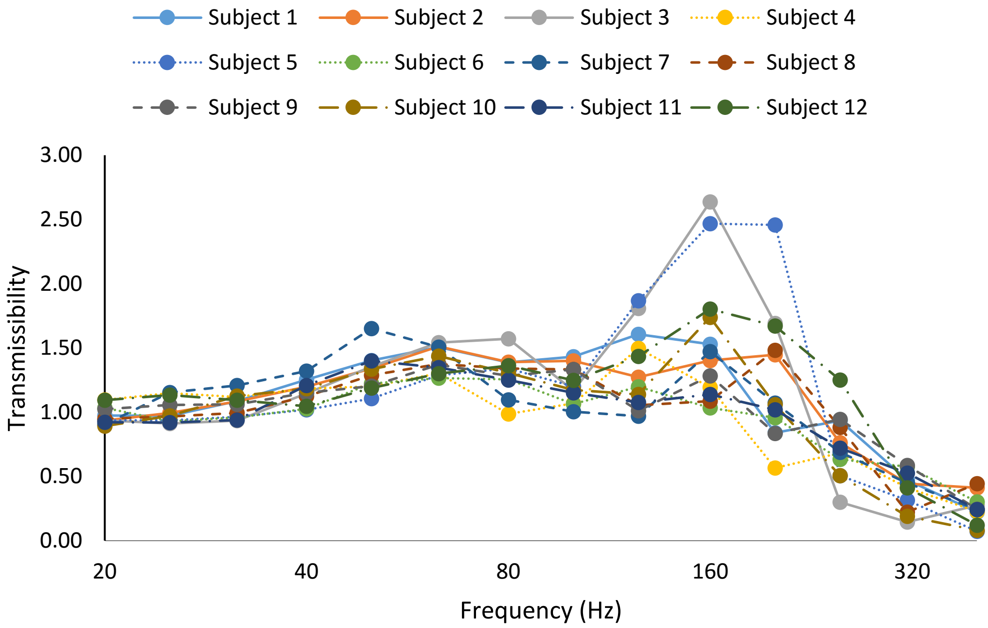


Figure 10 Transmissibility measurements against frequency for all subjects when using Material 3

3.3. The effect of grip force on the transmissibility of materials

All the materials showed variation in transmissibility among indivduals, making any trends in behaviour due to to grip force, hard to establish. Material 1 showed least variation among indivduals and Material 2 the most.

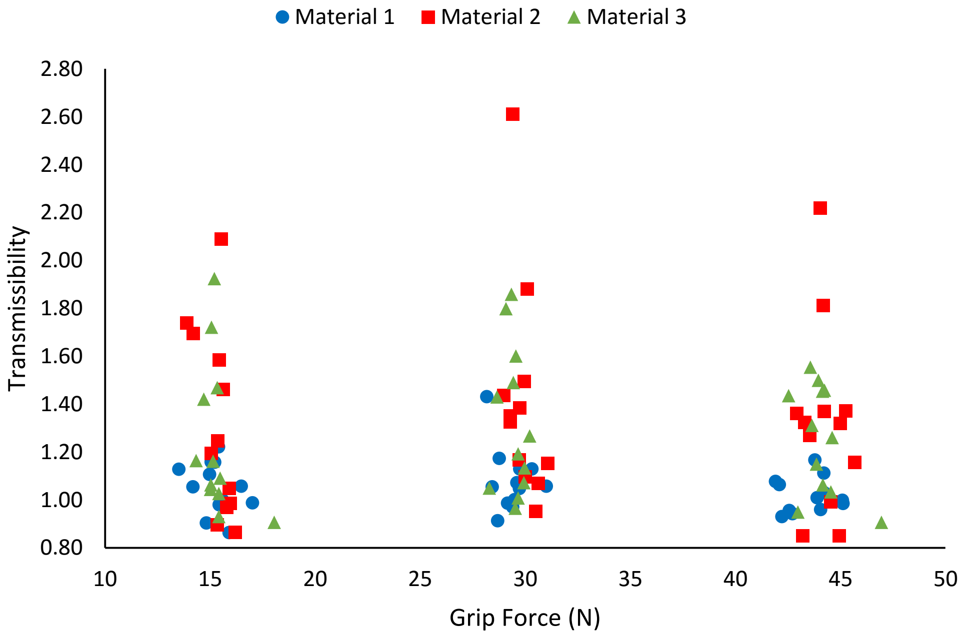


Figure 11 Transmissibility measurements against grip force for all subjects

4. Discussion

Many studies have been conducted using the palm adapter method, and most of the results show that there was very little attenuation below frequency of 200 Hz (Griffin 1998; Boyle and Griffin 2001; Xu, Dong et al. 2014). Although the same method was used in this study, there are differences between studies due to the difference in glove materials and subjects used. Another study tested different gloves and found that the transmissibility of gloves was largely affected by the design of the gloves (Welcome, Dong et al. 2014).

The AV glove materials examined in this study show little effect on vibrations below 100 Hz with possible amplification in the frequency range of 100-200 Hz and attenuation at frequencies beyond. Comparing this with other studies, they seem to be within the expected range of results for gloves.

One study tested the transmissibility of AV gloves using a 3-D laser vibrometer to measure vibration transmitted to the back of the finger (Welcome, Dong et al. 2014). It found that the AV gloves showed very little attenuation across the entire spectrum of frequencies and resonance at a frequency of 125 Hz when a grip force of 30 N is applied with inter-subject variability of the height and position of the peak. It should be noticed that the design of materials used in this present study did not match any of the glove designs in the previous studies.

Results from this study also show a strong agreement with the results obtained from a 3-D vibrometer (Welcome, Dong et al. 2014), which is very promising as that is the only study that measures the transmissibility at the finger and not on the palm.

The non-glove material (Material 1), seemed to be the one with the worst performance, with less attenuation than AV materials, but this was expected as it is the stiffest and not used in AV gloves and was not optimised for this application.

Materials 2 and 3 did not show enough attenuation over the range 150 to 250 Hz to be labelled as AV in accordance to ISO 10819. Since they had passed the ISO standard test, it can be assumed that they have less effect on fingers than on the palm (Welcome, Dong et al. 2014). The results of the present study suggested that the AV gloved fingers may only be effective at attenuating vibrations frequencies above 250 Hz.

According to a previous study, increasing the finger grip force increases the resonance frequency due to increased stiffness of the finger surface as well as the stiffness of the joints of the fingers (Welcome, Dong et al. 2014). This present study investigated the effects of grip force on vibration transmission of three different materials that could be found at a frequency of 125 Hz, with different grip forces 15, 30 and 45 N. As the results indicate (see section 3.3), all three materials showed no significant effect of grip force on transmissibility. This is reasonable, as unlike human tissue, polymers show relatively little nonlinearity at moderate strains.

The DMA results obtained represented the mechanical characteristics of the materials. Young's modulus affects the dynamic stiffness of the material layer, and is directly proportional to the energy stored during the loading period. The loss factor is the ratio of the energy lost to that stored and affects the mechanical damping of the material layer (ISO 6321-11996). As the resonance is affected not only by the modulus but also the geometry of the layers. Therefore, only modulus values can directly be compared in this study because the thickness is the same. DMA data found that Material 1 was stiffer than Material 2, and Material 3 used a less stiff structure than the other two. This is reasonable when combining DMA data with human subject testing. The resonance frequency increases with an increase in material stiffness. Material 1 showed resonance at frequencies from 200 Hz to 250 Hz and Material 3 resonated at 160 Hz.

Material 2 showed most variation in resonance frequency among individuals. However, there is a probable reason for the large variation in the resonance frequency (80 Hz to 250 Hz), which could be due to the surface of Material 2 is in blocks (see Figure 1) so that its effective area is less, therefore reducing the stiffness. It is hypothesised that these are the cause of the large variability.

The effects of the most effective frequencies and temperatures on Young’s modulus of tested materials are shown in Table 3 below.

Table 3 The effects of frequency and temperature on Young’s modulus of tested materials

Temperature ℃		Material 1			Material 2			Material 3		
		Frequency Hz								
Young’s Modulus, MPa		160	200	400	160	200	400	160	200	400
	0	2.40	2.42	2.49	1.29	1.33	1.48	0.66	0.67	0.70
	20	2.14	2.17	2.24	0.87	0.89	0.95	0.41	0.42	0.45
	23	2.08	2.10	2.18	0.84	0.85	0.91	0.38	0.39	0.42
	25	2.03	2.06	2.14	0.82	0.83	0.88	0.37	0.37	0.40
	30	1.93	1.95	2.03	0.77	0.79	0.83	0.33	0.34	0.36

DMA testing also allows the prediction of the behaviour of materials when they are cold. As the stiffness of the glove materials increases with an increase in vibration frequency, attenuation at higher frequencies could be lost due to an increase in resonance frequency.

5. Conclusion

Dynamic mechanical analysis testing for glove materials has shown that the mechanical properties of materials under sinusoidal loading and at different temperatures behave differently, largely depending on the structure of the materials. Thus, this study has suggested that the properties of different glove materials will change in real world work conditions (e.g. at low temperatures).

From the data gathered in this study, it can be concluded that AV gloves are less effective in protecting the fingers from vibration than they are in protecting the palm of the hand. Combining DMA data with human subjects testing allows the AV performance of glove materials to be predicted for different temperatures.

6. References

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