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Transmission of vibration through gloves: Effects of contact area

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Abstract

For three samples of material (12.5, 25.0, and 37.5 mm diameter) from each of three gloves, the dynamic stiffnesses and the vibration transmissibilities of the materials (to both the palm of the hand and the thenar eminence) were measured at frequencies from 10 to 300 Hz. Additional measurements showed the apparent masses of the hand at the palm and the thenar eminence were independent of contact area at frequencies less than about 40 Hz, but increased with increasing area at higher frequencies. The stiffness and damping of the glove materials increased with increasing area. These changes caused material transmissibilities to the hand to increase with increasing area. It is concluded that the size of the area of contact has a large influence on the transmission of vibration through a glove to the hand. The area of contact should be well-defined and controlled when evaluating the transmission of vibration through gloves.

Keywords: Anti-vibration gloves, biodynamics, transmissibility, impedance, hands

Practitioner summary

The transmission of vibration through gloves depends on both the dynamic stiffness of glove material and the dynamic response of the hand. Both of these depend on the size of the contact area between a glove material and the hand, which should be taken into account when assessing glove transmissibility.

1. **Introduction**

The vibration from powered tools can harm the hands of tool operators (Griffin and Bovenzi, 2002). ‘Anti-vibration gloves’ have been suggested to attenuate the transmission of vibration to the hand and reduce the risks arising from the operation of vibratory tools. The transmissibilities of gloves to the hand have been measured in various conditions with different powered tools (Pinto *et al.*, 2001; Dong *et al.*, 2014) but their benefits are unproven (e.g., McDowell *et al.*, 2013, Rezali and Griffin, 2016) and it is not understood how various factors influence the transmission of vibration though gloves to the hand and to the fingers (Griffin, 1998).

The transmission of vibration through a glove to the hand is influenced by several variables, but principally the stiffness and damping properties of the material and the biodynamic response of the hand (i.e., mechanical impedance or apparent mass, Griffin, 1990). There has been little study of how changes in the size of the contact area affect the biodynamic response of the hand. However, it has been reported that the driving-point mechanical impedance of the hand-arm system depends on the size of the contact area at frequencies greater than 100 Hz (Marcotte *et al.*, 2005), and that increasing the area of contact with a finger increases the apparent mass of the finger at frequencies greater than about 400 Hz (Mann and Griffin, 1996).

The stiffness and damping of materials used in gloves can also be expected to change if the size of the area of contact is changed. For a uniform material that behaves linearly, a doubling the area of contact can be expected to result in a doubling of both the stiffness and the damping of the material. However, for the materials used in gloves it is not reported how the stiffness and damping change with area, or how any change affects the transmission of vibration to the hand.

At high frequencies, the transmissibilities of glove materials increase with increasing glove dynamic stiffness (O’Boyle and Griffin, 2004; Rezali and Griffin, 2014) but decrease with increasing apparent mass of the part of the body in contact with the glove material (e.g., index finger or palm of the hand; Rezali and Griffin, 2016). To understand the effect of contact area on the transmissibility of a glove it is therefore necessary to understand how both the dynamic stiffness of the glove material and the dynamic response of the hand vary with area and with the frequency of vibration. When holding a powered vibratory tool, the contact area can be complex, difficult to define and measure, and vary from time-to-time. The effects of contact area on glove transmissibility are more easily understood by undertaking systematic laboratory investigations.

This study was designed to investigate how the size of the area of contact with the hand affects the dynamic response of the hand, the dynamic stiffness of glove materials, and the transmission of vibration to the hand. It was hypothesised that with increased area of contact, the apparent mass at the palm would increase at higher frequencies but be unchanged at lower frequencies. With increasing area of contact, the stiffness and damping of the material were expected to increase. The transmission of vibration to the hand was expected to either increase or decrease with increasing area, depending on the relative changes in the material dynamic stiffness and the apparent mass of the hand.

2. Methods

2.1 Materials and contact area

Three materials, two foams and a gel (denoted as Foam A, Foam B and Gel A), with thicknesses of 6.4, 6.0, and 5.0 mm, respectively, were prepared with three contact areas having diameters of 12.5, 25.0, and 37.5 mm. All nine samples weighed less than 2 grams, except for the largest gel that weighed 4 grams. The relative area of the contact areas increased to 400% and 900% from 12.5 to 25.0 and 37.5 mm. Foam A (i.e., material from an anti-vibration glove available in the market at the time of the study) and Gel A were cut from gloves that, respectively, passed and failed the test for anti-vibration gloves in ISO 10819:1996. Foam A and Foam B were closed-cell foams. Foam A was perforated with 0.5-mm diameter holes.

2.2 Subjects

Ten male subjects participated in the experiment: median age 29 years (range 24 to 42), stature 167 cm (160 – 181), weight 67 kg (59 – 120), hand circumference 200 mm (165 – 230), and hand length 183 mm (172 – 205).

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (reference number 8824).

2.3 Measuring apparent mass at the palm and at the thenar eminence

A force transducer (Kistler 4576A) was secured to a metal plate attached to the table of a vibrator (Derritron VP30), so as to measure the static downward force, and support an impedance head (B&K 8001) to measure vertical dynamic force and acceleration (Figure 1). A metal plate (12.5-, 25.0- or 37.5-mm diameter and weighing 1, 12 or 20 grams, respectively) was attached to the top of the impedance head and supported a 12.5-, 25.0 or 37.5-mm diameter wooden adapter (weighing less than 1, 3 or 5 grams) containing an accelerometer (B&K 4374).

FIGURE 1 ABOUT HERE

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The participants placed the palms of their hands, or their thenar eminences, on the circular wooden adapter. The arm was not otherwise supported. They pushed the circular wooden plate downward with a force of 10 N, as indicated on an oscilloscope (i.e., this setup was similar to Rezali and Griffin (2016) with a small difference in the transducers used to measure static and dynamic forces). This force was applied for all measurements. Subjects underwent training for about 5 minutes before the experiment commenced.

A 10-s period of random vertical vibration (with an acceleration spectrum from 5 to 500 Hz) was generated using MATLAB (R2011b) with the *HVLab* toolbox (version 1.0). The vibration was presented at a magnitude of 2.0 ms^{-2} r.m.s. (frequency-weighted using W_h according to ISO 5349-1:2001).

2.4 Measuring the transmissibility of the material to the palm and to the thenar eminence

The procedures in Section 2.3 were repeated to measure the transmission of vibration to the palm and to the thenar eminence with each of the three materials and all three contact areas. The material samples were placed on top of a circular metal plate and below a wooden adapter of the same diameter.

The material transmissibility was measured using the same 10-s 2.0 ms^{-2} r.m.s. random vertical vibration used to measure the apparent mass of the hand.

The order of measuring apparent mass and material transmissibility of all three sizes and the three materials was randomised.

2.5 Determining the dynamic stiffness of the material

The dynamic stiffnesses of the three diameters of the three materials were measured using an indenter rig as shown in Figure 2. The material was placed on a plate attached to the vibrator platform. In the upper part of the indenter rig, a force transducer was suspended through a bearing so as to apply a downward force of 10 N on the material by turning the preload screw. The force was applied via an impedance head so as to measure the dynamic force during vibration. Vertical acceleration was measured using an accelerometer (B&K 4374) on the table of the vibrator.

FIGURE 2 ABOUT HERE

A 10-s period of random vertical vibration (with an acceleration spectrum from 5 to 500 Hz) was generated using MATLAB (R2011b) with the *HVLab* toolbox (version 1.0). The vibration was presented at a magnitude of 0.75 ms^{-2} r.m.s. (frequency-weighted) using a Derritron VP4 vibrator. To obtain measurable forces over the range 20 to 300 Hz, a different vibration spectrum was used to measure material dynamic stiffness.

2.6 Analysis

The data were acquired with a sampling rate of 4096 samples per second via anti-aliasing filters at 1000 Hz. Constant bandwidth frequency analysis was performed with a resolution of 2 Hz and 84 degrees of freedom.

Apparent mass

The effect of the masses supported on the force cell of the impedance head was eliminated by subtracting the vertical acceleration multiplied by these masses from the measured force in the time domain (i.e., mass cancellation).

The apparent mass of the hand, $M(f)$, was determined from the ratio of the cross-spectral density of the input acceleration and the output force, $F_{io}(f)$, to the power spectral density of the input acceleration, $A_{ii}(f)$:

$$M(f) = \frac{F_{io}(f)}{A_{ii}(f)} \tag{1}$$

The apparent mass of the hand with wooden adapter, $M_{hw}(f)$, was calculated using:

$$M_{hw}(f) = \frac{F_{hwio}(f)}{A_{ii}(f)} \tag{2}$$

where F_{hwio} (f) is the force exerted at the wooden adapter and given by:

$$F_{hwio}(t) = F_{io}(t) - M_{s-w}(t)A_{ii}(t) \tag{3}$$

where $M_{s\text{-}w}$ (t) is the mass of the equipment supported by the force cell of the impedance head excluding the wooden adapter.

Transmissibility

The transmissibility of the glove material, $T(f)$, was determined from the ratio of the cross-spectral density of the input and output acceleration, $a_{io}(f)$, to the power spectral density of the input acceleration, $a_{ii}(f)$:

$$T(f) = \frac{a_{io}(f)}{a_{ii}(f)} \tag{4}$$

Dynamic stiffness

The dynamic stiffness of glove material, $S(f)$, was given by:

$$S(f) = \frac{F_{Mio}(f)}{-\omega^{-2}A_{Mii}(f)} \tag{5}$$

where $F_{\mathrm{Mio}}(f)$ is the cross-spectral density of the input acceleration and the output force transmitted by the material, $A_{\mathrm{Mii}}(f)$ is the power spectral density of the input acceleration, and ω is the angular frequency ($\omega = 2\pi f$).

The dynamic stiffness of the material was assumed to be represented by $S(f) = k + \mathrm{i}c\omega$, where k is the stiffness of the material and c is the material viscous damping coefficient.

2.7 Predicting the transmissibility of material to the palm and to the thenar eminence

A mechanical impedance model was used to predict the transmissibility of the material to the palm of the hand (Rezali and Griffin, 2016):

$$\frac{a_{\mathrm{io}}(f)}{a_{\mathrm{ii}}(f)} = \frac{\omega^{-2} S(f)}{\omega^{-2} S(f) - M_{hw}(f)} = T(f) \qquad (6)$$

3. **Results**

The coherencies of all measurements of dynamic stiffness, apparent mass, and transmissibility were greater than 0.8 at all frequencies in the range 10 to 300 Hz.

3.1 Dynamic stiffnesses of the materials

The dynamic stiffness and the viscous damping of each of the three materials increased with increasing contact area (Figure 3). The viscous damping of the three materials decreased with increasing frequency of vibration. Foam B was the stiffest material and had the greatest damping, while Foam A was the softest material and had the least damping.

FIGURE 3 ABOUT HERE

3.2 Apparent mass at the palm and at the thenar eminence

Inter-subject variability in the apparent mass measured at the palm and at the thenar eminence is shown in Figure 4.

FIGURE 4 ABOUT HERE

The apparent mass measured at the palm of the hand decreased as the frequency of vibration increased (Figure 5). The first principal resonance frequency in the median apparent mass at the palm, around 14 Hz, did not change with a change in contact area ($p>0.277$; Friedman). The median apparent mass at the palm was independent of contact area at frequencies less than about 52 Hz ($p>0.061$; Friedman), but increased with increasing contact area at higher frequencies (Friedman $p<0.045$).

FIGURE 5 ABOUT HERE

With all three contact areas, the first principal resonance frequency in the median apparent mass at the thenar eminence, around 26 Hz, was unchanged with a change in contact area ($p>0.112$; Friedman). The median apparent mass at the thenar eminence was independent of contact area at frequencies less than about 38 Hz ($p>0.061$; Friedman), but increased with increasing contact area at higher frequencies ($p<0.045$; Friedman).

With the same contact area, the median apparent mass was greater at the palm than at the thenar eminence for all frequencies greater than about 60 Hz ($p< 0.001$; Friedman).

3.3 Transmissibilities of glove materials to the palm and to the thenar eminence

The effects of the area of contact on the median transmissibilities to the palm and to the thenar eminence are shown in Figure 6.

FIGURE 6 ABOUT HERE

For Foam A, the median transmissibility to the palm of the hand was less than 1.0 at all frequencies of vibration (in the range 10 to 300 Hz) and for all three contact areas. At frequencies greater than 20 Hz, the transmissibilities to both the palm and the thenar eminence increased as the diameter of the contact area increased from 12.5 to 37.5 mm (Figure 6; $p<0.0136$ for palm, $p<0.0247$ for thenar eminence; Friedman). However, at high frequencies, the transmissibility of Foam A to both the palm and the thenar eminence was similar for 12.5 and 25.0 mm diameter material ($p>0.193$ for frequencies greater than 134 Hz at the palm, $p>0.106$ for frequencies greater than 66 Hz at the thenar eminence; Wilcoxon).

For Foam B, at very low frequencies the transmissibilities to the palm of the hand and to the thenar eminence were similar with all three contact areas. As the frequency increased to 300 Hz, the transmissibilities to the palm and the thenar eminence were less with the smaller area and greater with the larger area (Figure 6; $p<0.006$ for frequencies greater than 14 Hz for the palm of the hand, $p<0.025$ for frequencies greater than 8 Hz for the thenar eminence; Friedman). There was a broadly similar trend with Gel A (Figure 6).

At high frequencies, for the same material and same contact area, the transmissibilities to the palm were lower than the transmissibilities to the thenar eminence ($p< 0.001$; Friedman).

The transmissibilities of the three glove materials to the palm and to the thenar eminence are shown for individual subjects in Figures 7, 8 and 9.

FIGURES 7, 8 and 9 ABOUT HERE

3.4 Predicted material transmissibilities to the palm and to the thenar eminence

The predicted transmissibilities are compared with the measured transmissibilities for individual subjects and Foam A, Foam B, and Gel A in Figures 7, 8 and 9, respectively.

For Foam A and Gel A, with the two larger contact areas the transmissibilities predicted for individual subjects are similar to the measured transmissibilities (Figures 7 and 9). There are some discrepancies for both materials and both locations with the smaller contact area (12.5-mm diameter).

With Foam B, for all contact areas, the transmissibilities predicted for individual subjects can be seen to reflect how the measured transmissibility depends on individual variability in apparent mass and increasing dynamic stiffness with increasing contact area (Figure 8).

For all three materials, the predicted median transmissibilities to the palm of the hand and to the thenar eminence (predicted from the measured individual apparent masses at the palm and the thenar eminence and the measured dynamic stiffnesses of the materials) were similar to the measured median transmissibilities (Figure 10).

For the measured and the predicted transmissibilities to both locations, there is a progressive increase in glove transmissibility at higher frequencies as the diameter of the contact area increased from 12.5 to 37.5 mm (Figure 10).

FIGURE 10 ABOUT HERE

4. Discussion

4.1 Apparent mass at the palm and at the thenar eminence

The dynamic response of the soft tissue adjacent to the point of contact dominates the apparent mass of the hand at high frequencies (Dong *et al.*, 2005b, Adewusi *et al.*, 2012), because high frequency vibration is not greatly transmitted to more distant locations. In the present study it was therefore hypothesised that increasing the contact area would increase the apparent mass at higher frequencies at both the palm and the thenar eminence. This is evident in the results shown in Figure 5. At low frequencies, vibration is transmitted to the greater masses of the hand and arm, so the apparent mass of the soft tissue close to the point of contact has a smaller influence on the total apparent mass of the hand, and so changes in contact area have less effect on the apparent mass at low frequencies (see Figure 5).

The apparent mass measured at the palm of the hand in this study is similar to that reported for the palm in previous studies with similar conditions (i.e., similar contact area, contact force, direction of vibration excitation, and posture of the hand; Figure 11) but different subjects (Rezali and Griffin, 2016). Even with the largest contact area, the apparent mass is less than the apparent mass measured in the horizontal axis of the hand gripping a handle (Dong *et al*., 2005a) and less than the horizontal axis apparent mass of the flat hand pushing down on a flat surface (Xu *et al.*, 2011) at frequencies up to 300 Hz. This is consistent with the combination of a greater contact area (i.e., as in this study) and a greater contact force (e.g., O'Boyle and Griffin, 2004) increasing the apparent mass at high frequencies, as well as the direction of vibration excitation and posture having an influence.

FIGURE 11 ABOUT HERE

4.2 Effect of apparent mass and dynamic stiffness on material transmissibility

Although both the hand and a material are complex dynamic systems, some simple approximations may provide useful indications of how transmissibility will depend on material dynamic stiffness and the apparent mass of the hand, and therefore the area of contact. At the higher frequencies, the transmissibility of a glove material will tend to increase if there is an increase in the material dynamic stiffness (e.g., Rezali and Griffin, 2014) and decrease if there is an increase in the apparent mass of the hand (e.g., Rezali and Griffin, 2016). For all three materials in this study, the transmissibilities to the palm of the hand increased with increasing area of contact. This suggests that, with increasing area of contact, the increase in material dynamic stiffness had a greater effect on the transmissibility than the increase in apparent mass of the hand.

The softest material, from a glove that passed the test in ISO 10819:1996 (i.e., Foam A), had the least increase in stiffness and damping as the area of contact increased (see Figure 3). This resulted in the smallest increase in transmissibility as the area of contact increased (Figure 6).

Reducing the contact area of a material can reduce its dynamic stiffness and may reduce transmissibility. The materials used in this study were solid, of uniform construction, and constant thickness. It might be possible to reduce the overall contact area of a uniform material, or the contact area might be reduced by making the material non uniform (e.g., by the addition of holes or channels). Alternatively, the dynamic stiffness might be reduced by using two or more materials with different dynamic properties in parallel. Varying the area of material contacting the hand is a practical way of varying the dynamic response of a glove. Increasing the thickness of a glove material can also reduce its dynamic stiffness and reduce the transmissibility (Rezali and Griffin, 2016).

Since the area of contact can have a large influence on material transmissibility, there are implications for the design of materials used in gloves and the method of testing the transmissibility of gloves. To obtain reliable measures of the effectiveness of gloves in attenuating vibration, the area of contact must be well-defined and suitably controlled.

4.3 Predicting the effects of contact area on glove transmissibility

An impedance model can predict the effect of material thickness on the transmissibility of materials to the hand and to the fingers (Rezali and Griffin, 2016). This study shows that the model also provides useful predictions of the effects of the size of the area contact on transmissibility through materials to the hand.

To better understand the relative importance of the dynamic stiffness of the material and the apparent mass of the hand, the transmissibility of Foam A to the palm of the hand was predicted for three cases: (i) the apparent mass varying with contact area but the dynamic stiffness fixed for a contact area of 12.5 mm, (ii) the dynamic stiffness varying with contact area but the apparent mass fixed for a contact area of 12.5 mm, and (iii) both apparent mass and dynamic stiffness varying with the area of contact area, as in this study (Figure 12).

For Case 1, the predicted transmissibility to the palm of the hand decreased at high frequencies as the diameter of the contact area increased, although the decrease was relatively small.

For Case 2, the predicted transmissibility to the palm of the hand increased with increasing contact area. The increase was large and the trend is similar to that in the measured transmissibility (see Figure 6).

For Case 3 (i.e., the same as for the predicted transmissibilities in Figure 10), the predicted transmissibility to the palm increased with increasing contact area. For areas of contact with diameters of 25 mm and 37.5 mm, the transmissibilities predicted for Case 3 are slightly lower than those predicted for Case 2, due to the increasing apparent mass of the hand with increasing contact area.

FIGURE 12 ABOUT HERE

4.4 Inter-subject variability

The material transmissibilities predicted for individual subjects from their individual apparent masses were similar to the measured individual transmissibilities (Figures 7, 8, and 9). This shows that, as expected, individual variability in the apparent mass at the palm and at the thenar eminence affect the transmission of vibration through gloves. This has implications for the design of materials used in gloves and the method of testing glove transmissibility.

A glove that attenuates or amplifies vibration for one worker may, respectfully, attenuate or amplify vibration for another worker. It might even be possible to predict the effect of wearing a glove for an individual worker (Rezali and Griffin, 2016). To obtain useful measures of the effectiveness of a glove in attenuating vibration, the dynamic characteristics of the test subjects (e.g., a suitable measure of the apparent mass of the hand) should be defined and controlled.

4.5 Glove transmissibility measured in this study and in International Standard ISO 10819:2013

The transmissibilities of the glove materials measured in this study are expected to be different from the transmissibilities of the glove materials measured using ISO 10819:2013. This is due to differences in the area of contact (1.1 x 10^{-3} m^2 for the largest adapter used in this study compared with 2.0x10^{-3} m^2 in ISO 10819:2013), a difference in contact force (10 N in this study compared with 50 N at the palm in ISO 10819:2013), and differences in the posture of the hand and the direction of the vibration (vertical vibration in this study compared with horizontal vibration in ISO 10819:2013). For similar reasons it is expected that the transmissibility of a glove measured in conditions similar to those defined in ISO 10819:2013 will differ from the transmissibility of the glove when used with vibratory hand tools. Nevertheless, the underlying reasons for contact area affecting the transmissibilities of gloves as found in this study will apply when they are tested using ISO 10819:2013 or on vibratory tools.

5. Conclusions

With increasing area of contact of a glove material with the hand, there are increases in both the dynamic stiffness of the glove material and the apparent mass of the hand (at the area of contact with the palm or the thenar eminence).

For the three materials used in this study, the transmissibility through the material to the hand increased at the higher frequencies when the area of contact increased. This increase in transmissibility is mainly attributed to the increased dynamic stiffness of the material as the diameter of the contact area increases.

Manipulating the area of contact of a glove material with the hand is a practical means of modifying the transmissibility of a glove.

It is concluded that the area of contact must be defined and controlled when measuring and evaluating the vibration transmissibility of gloves.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Adewusi S, Rakheja S, Maracotte P (2012) Biomechanical models of the human hand-arm to simulate distributed biodynamic responses for different postures. International Journal of Industrial Ergonomics, 42, 249-260

Dong RG, Rakheja S, McDowell TW, Welcome DE, Wu JZ, Warren C, Barkley J, Washington B and Schopper AW (2005a) A method for assessing the effectiveness of anti-vibration gloves using biodynamic responses of the hand–arm system. Journal of Sound and Vibration, 282, 1101-1118.

Dong RG., Wu JZ, McDowell TW, Welcome DE and Schopper AW (2005b) Distribution of mechanical impedance at the fingers and the palm of the human hand. Journal of Biomechanical, 38, 1165-75.

Dong RG, Welcome DE, Peterson DR, Xu XS, McDowell TW, Warren C, Asaki T, Kudernatsch S, Brammer A, and Cherniack M. (2014). Tool-Specific Performance of Vibration-Reducing Gloves for Attenuating Palm-Transmitted Vibrations in Three Orthogonal Directions. International Journal of Industrial Ergonomics, 44(6), 827-839.

Griffin MJ (1990) Handbook of Human Vibration, Elsevier Academic Press.

Griffin MJ (1998) Evaluating the effectiveness of gloves in reducing the hazards of hand-transmitted vibration. Occupational and Environmental Medicine, 55, 340-348.

Griffin MJ and Bovenzi M (2002) The diagnosis of disorders caused by hand-transmitted vibration: Southampton Workshop 2000. International Archives of Occupational and Environmental Health, 75, (1-2), 1-5.

International Organization for Standardization (1996) Mechanical vibration and shock - Hand-arm vibration - Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand, International Standard, ISO10819:1996.

International Organization for Standardization (2001) Mechanical vibration - Measurement of human exposure to hand-transmitted vibration Part 1: General requirements, International Standard, ISO 5349-1:2001.

International Organization for Standardization (2013) Mechanical vibration and shock - Hand-arm vibration - Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand, International Standard, ISO10819:2013.

Mann NAJ and Griffin MJ (1996) Effect of contact conditions on the mechanical impedance of the finger. Central European Journal of Public Health, 4, 46-49.

Marcotte P, Aldien Y, Boileau PE, Rakheja S, and Boutin J (2005) Effect of handle size and hand-handle contact force of the biodynamic response of the hand-arm system under z_h-axis vibration. Journal of Sound and Vibration, 283, 1071-1091

McDowell TW, Dong RG, Welcome DE, Xu XS, and Warren C. (2013). Vibration-Reducing Gloves: Transmissibility at the Palm of the Hand in Three Orthogonal Directions. Ergonomics, 56(12), 1823-1840.

O'Boyle M and Griffin MJ (2004) Predicting the effects of push force on the transmission of vibration through glove materials to the palm of the hand. 10th International Conference on Hand-Arm Vibration, 07-11 June 2004 Las Vegas, Nevada, USA.

Pinto I, Stacchini N, Bovenzi M, Paddan GS, Griffin MJ (2001). Protection effectiveness of anti-vibration gloves: Field evaluation and laboratory performance assessment. 9th International Conference on Hand-Arm Vibration. Held at Institut National de Recherche et de Securite, Nancy, France, 5-8 June 2001.

Rezali KAM and Griffin MJ (2014) The transmission of vibration through gloves to the hand and to the fingers: Effects of material dynamic stiffness, Applied Mechanics and Materials Vol 564 pp 149-154

Rezali KAM and Griffin MJ (2016) The transmission of vibration through gloves: Effects of material thickness. Ergonomics (awaiting publication); http://dx.doi.org/10.1080/00140139.2015.1102334.

Xu XS, Welcome DE, McDowell TW, Wu JZ, Wimer B, Warren C and Dong RG (2011) The vibration transmissibility and driving-point biodynamic response of the hand exposed to vibration normal to the palm. International Journal of Industrial Ergonomics, 41, 418-427.

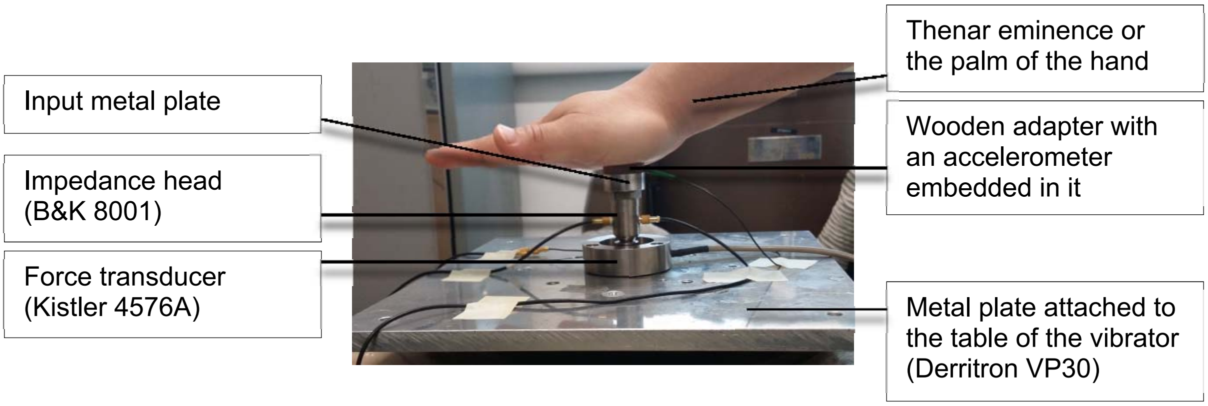

Figure 1 Posture of the hand for the measurement of the apparent mass at the thenar eminence.

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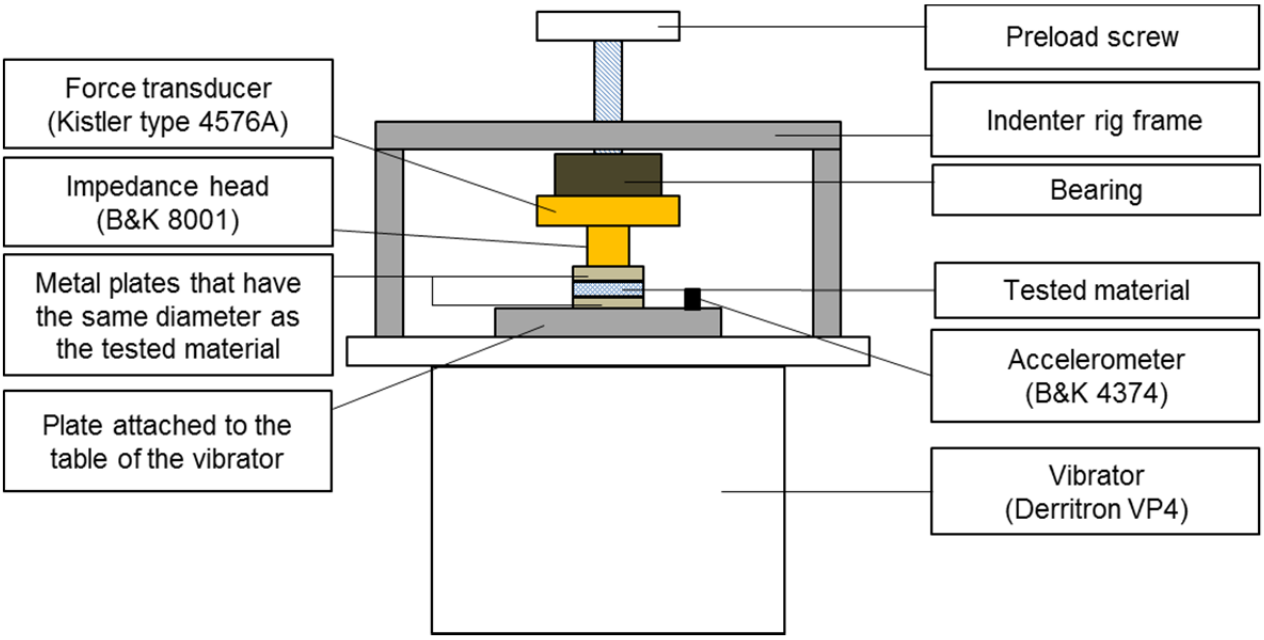

Figure 2 Diagrammatic representation of the rig used to determine the dynamic stiffness of the material.

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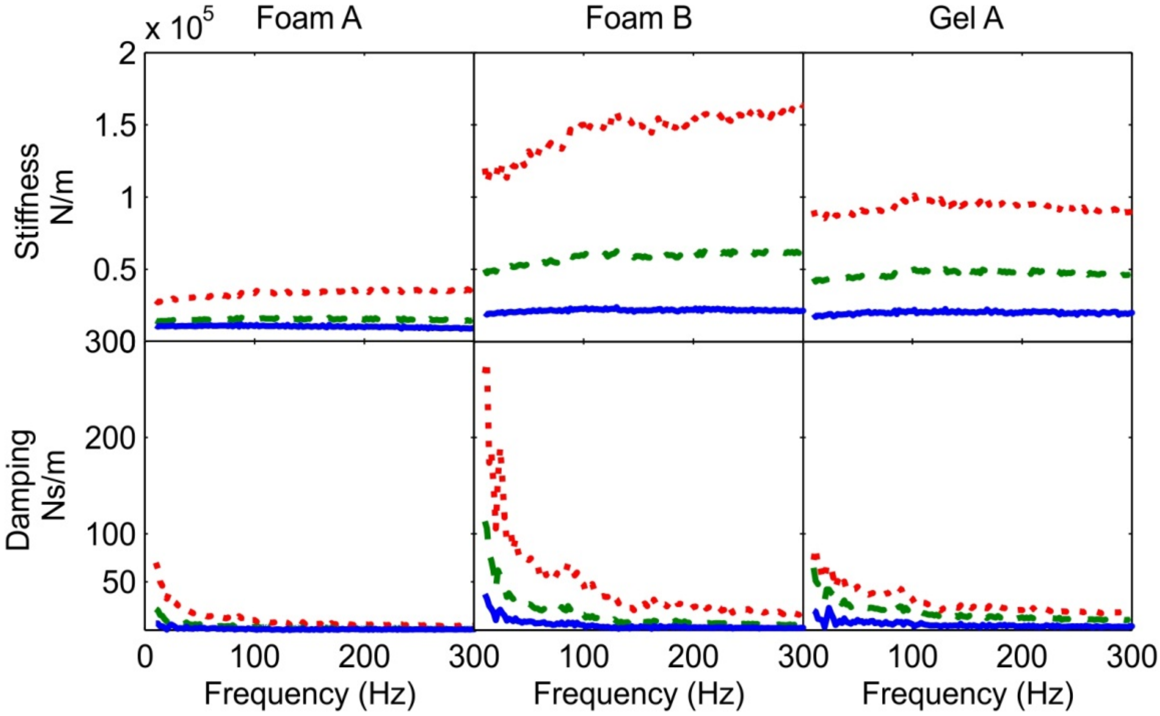

Figure 3 Dynamic stiffnesses of the materials according to the diameter of the contact area (12.5-mm, 25.0-mm, 37.5-mm).

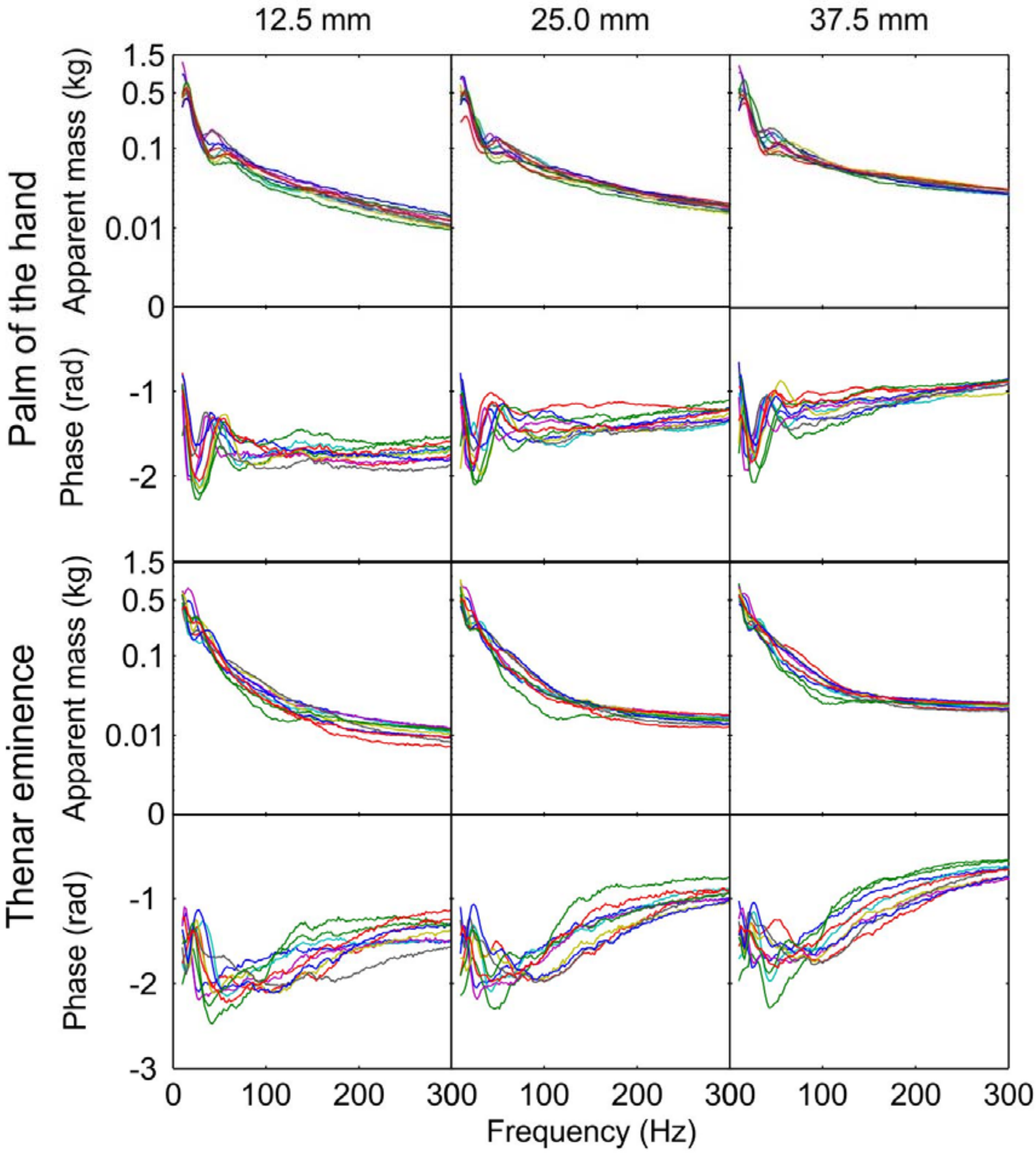

Figure 4 Individual apparent mass (modulus and phase) at the palm of the hand (upper figures) and at the thenar eminence (lower figures) according to its diameter of contact area. 10 Subjects.

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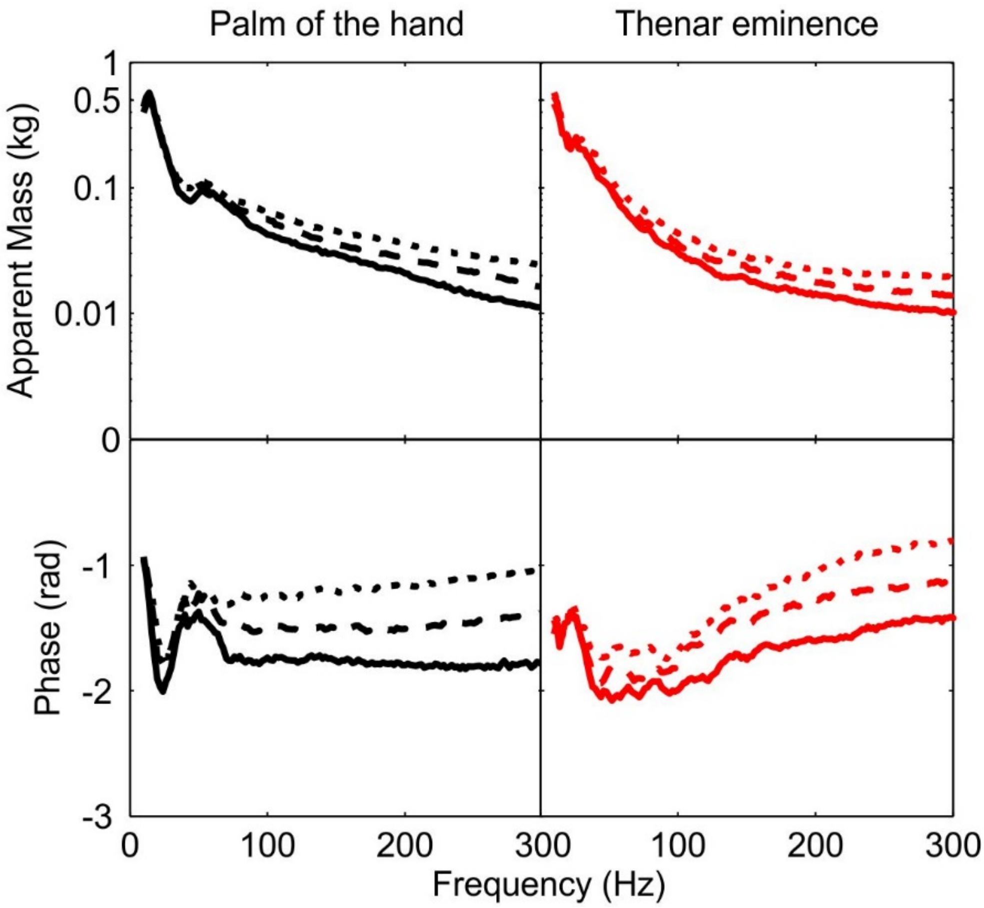

Figure 5 Apparent mass (modulus and phase) at the palm of the hand and at the thenar eminence according to the diameter of the contact area (▬▬▬ 12.5-mm, ▬ ▬ ▬ 25.0-mm, ······ 37.5-mm).. Medians of 10 subjects.

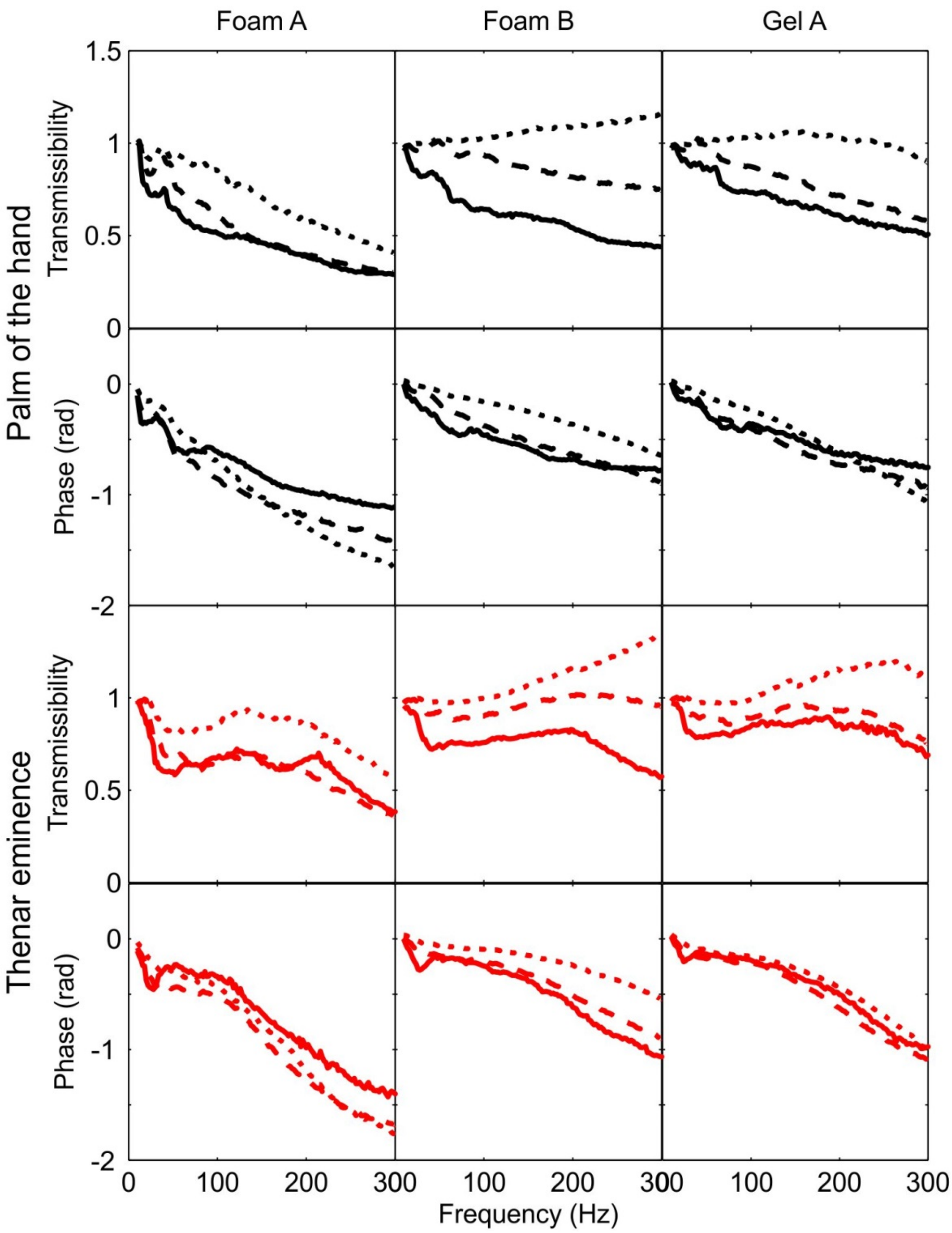

Figure 6 Median transmissibilities (modulus and phase) of the three materials to the palm and to the thenar eminence according to the diameter of the contact area (—— 12.5-mm, – – – 25.0-mm, ······ 37.5-mm). Median values from 10 subjects.

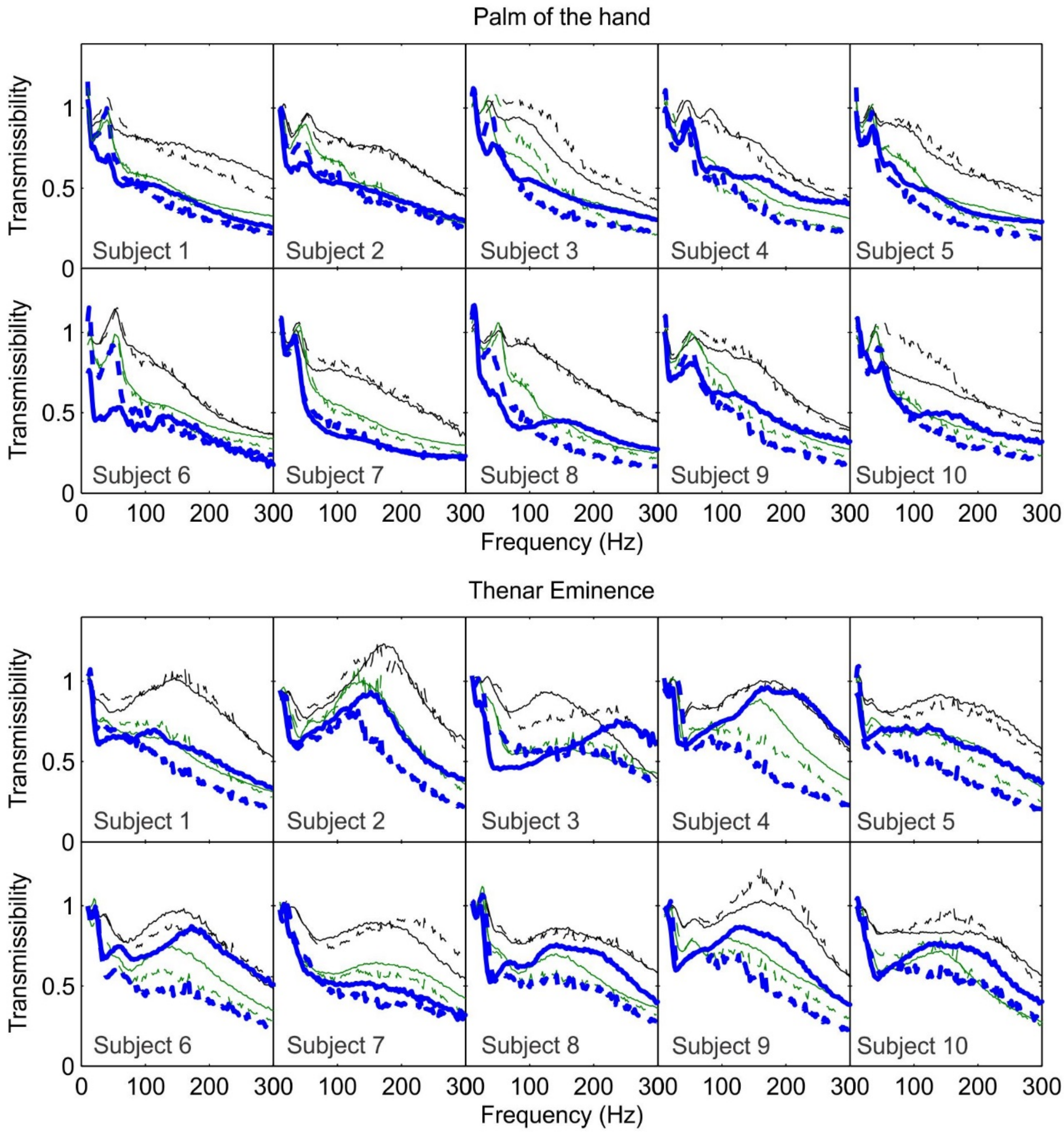

Figure 7 Individual transmissibilities (predicted and measured) for Foam A to the palm (upper figures) and to the thenar eminence (lower figures) according to the diameter of the contact area (▬ 12.5-mm, ▬ 25.0-mm, ▬ 37.5-mm; continuous line: measured, broken line: predicted).

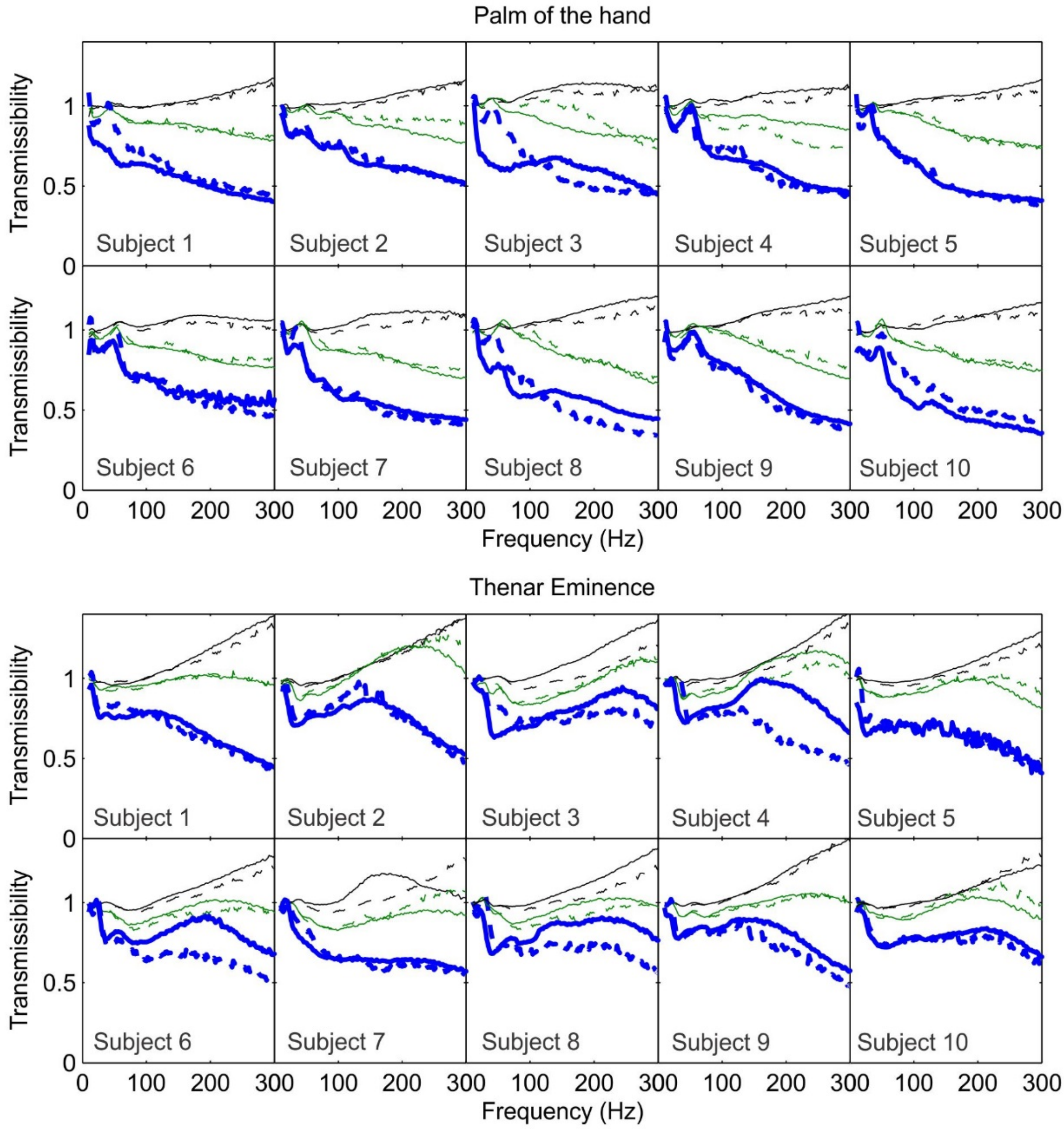

Figure 8 Individual transmissibility (predicted and measured) of Foam B to the palm (upper figures) and the thenar eminence (lower figures) according to the diameter of contact area (12.5-mm, 25.0-mm, 37.5-mm; continuous line: measured, broken line: predicted).

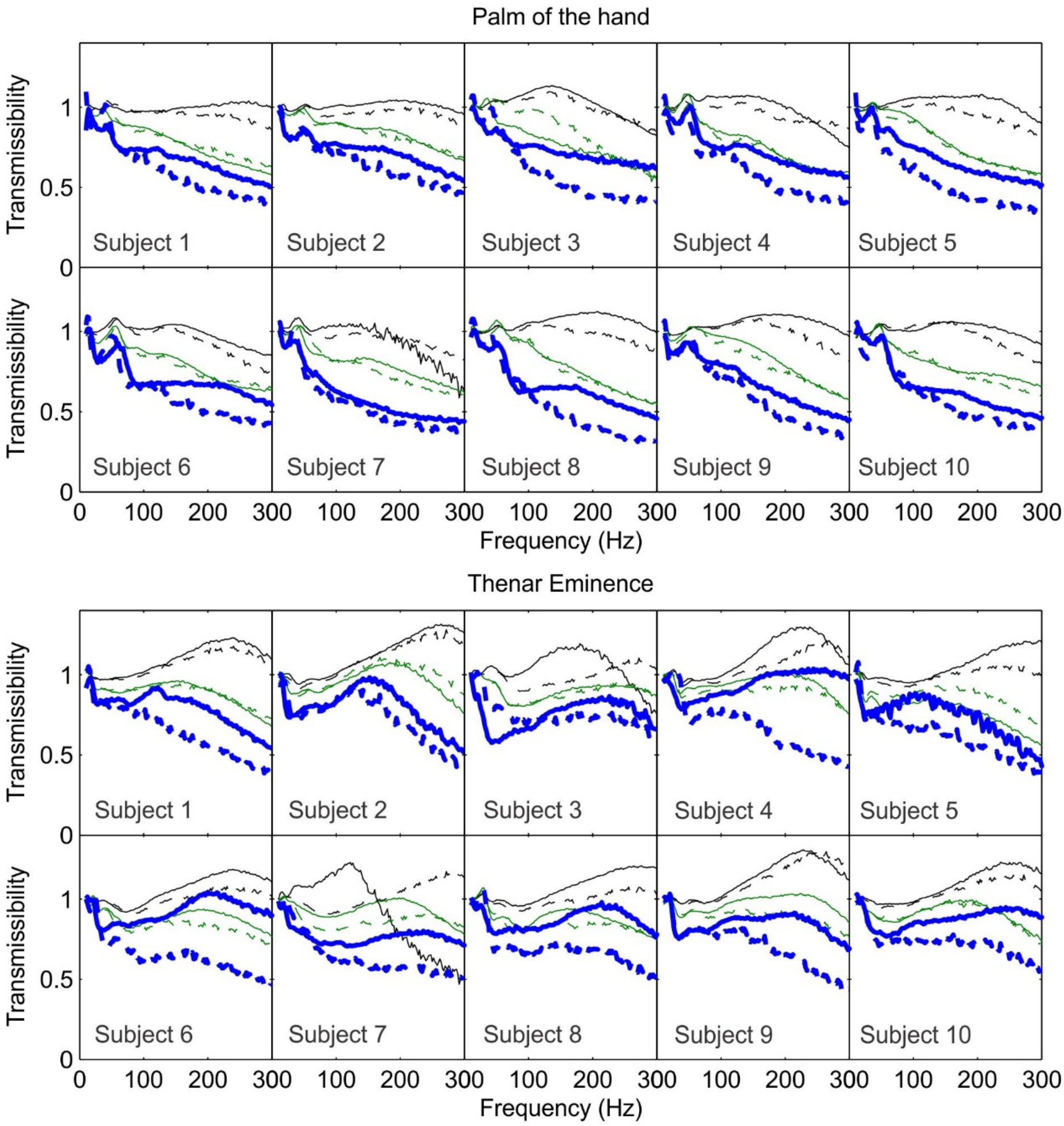

Figure 9 Individual transmissibility (predicted and measured) of Gel A to the palm (upper figures) and the thenar eminence (lower figures) according to the diameter of contact area (▬ 12.5-mm, ▬ 25.0-mm, ▬ 37.5-mm; continuous line: measured, broken line: predicted).

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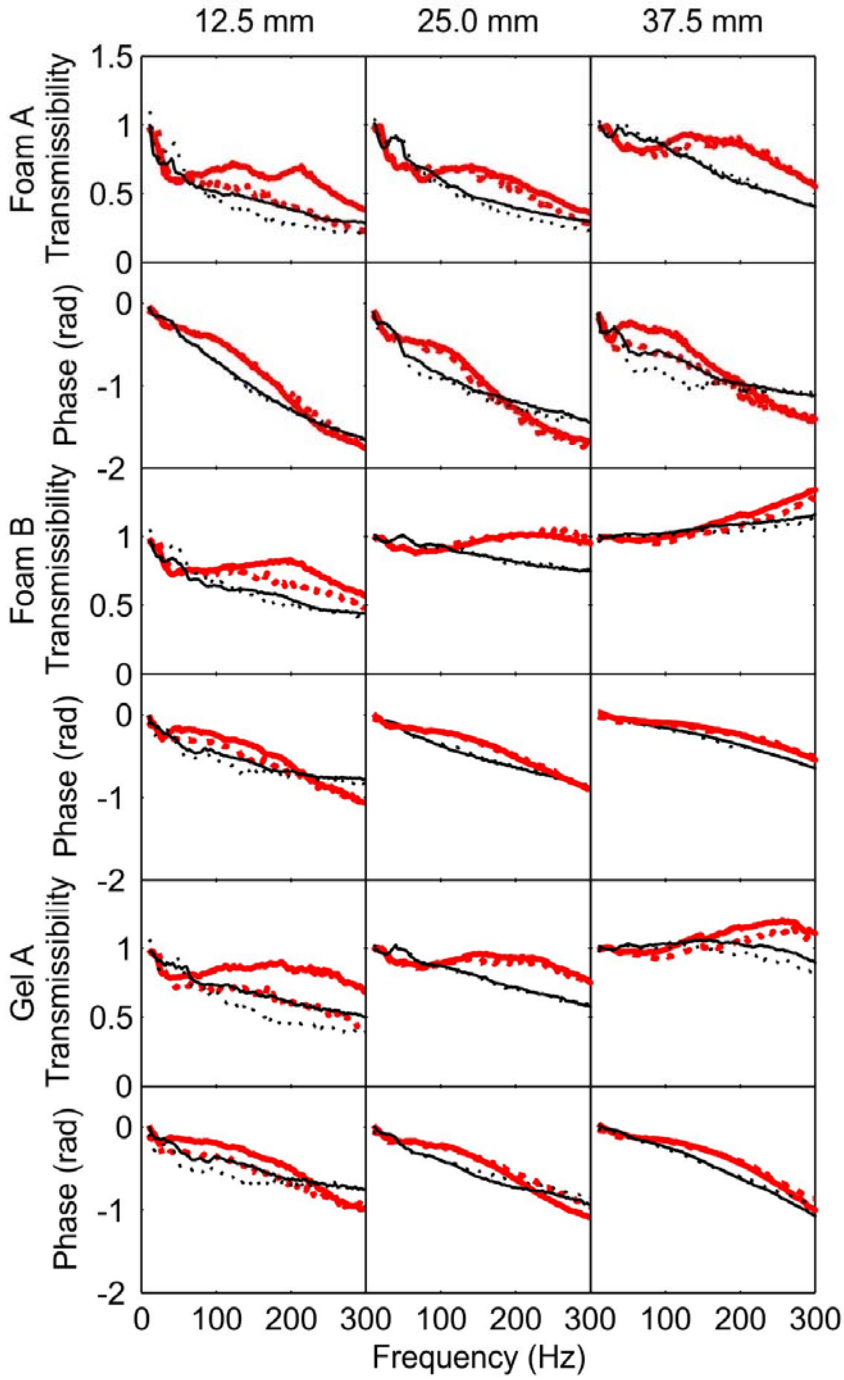

Figure 10 Median transmissibility (predicted and measured) with Foam A, Foam B, and Gel A to the palm and to the thenar eminence according to the diameter of the contact area (measured thenar eminence, predicted thenar eminence, measured palm, predicted palm). Median values from 10 subjects.

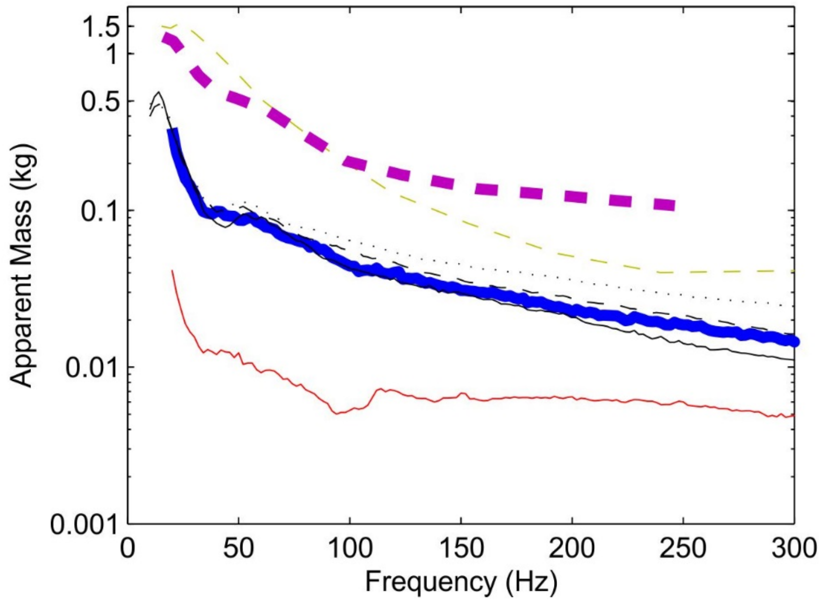

Figure 11 Median measured apparent mass at the palm of the hand with a force of 10 N, vibration in vertical direction. This study (▬▬ 12.5-mm, ▬ ▬ ▬ 25.0-mm, ⋯⋯ 37.5-mm contact areas); ▬▬ palm pushing a flat surface at 10 N on a 25-mm diameter plate, vibration in vertical direction, Rezali and Griffin (2016); ▬▬ index finger pushing a flat surface at 10 N on a 25-mm diameter plate, vibration in vertical direction, Rezali and Griffin (2016); ▬ ▬ ▬ palm pushing a cylindrical handle with adapter at 50 N, vibration in horizontal direction, Dong *et al.* (2005a); and ▬ ▬ ▬ full-hand pushing on flat surface, vibration in horizontal direction, Xu *et al.* (2011).

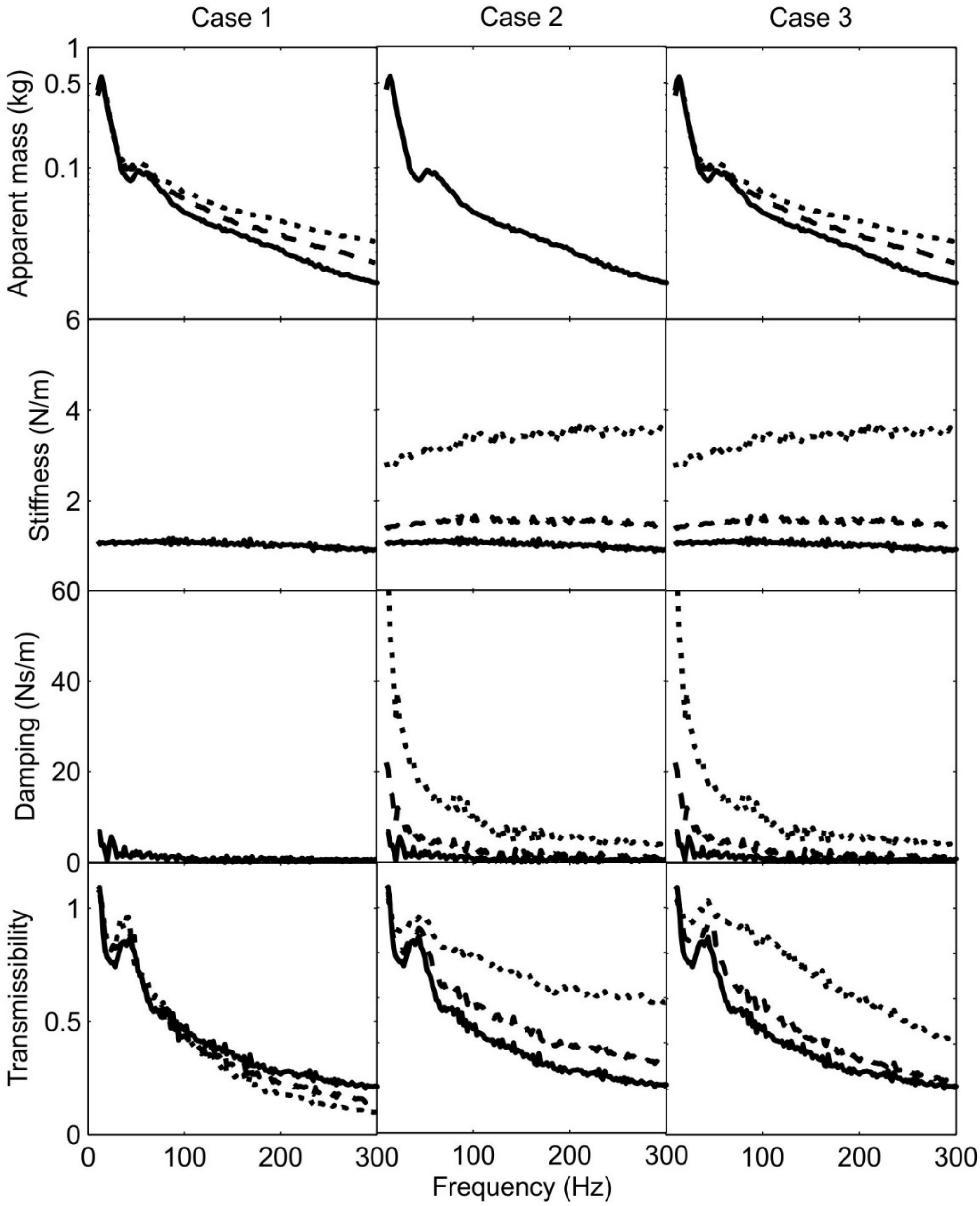

Figure 12 The predicted transmissibility (modulus and phase) of the three materials to the palm of the hand for three cases: (i) the dynamic stiffness unaffected by the area of contact, (ii) the apparent mass unaffected by the area of contact, (iii) both apparent mass and dynamic stiffness affected by the area of contact area, as in this study, Diameter of the contact area: (▬▬▬ 12.5-mm, ‒ ‒ ‒ ‒ 25.0-mm, ⋯⋯ 37.5-mm). Median values from 10 subjects.