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PREDICTING THE TRANSMISSIBILITY OF A GLOVE MATERIAL TO THE PALM USING A SIMPLE LUMPED PARAMETER MODEL OF THE HAND AND THE GLOVE

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Abstract

Assessing a glove for its ability to reduce vibration transmitted to the hand can be improved if the transmissibility of the glove to the hand can be predicted. This study proposes a simple lumped parameter model of the hand and the glove for predicting the transmissibility of a glove to the hand. The model of the hand consists of three main body segments: the palm, the fingers, and the palm tissues, connected via translational and rotational springs and dampers. The glove material was represented by translational spring and damper. The results showed that the glove transmissibility predicted using the model overestimated the glove transmissibility measured experimentally at frequencies greater than 62 Hz, implying that a simple three degree-of-freedom model of the hand and the glove may not be able to provide a reasonable prediction of glove transmissibility.

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

Abstrak

Proses menilai keupayaan sesebuah sarung tangan dalam mengurangkan getaran di tangan boleh diperbaiki jika kebolehpindahan getaran ke tangan melalui sarung tangan boleh diramal. Kajian ini mencadangkan satu model mudah tangan dan sarung tangan, digunakan untuk meramal kebolehpindahan getaran melalui sarung tangan ke tangan. Model tangan terdiri daripada tiga segmen utama: tapak tangan, jari, dan tisu tapak tangan, disambungkan antara satu sama lain melalui peralihan dan putaran pegas dan peredam. Bahan sarung tangan diwakili oleh peralihan pegas dan peredam. Hasil kajian menunjukkan bahawa kebolehpindahan sarung tangan yang diramalkan menggunakan model tangan dan sarung tangan remeh berbanding kebolehpindahan sarung tangan diukur secara eksperimen pada frekuensi melebihi daripada 62 Hz. Ini menunjukkan bahawa model mudah tiga darjah kebebasan bagi tangan dan sarung tangan mungkin tidak dapat memberikan ramalan yang munasabah pada kebolehpindahan sarung tangan.

Kata kunci: Sarung tangan anti-getaran, biodinamik, kebolehpindahan, tangan.

1.0 INTRODUCTION

Vibration transmissibility of a glove to the hand primarily depends on two main factors, the biodynamic response of the hand and the dynamic stiffness of the glove material [1].
Several lumped parameter models of the hand and the glove have been previously proposed to study the motion of the hand [e.g., 2, 3, 14, 15, 16]. However, many of them were not used to predict glove transmissibility.

A mechanical impedance model of the hand and the glove was developed [4] and has been used to predict glove transmissibility [4, 17]. With this model, the glove transmissibility is predicted by using the measured apparent mass of the hand and the measured glove dynamic stiffness. The model provides a reasonable

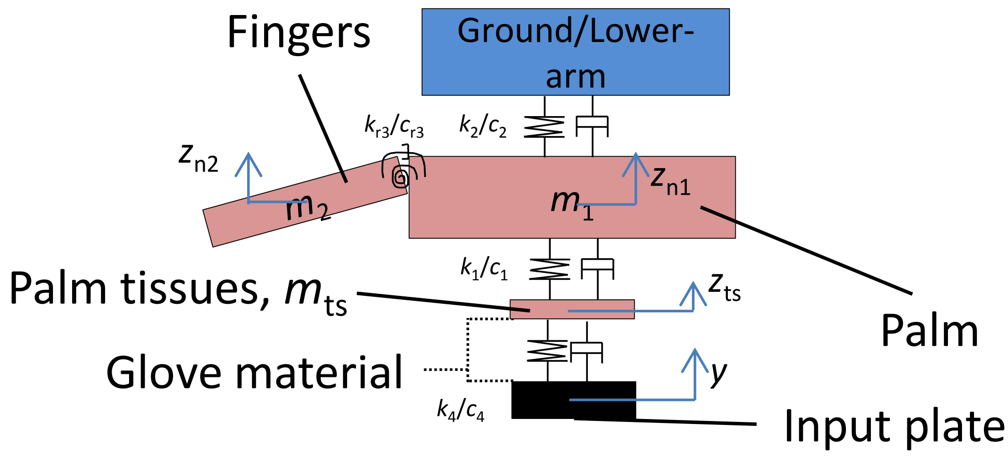

Figure 1 A three degree-of-freedom model the glove and the hand

prediction of glove transmissibility but may not be able to be used to understand the mechanisms of the motion of the hand.

The objective of this study was to investigate whether a simple lumped parameter model of the hand and the glove can provide a reasonable prediction of glove transmissibility to the hand. It has been shown previously that the glove transmissibility to the hand predicted using a measured apparent mass of the hand and a measured glove dynamic stiffness is similar to the glove transmissibility measured experimentally (i.e., mechanical impedance model of the hand and the glove) [4, 5]. Hence, it was expected that if the dynamic response of the hand and the dynamic stiffness of the glove material can be represented by simple lumped parameter models (i.e., a model of the hand and a model of the glove material), the combined model of the hand and the glove material can provide a reasonable prediction of glove transmissibility to the hand.

2.0 METHODS

2.1 Model Description

A two degree-of-freedom multi-body biodynamic model of the hand and a kelvin-voigt viscoelastic model of the glove material were used in this study. The combined model of the hand and the glove produces a three degree-of-freedom model Figure 1.

The palm, m_1 was supported by two translational springs, k_1 and k_2, and dampers, c_1 and c_2, attached to palm tissues, m_{ts} and to a grounded lower-arm. The fingers, m_2 were attached to the palm, m_1 via rotational spring, k_{r3} and damper, c_{r3}. The palm was assumed to be only moving vertically.

The glove material dynamic stiffness was represented by a spring, k_4 and a damper, c_4 placed in parallel (i.e., kelvin voigt viscoelastic material model).

2.2 Geometry and Inertial Properties

All body segments were assumed to be rigid and in the shape of a rectangular box. The properties of the hand (i.e., mass, length and depth) were taken from previous studies [6 - 7] and are shown in Table 1. The mass of the palm was assumed to have three-quarters of the mass of the hand whilst the fingers were assumed to have one-quarter of the mass of the hand [8].

The initial angle for the fingers was assumed to be inclined at 5 degrees. The palm was assumed to be lying flat on the vibrating surface. In this study, the glove material was assumed to be massless.

Table 1 Dimension and mass of the hand segments [6 - 8].

Body segment	Mass (kg)	Length (m)	Depth (m)
Palm, m_1	$0.75*0.006*M_t$	$l_1 = 0.106$	$d_1 = 0.045$
Fingers, m_4	$0.25*0.006*M_t$	$l_2 = 0.079$	$d_2 = 0.019$

where M_t is the total body mass of a subject (61.2 kg) [6].

2.3 Equations of Motion

The model of the hand is a two degree-of-freedom model with vertical displacement of the palm, z_1 and anti-clockwise rotational deflection of fingers, θ_2. All springs and dampers were assumed to be linear. The palm and the fingers vibrated with small oscillation with a change of angle of less than 5 degrees of the equilibrium position. The equations of motion were obtained using Lagrange formula. The kinetic energy, T, potential energy, U and dissipation energy, D, of the system are:

$$T = \frac{1}{2}m_1(\dot{z}_{n1}^2 + \dot{x}_{n1}^2) + \frac{1}{2}m_2(\dot{z}_{n2}^2 + \dot{x}_{n2}^2) + I_2\dot{\theta}_2^2 \quad (1)$$

$$U = \frac{1}{2}k_1(z_1 - y)^2 + \frac{1}{2}k_2(z_1)^2 + \frac{1}{2}k_{r_3}(\theta_2)^2 \quad (2)$$

$$D = \frac{1}{2}c_1(\dot{z}_1 - \dot{y})^2 + \frac{1}{2}c_2(\dot{z}_1)^2 + \frac{1}{2}c_{r_3}(\dot{\theta}_2)^2 \quad (3)$$

where $z_{n1} = z_1$, and $x_{n1} = x_1$. z_1 and $x_1$are the change in the position vectors for m_1

The potential energy associated with gravity was excluded in the potential energy, U. The position vectors of the centres of gravity for the rotating rigid body are:

$$z_{n2} = z_1 - \frac{l_2}{2}\sin(\acute{\theta}_2)$$
$$x_{n2} = x_1 - \frac{l_2}{2}\cos(\acute{\theta}_2) - \frac{l_1}{2}$$

where, $\acute{\theta} = (\theta_0 + \theta)$ is the angle of inclination during vibration for the rotating rigid body, θ is the change in the angle of inclination of the rotating rigid body, and θ_0 is the initial inclination angle of the rotating rigid body.
The equations of the geometry shown above was simplified using the trigonometry angle of transformation formulae:

$$sin(\acute{\theta}) = sin(\theta_0 + \theta) = sin\,\theta_0\, cos\,\theta + cos\,\theta_0\, sin\,\theta$$
$$cos(\acute{\theta}) = cos(\theta_0 + \theta) = cos\,\theta_0\, cos\,\theta - sin\,\theta_0\, sin\,\theta$$

As mentioned previously, the change of inclination angle, $\theta\ is < 5^0$. So, $\sin(\theta) \approx \theta$ and $\cos(\theta) \approx 1$, so,

$$sin(\acute{\theta}) = sin(\theta_0 + \theta) = sin\,\theta_0 + cos\,\theta_0\,\theta$$
$$\cos(\acute{\theta}) = \cos(\theta_0 + \theta) = \cos\theta_0 - \sin\theta_0\,\theta$$

Thus, the position vectors for the rigid bodies are as follows:

$$z_{n2} = z_1 - \frac{l_2}{2}\sin\theta_{20} - \frac{l_2}{2}cos\theta_{20}\theta_2,$$
$$x_{n2} = x_1 - \frac{l_2}{2}\cos\theta_{20} + \frac{l_2}{2}sin\theta_{20}\theta_2 - \frac{l_1}{2},$$

where θ_2 is the change in the angle of inclination of the rotating rigid body, and θ_{20} is the initial inclination angle of the rotating rigid body. $x_1 = 0$ (i.e., m_1 was assumed to be only moving in vertical direction).

The apparent mass of the hand is the complex ratio of the resultant force on the input surface to the acceleration on the input surface. The apparent mass at the palm of the hand, m_{ap} (f) is given by:

$$m_{ap}(f) = m_{ts} + \left(\frac{(k_1 + iwc_1)(1 - \frac{z_1}{y})}{-w^2}\right) \qquad (4)$$

where m_{ts} is the mass of the palm tissues.

The dynamic stiffness of the material for the kelvin voigt viscoelastic model is given by:

$$d_p(f) = k_4 + ic_4 w \qquad (5)$$

The transmissibility of the glove material to the palm of the hand (i.e., combined model of the hand and the glove as shown in Figure 3) is given by:

Transmissibility of the glove material to the palm

$$TR = \frac{z_{ts}}{y} \qquad (6)$$

2.4 Measuring The Apparent Mass At The Palm Of The Hand, Glove Transmissibility To The Palm Of The Hand, And The Glove Dynamic Stiffness

The apparent mass at the palm was measured previously at frequencies from 20 to 350 Hz with a magnitude of 3.24 m/s^2 r.m.s. (frequency-weighted using Wh according to ISO 5349-1:2001) [9]. In the experiment, fourteen male subjects sat with their arms not supported and placed the palm of their hand on a 25-mm diameter wooden adapter (i.e., located on top of a 25-mm diameter input plate). Subjects were required to push down the wooden adapter with a force of 10 N and maintain the push force throughout the vibration exposure (i.e., an oscilloscope was placed in front of the subjects for easy monitoring of the push force). Random vibration was generated using MATLAB and HVLab toolbox (version 1.0). A glove material with a diameter of 25 mm was placed between the wooden adapter and the input plate during the measurement of glove transmissibility.

An indenter rig was used to measure the glove dynamic stiffness in a previous experiment [9]. The dynamic stiffness was measured with a preload force of 10 N at frequencies from 20 to 350 Hz with a magnitude of 3.5 m/s^2 r.m.s. (frequency-weighted using Wh according to ISO 5349-1:2001). The glove material had a diameter of 25 mm with thicknesses of 6.4 mm.

2.5 Calibrating The Model Of The Hand And The Model Of The Glove Material

The optimized parameters were obtained using the 'fmincon' function in MATLAB. The optimization function identified the model parameters by minimising the mean square errors [10] between the computed and the measured vertical median apparent mass at the palm of the hand at frequencies from 20 to 200 Hz.

$$Error, E = \sum_{i=1}^{N}(abs\left(m_{ap}(i)\right) - abs(m_{am}(i)))^2 + 0.25 * \sum_{i=1}^{N}(angle\left(m_{ap}(i)\right) - angle(m_{am}(i)))^2 \qquad (7)$$

where m_{ap} is the calibrated apparent mass at the palm, and m_{am} is the measured median apparent mass at the palm. Both values are complex numbers.

The model of the glove material was calibrated with the measured glove dynamic stiffness at frequencies from 20 to 200 Hz using the following equation.

$$Error, E = \sum_{i=1}^{N}(Real\left(d_p(i)\right) - Real\left(d_m(i)\right))^2 + \sum_{i=1}^{N}(imag\left(d_p(i)\right) - imag(d_m(i)))^2 \qquad (8)$$

where d_p is the calibrated dynamic stiffness in complex number, d_m is the measured dynamic stiffness in complex number.

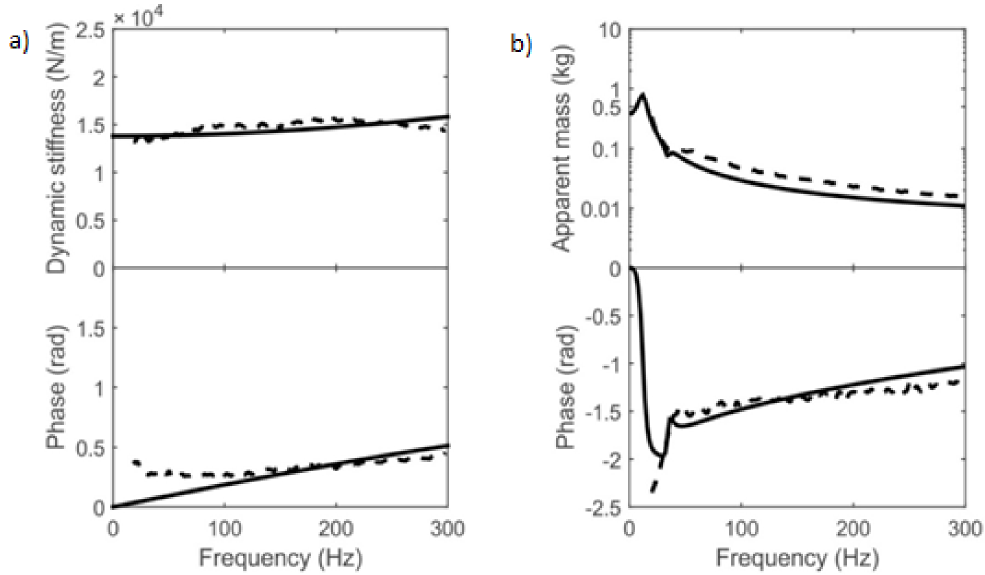

Figure 2 a) fitted and measured dynamic stiffness of the glove material, b) fitted and measured apparent mass at the palm of the hand (——— fitted, – – – – measured).

The model of the hand and the model of the glove material were optimized separately. The calculated or optimized parameters are shown in Table 2.

Constant bandwidth frequency analysis was performed across the frequency range 2 to 300 Hz with a frequency resolution of 2 Hz.

Table 2 Optimized and calculated model parameters.

	Parameters	Optimized / Calculated parameters
Springs (N/m)	k_1	2345
	k_2	0.018
	k_{r3}	8.14
	k_4	1379
Dampers (Ns/m)	c_1	17.66
	c_2	0.0002
	c_{r3}	0.005
	c_4	4.12
Mass (kg)	m_1	0.28
	m_4	0.09
	m_{ts}	0.006

3.0 RESULTS

3.1 Dynamic Stiffness of the Glove Material

The modulus of the fitted glove dynamic stiffness was similar to the modulus of the glove dynamic stiffness measured experimentally at all frequencies of vibration from 20 to 300 Hz (Figure 2).

However, there were discrepancies in the phase between the measured and the fitted glove dynamic stiffness at low frequencies.

3.2 Apparent Mass at the Palm of the Hand

The fitted apparent mass using the model of the hand underestimated the measured apparent mass at frequencies greater than 34 Hz (Figure 2) but similar to the measured apparent at frequencies less than 32 Hz. There were resonances at about 12 Hz and about 40 Hz in the fitted apparent mass at the palm.

3.3 Predicting the Glove Transmissibility to the Hand

The glove transmissibility predicted using the combined model of the hand and the glove material was similar to the measured transmissibility at frequencies less than about 60 Hz but overestimated the measured transmissibility at frequencies greater than 62 Hz (Figure 3).

4.0 DISCUSSION

4.1 Proposed Model Of The Hand

Previous studies have shown that at frequencies less than 30 Hz, the mechanical impedance of the hand decreases with decreasing angle between the upper and the lower arm [8, 11 - 13]. This indicates that the change in the posture of the upper-arm and the lower-arm mainly influences the hand's dynamic response at frequencies less than 30 Hz, implying that excluding the lower-arm and the upper-arm from the model of the hand may not give a large impact on the prediction of glove transmissibility to the hand at high frequencies.

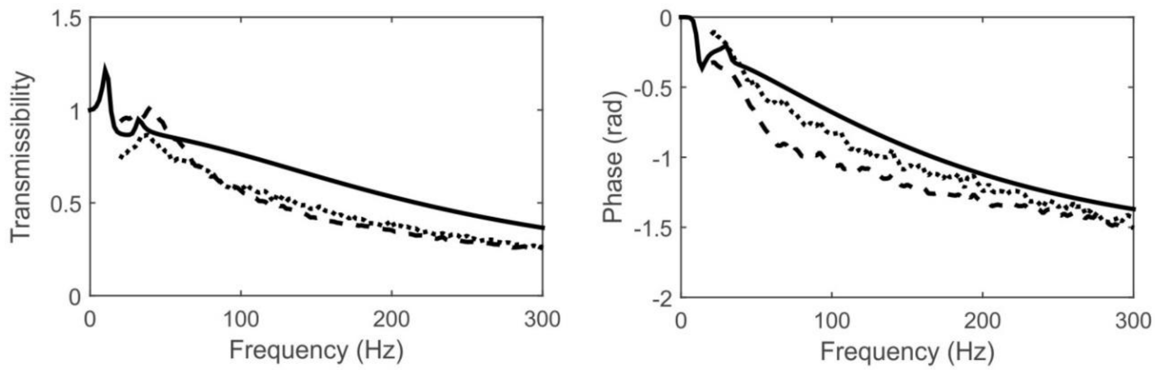

Figure 3 Transmissibility of the glove material to the palm of the hand (——— predicted using model of the hand (this study), ······ predicted using mechanical impedance model, — — — measured) [5].

Hence, the model of the hand discussed in this study was proposed without considering the influence of the motion of the lower-arm and the upper-arm. However, based on the results showed in this study, the fitted apparent mass at the palm underestimated the measured apparent mass at frequencies greater than 34 Hz. This may indicate that the exclusion of the motion of the lower-arm and the upper-arm could be one of the factors of the model underestimation of the apparent mass at the palm. This is because the mass of the lower-arm and the mass of the upper-arm are significantly heavier than the palm and the fingers: excluding both masses, the lower-arm and the upper-arm, can affect the apparent mass of the hand at high frequencies although that it may be smaller than the effects of the mass of the palm and the mass of the fingers.

The rotational and the translational springs and dampers were assumed to be linear. The translational spring and damper, k_2 and c_2, were optimized but capped to have small values so that they will not influence the motion of the palm and the fingers at high frequencies. The translational spring and damper, k_1 and c_1, were optimized so that the first resonance will occur at about 15 Hz based on a previous study [4].

4.2 Calibrating the Model Of The Hand

A study conducted previously has shown that there is a resonance occurred at frequency less than 20 Hz [4]. This resonance is observed in the fitted apparent mass in this study but apparent mass at frequency less than

20 Hz were not included in the calibration process (i.e., the model was calibrated at frequencies greater than 20 Hz). A better estimation of the apparent mass from the model could be obtained if the model of the hand is calibrated from frequency lower than the resonance.

4.3 Predicting Transmissibility Of A Glove Material To The Hand

The glove transmissibility predicted using the model overestimated the measured glove transmissibility at frequencies greater than about 62 Hz whilst the fitted apparent mass at the palm underestimated the measured apparent mass at the palm at frequencies greater than about 34 Hz. Inversely, the fitted glove dynamic stiffness was similar to the measured glove dynamic stiffness at all frequencies greater than 60 Hz. This implies that the overestimation of the glove transmissibility prediction at high frequencies (Figure 3) may be due to the underestimation of the fitted apparent mass at the palm (Figure 2). A better estimation of apparent mass from the model could be obtained if the motions of the lower-arm and the upper-arm are included in the model as suggested previously. The estimation of apparent mass in this study could also be improved if the calibration process is including frequencies less than 20 Hz as discussed previously.

Transmissibility of a glove to the hand has previously been predicted using mechanical impedance model of the hand and the glove [5]. The impedance model uses experimentally measured apparent mass of the hand and glove dynamic stiffness to predict glove transmissibility to the hand. The mechanical impedance model of the hand and the glove provided better prediction of glove transmissibility than the lumped parameter model of the hand and the glove at high frequencies (i.e., this study; Figure 3).

5.0 CONCLUSION

It was concluded that a simple three degree-of-freedom multi-body biodynamic model of the hand and the glove may not be able to provide a reasonable prediction of glove transmissibility especially at high frequencies.

The inclusion of the motions of the lower-arm and the upper-arm in the model of the hand may improve the model predictability of glove transmissibility.

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