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VIBRATION TRANSMISSIBILITY BEHAVIOUR OF HIGH ORDER BIODYNAMIC MODELS USED IN VEHICLE SEAT DESIGN

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Abstract

The effects of vibration transmissibility using high order biodynamic models of four, five and seven degrees of freedom that can replicate a human body exposed to vibration transmissibility while driving was investigated to identify resonant frequencies associated with injury. It was found that these models address vehicle seat deformities and represent the body hop motion when driving. The five degree of freedom models provided the best results to approximate resonant frequencies associated with the legs, lower torso, spine and whole body vibration at the seat person interface, while the driver's hands were on the steering and was supported with a backrest. The four degree of freedom model excluding the backrest was able to replicate experimental data and a sensitivity analysis of the stiffness and damping parameters indicated that this model was more robust compared to the others, and could predict whole body vibration to accommodate for intra subject variability. Non-linear damping and stiffness properties were noticed for acceleration magnitudes greater than 1g root mean square (rms) and for high order models, which provide greater anatomical description to predict injury in contrast to simple models that have large lumped masses to represent the upper and lower torso. In addition, biodynamic models greater than seven degrees of freedom can be utilised with non-linear stiffness and damping techniques to predict vibration and impedance behaviour for greater number of body ligaments applied to old seats or retrofit seat design applications.

Keywords: *vehicle seat, biodynamic model of higher order, vibration transmissibility, mechanical impedance*

1. Introduction

Four biodynamic models of 4 degrees of freedom (DOF), 5-DOF and 7-DOF, which replicate a vehicle passenger or driver, are studied for vertical vibration transmissibility and impedance behaviours. This study is to assist in new seat design and also predict injury by identifying resonant frequencies associated with anatomical structures. The models accommodate for hands on steering wheel, differences in human physiology and in certain cases the exclusion of a backrest support during driving. The benefits of using higher order biodynamic models to simulate vibration transmissibility is much cheaper compared to cost of experiments or use of manikins since there is no reason to assume they have similar mechanical impedance or transmissibility characteristics of a human. Higher order models are suited to study vibration transmissibility for an acceleration larger than 1g rms or when the stiffness and damping is non-linear due to body hop motion. The models are also applicable to structure of old seats from Wu et al. [11] and Griffin [3] in contrast to simple 2-DOF and 3-DOF biodynamic models. Simulations using higher order models were compared to experimental results published standards for accuracy, and resonant frequencies that can cause injury were further investigated.

2. Biodynamic Models and Vibration Transmissibility Behaviour

2.1. 4-DOF Model from Rakheja Wu and Boileau: 2002 and ISO 5982:2001

Figure 1 shows a biodynamic model derived by Rakheja et al. 2002 [7] and ISO 5982: 2001 [4] that is exposed to vertical vibration where m_1, m_2, m_3 and m_o, represent the upper torso, head, and leg-thigh with lower torso mass respectively.

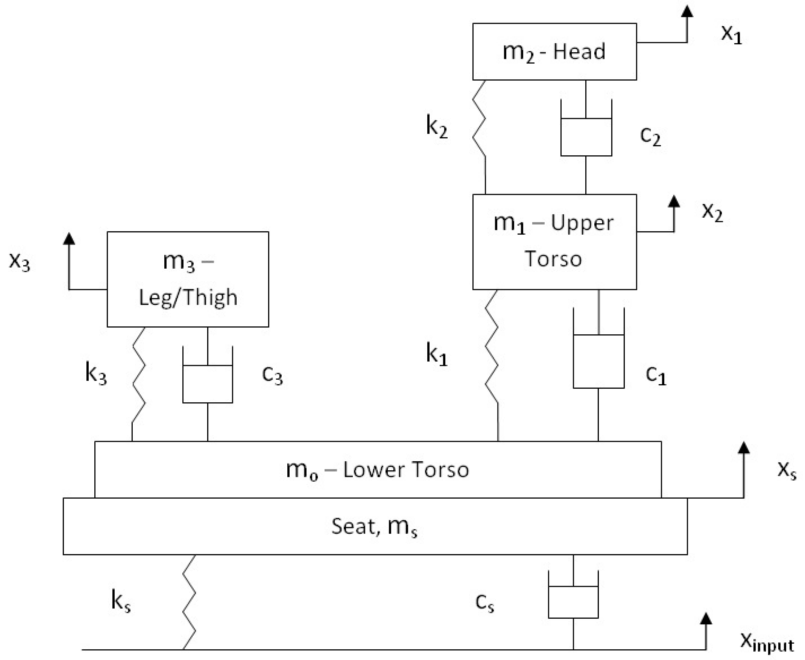

Fig. 1. Schematic of 4 DOF model by Rakheja et al. [7] and ISO 5982:2001 [4]

The 4-DOF and 5-DOF models described in Fig. 1 and 2 assume 73% of the total mass is resting on the seat and Rakheja et al. [7] suggests that the mass m_3, stiffness k_3 and damping c_3 primarily describe the driving point mechanical impedance or apparent mass responses in the vicinity of the resonant peak, whereas the masses m_1 and m_2 contributes to the seat to head transmissibility.

The set of equation of motion for the model presented in Fig. 1 is shown below (1-4):

$$m_2\ddot{x}_1 = k_2(x_2 - x_1) + c_2(\dot{x}_2 - \dot{x}_1), \tag{1}$$

$$m_1\ddot{x}_2 = k_2(x_1 - x_2) + c_2(\dot{x}_1 - \dot{x}_2) + k_1(x_s - x_2) + c_1(\dot{x}_s - \dot{x}_2), \tag{2}$$

$$m_3\ddot{x}_3 = k_3(x_s - x_3) + c_3(\dot{x}_s - \dot{x}_3), \tag{3}$$

$$(m_o + m_s)\ddot{x}_s = k_3(x_3 - x_s) + c_3(\dot{x}_3 - \dot{x}_s) + k_1(x_2 - x_s) + \ldots$$
$$\ldots + c_1(\dot{x}_2 - \dot{x}_s) + k_s(x_{input} - x_s) + c_s(\dot{x}_{input} - \dot{x}_s), \tag{4}$$

where:
k – stiffness,
c – damping.

All the marks are corresponding to these in Fig. 1 above.

2.2. 5-DOF Model by Rakheja and Boileau: 1998

The 4-DOF (Fig. 1) and 5-DOF model shown in Fig. 2 were developed with hands in a driving position and without a backrest support that depicts normal driving conditions where the driver's upper back and neck regions remain unsupported. The masses due to the lower legs, feet, hand and arm motion of the 5-DOF model shown below are excluded assuming negligible contributions to the biodynamic response of the seated body [6]. Using lower stiffness values of k_1, k_2 and k_3 provides closer agreement with the mechanical impedance response, whereas larger stiffness values results in closer agreement with the seat to head transmissibility. The reverse trend is observed for the stiffness k_4. With the exception of the damping magnitude c_4, any variations made in the remaining damping parameters results in insignificant changes to the impedance and vertical vibration transmissibility responses [6].

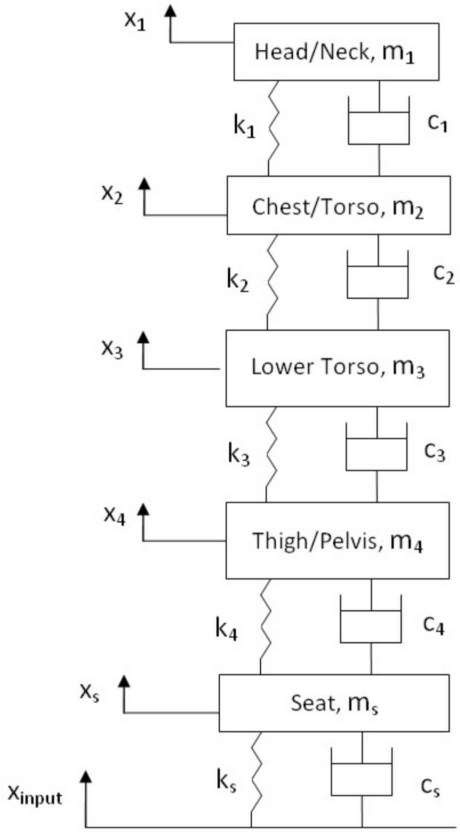

Fig. 2. Schematic of 5-DOF model by Rakheja et al. in 1998[6]

Although the 4-DOF and 5-DOF models mentioned above cannot be adequately used in seat design analysis since they are developed without a backrest, these models can be used to better understand the impedance and transmissibility responses of the human body.

Equations of motion for this model are listed below (5-9):

$$m_1\ddot{x}_1 = k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1), \tag{5}$$

$$m_2\ddot{x}_2 = k_1(x_1 - x_2) + k_2(x_3 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) + c_2(\dot{x}_3 - \dot{x}_2), \tag{6}$$

$$m_3\ddot{x}_3 = k_2(x_2 - x_3) + k_2(x_4 - x_3) + c_2(\dot{x}_2 - \dot{x}_3) + c_3(\dot{x}_4 - \dot{x}_3), \tag{7}$$

$$m_4\ddot{x}_4 = k_3(x_3 - x_4) + k_4(x_s - x_4) + c_3(\dot{x}_3 - \dot{x}_4) + c_4(\dot{x}_s - \dot{x}_4), \tag{8}$$

$$m_s\ddot{x}_s = k_4(x_4 - x_s) + k_s(x_{input} - x_s) + c_4(\dot{x}_4 - \dot{x}_s) + c_s(\dot{x}_{input} - \dot{x}_s). \tag{9}$$

2.3. 5-DOF Linear Model by Smith: 1997 and Smith: 1994

Figure 3 below shows a 5-DOF model from [10], which provides adequate anatomical description of the major body segments of the human body, and is effective in predicting cushion effects for different seat designs at higher frequencies while also decreasing vibration transmission to the spinal column. A non-linear version of the model was developed by Smith [9] to establish the resonance regions for each body segment associated with the impedance response, which was valid for higher acceleration greater than 0.5g RMS, whereas Smith [8] found that a linear model can be used for the impedance response at lower acceleration.

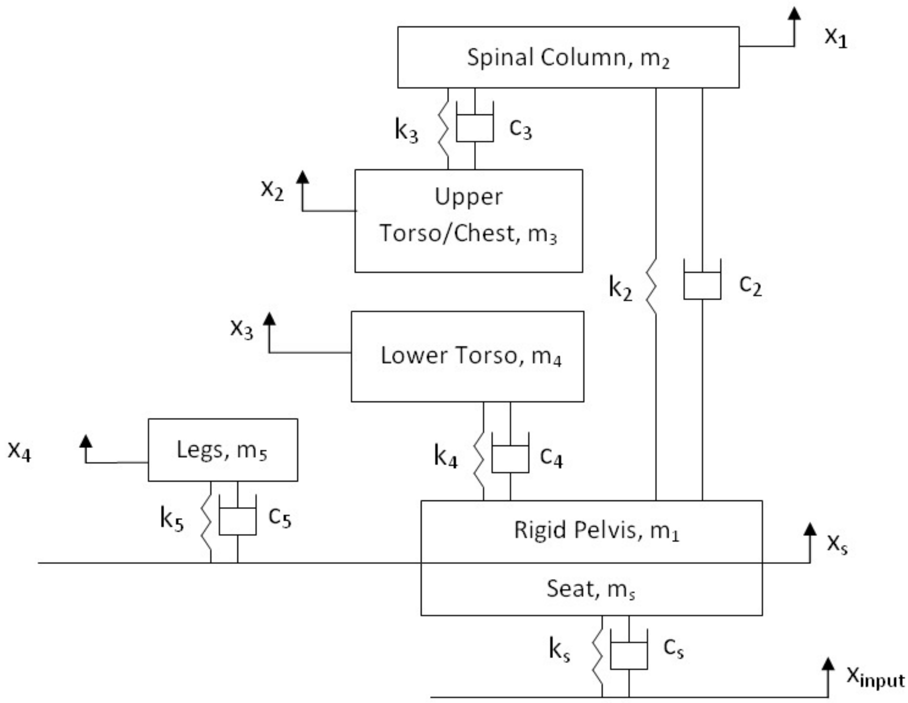

Fig. 3. Schematic of 5-DOF model by Smith in [8] and [10]

The linear model is capable of simulating both the mechanical impedance and vertical vibration transmissibility responses while the feet is unsupported/ (legs hang freely). It was found from [10] that the lower torso (m_4) and spine column (m_2) contributes to the peak impedance magnitudes at high frequency, whereas the peak transmissibility is caused by the upper torso (m_3). This model is also capable of predicting the peak leg responses, which may be dampened depending on the type of seat/cushion used.

The motion in the model above is described by the following equations (10–14):

$$m_2\ddot{x}_1 = k_3(x_2 - x_1) + k_2(x_s - x_1) + c_3(\dot{x}_2 - \dot{x}_1) + c_2(\dot{x}_s - \dot{x}_1), \tag{10}$$

$$m_3\ddot{x}_2 = k_3(x_1 - x_2) + c_3(\dot{x}_1 - \dot{x}_2), \tag{11}$$

$$m_4\ddot{x}_3 = k_4(x_s - x_3) + c_4(\dot{x}_s - \dot{x}_3), \tag{12}$$

$$m_5\ddot{x}_4 = k_5(x_s - x_4) + c_5(\dot{x}_s - \dot{x}_4), \tag{13}$$

$$(m_1 + m_s)\ddot{x}_s = k_2(x_1 - x_s) + k_4(x_3 - x_s) + k_5(x_4 - x_s) + k_s(x_{input} - x_s) + \ldots$$

$$\ldots + c_2(\dot{x}_1 - \dot{x}_s) + c_4(\dot{x}_3 - \dot{x}_s) + c_5(\dot{x}_4 - \dot{x}_s) + c_s(\dot{x}_{input} - \dot{x}_s). \tag{14}$$

2.4. 7-DOF Model by Muksian and Nash: 1974 and later by Brindeu, Poppa, et al.: 2000

Figure 4 shows a 7-DOF model in the seated position where m_2 and m_3 are an oversimplification for the back and torso respectively. The back consists of the sacrum and vertebrae whereas the torso includes the ribs, thoracic vertebrae, costal cartilages and the sternum.

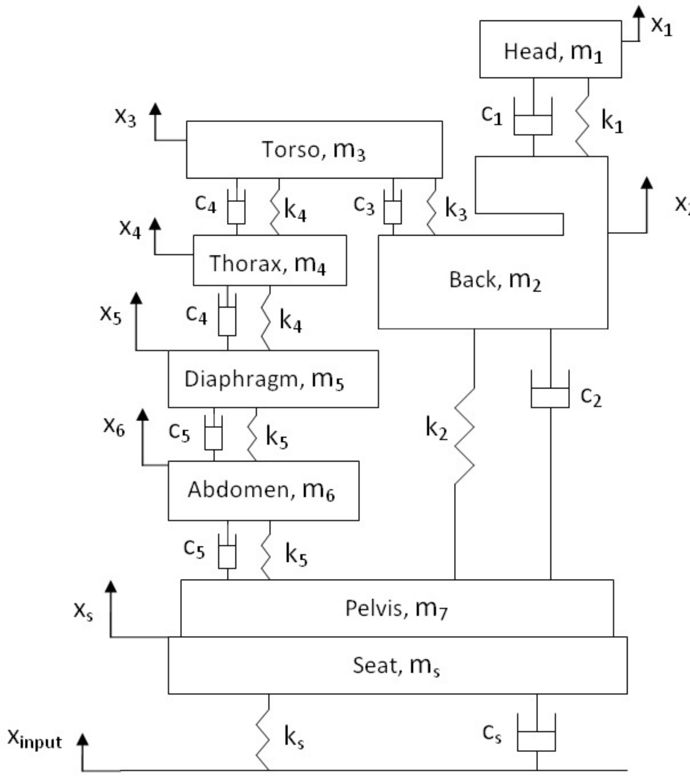

Fig. 4. Schematic of 7-DOF model by Muksian et al. [5] and Brindeu et al. [2]

The damping values c_3, c_4 and c_5 and stiffness values k_3, k_4 and k_5 are considered non-linear by Muksian et al. [5] however Brindeu et al. [2] suggest that these stiffness and damping parameters can be made linear when determining the undamped natural frequency associated with each anatomical region of this model. The non-linear model by Muksian et al. [5] also included a force approximating the heartbeat located between m_3 and m_4, force approximating diaphragm motion located on mass m_5 and coulomb friction forces between m_2 and m_3. These forces together with the non-linear stiffness and damping parameters were derived to simulate the back to seat ratio and the seat to head ratio. The non-linear seat to head ratio by Muksian et al. [5] is similar to that obtained by the 5-DOF linear model by Smith [10].

Equations of motion for the described above model are presented below (15 – 21):

$$m_1\ddot{x}_1 = k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1), \tag{15}$$

$$m_2\ddot{x}_2 = k_1(x_1 - x_2) + k_2(x_s - x_2) + k_3(x_3 - x_2) + \ldots$$
$$\ldots + c_1(\dot{x}_1 - \dot{x}_2) + c_2(\dot{x}_s - \dot{x}_2) + c_3(\dot{x}_3 - \dot{x}_2), \tag{16}$$

$$m_3\ddot{x}_3 = k_3(x_2 - x_3) + k_4(x_4 - x_3) + c_3(\dot{x}_2 - \dot{x}_3) + c_4(\dot{x}_4 - \dot{x}_3), \tag{17}$$

$$m_4\ddot{x}_4 = k_4(x_3 - x_4) + k_4(x_5 - x_4) + c_4(\dot{x}_3 - \dot{x}_4) + c_4(\dot{x}_5 - \dot{x}_4), \tag{18}$$

$$m_5\ddot{x}_5 = k_4(x_4 - x_5) + k_5(x_6 - x_5) + c_4(\dot{x}_4 - \dot{x}_5) + c_5(\dot{x}_6 - \dot{x}_5), \tag{19}$$

$$m_6\ddot{x}_6 = k_5(x_5 - x_6) + k_5(x_s - x_6) + c_5(\dot{x}_5 - \dot{x}_6) + c_5(\dot{x}_s - \dot{x}_5), \tag{20}$$

$$(m_7 + m_s)\ddot{x}_s = k_2(x_2 - x_s) + k_5(x_6 - x_5) + k_s(x_{input} - x_s) + \ldots$$
$$\ldots + c_2(\dot{x}_2 - \dot{x}_s) + c_s(\dot{x}_6 - \dot{x}_5) + c_s(\dot{x}_{input} - \dot{x}_s). \tag{21}$$

3. Results and Comparison of Models

A Laplace Transform is used to derive the vibration transmissibility and mechanical impedance with stiffness, mass and damping properties as described in Tab. 1 for each model using the equations of motion (1-21) listed earlier.

Tab. 1. Biodynamic mass, stiffness and damping parameters for all of the analysed models

Biodynamic Model	Mass [kg]	Stiffness [kN/m]	Damping [Ns/m]
4-DOF model Rakheja et al. [7] and ISO 5982: 2001 [4]	m_o=2.73, m_2=2.73 m_1=8.18, m_3=61.36	k_1=9.99, k_2=34.4 k_3=36.2	c_1=387, c_2=234 c_3=1390
5-DOF Model [6]	m_1=7.21, m_2=38.71 m_3=11.71, m_4=17.4	k_1=310, k_2=183 k_3=162.8, k_4=90	c_1=400, c_2=4750 c_3=4585, c_4=2064
5-DOF Model Smith [8] and [10]	m_1=23.3, m_2=11.4 m_3=18.3, m_4=6.7	k_2=115.36, k_3=37.7 k_4=39.86, k_5=39.19	c_2=26.3, c_3=350.2 c_4=245.2, c_5=367.8
7-DOF Model Muksian et al. [5] and Brindeu et al. [2]	m_1=5.11, m_2=6.39 m_3=30.68, m_4=1.28 m_5=0.43, m_6=5.54 m_7=25.57	k_1, k_2 and k_3 =52.56 k_4 and k_5=0.88	c_1, c_2 and c_3=3576.8 c_4 and c_5=292

Figure 5 shows the seat to head transmissibility and mechanical impedance versus frequency, with two resonant frequencies occurring less than 5 Hz, representing whole body vibration, whereas the second frequency at 7 Hz represents the legs.

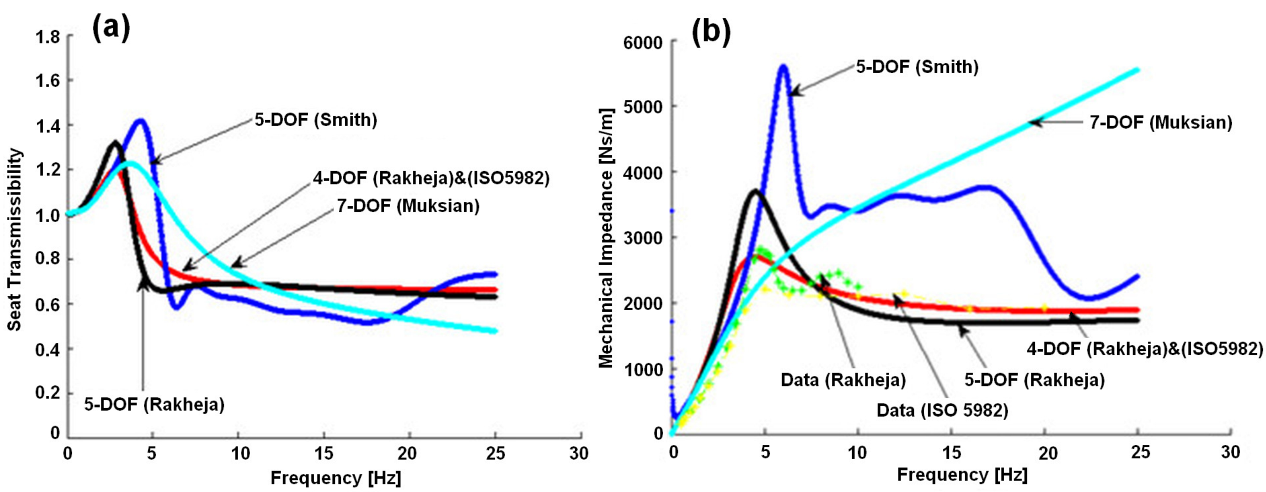

Fig. 5. Seat to Head transmissibility (a) and Mechanical Impedance (b) as a function of frequency

A third resonance frequency is observed for the 5-DOF Smith [8] impedance curve that occurs between 12-15 Hz and affects the lower torso, abdomen and pelvis, whereas the fourth resonance region located between 15-18 Hz is associated with spinal resonance. The 5-DOF Smith [8] curve overestimates published impedance data, however it can be used to identify anatomical structures affected by resonance. The 7-DOF by Muksian et al. [5] curve cannot approximate any of the other curves or experimental data related to seat to head transmissibility or mechanical impedance responses since the biodynamic configuration in Fig. 4 has distinct anatomical structures, which require a non-linear modelling strategy. The damping parameters for this model are frequency dependant and for frequencies larger than 8 Hz higher damping values are required [5]. The underestimation of the peak transmissibility magnitude, lower resonant frequency and discrepancy in the mechanical impedance response in comparison to the other curves and published data therefore suggest that higher order biodynamic models exhibit non-linear transmissibility and impedance response behaviour from [3] and [5].

Experimental data for peak impedance is 2867 Ns/m at 4.875 Hz [6] and the experimental data for peak impedance suggested by [4] is 2201 Ns/m at 5 Hz. The models capable of approximating published data are the 5-DOF Rakheja et al. [6], 4-DOF Rakheja et al. [7] and ISO 5982: 2001 [4] curves due to the correct anatomical structure including stiffness and damping parameters used in the study. A sensitivity analysis was performed on the models by varying the stiffness and damping parameters by 50 percent to accommodate inter subject variability due to gender, age and size of passenger. It was found that the transmissibility and impedance response behaviour were sensitive to stiffness and damping adjustments for all models except the 4-DOF Rakheja et al. [7] and ISO 5982: 2001 [4] model, which was still able to predict experimental whole body resonant frequencies within the experimental range of peak seat to head vibration transmissibility and mechanical impedance. Studies conducted earlier by the author [1] indicated that simple models of 2-DOF, 3-DOF and 5-DOF were able to predict whole body resonant behaviour since the pelvis, legs and skeletal frame could be easily described while resting on the seat. Higher order models usually 5-DOF to 7-DOF can be used to study transmissibility behaviour with greater physiological granularity, however the stiffness and damping is non-linear for old seats that have cushion bottoming and also depends on acceleration magnitude.

4. Conclusions

The 4-DOF, 5-DOF and 7-DOF models based on the mechanical impedance, vibration transmissibility and sensitivity analysis accurately simulated resonance behaviours of the human body with sufficient anatomical characteristics when compared to published experimental data for low acceleration magnitude that can be applied for new vehicle seat design. These models exhibit non-linear stiffness and damping behaviour when investigating retrofit seat design applications or when exposed to high acceleration magnitude usually greater than 0.5g rms, especially for 5-DOF or 7-DOF biodynamic models. Simple models of 2-DOF and 3-DOF can be used to predict whole body resonant behaviours whereas the sensitivity analysis suggests that various physiological behaviours can be studied using higher order models.

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