Biomechanical matrix-multibody coupled human body model for seat to head transmissibility

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Abstract. Health hazards of human body to whole body vibrations (WBV) have been linked with the incidence of spinal ailments within the drivers of vibrating moving equipment. The investigations on the biodynamic responsiveness of body segments; thus, it is relevant for a profound understanding of prospective impairment anticipations and design refinements. Current research work concentrates on seated body biodynamic direct and cross axis responses to seat induced vertical vibration, and establishment of an analytical model for the prediction of human anatomy comfort parameters. In the course of WBV vibrations of the human anatomy in a seated position (driver or passenger), the movement of the head is affected by the backrest forces transmitting to the lumbar section of the spinal column. Accordingly, it is crucial to reflect backrest assistance while building the human body model to captivate direct and cross axis seat to head transmissibility. Thus, the model results should accurately represent the internal forces, power absorbed, body acceleration accurately. The human anatomy is viewed as a biodynamic system of interconnected masses. A two-dimensional nine degree of freedom (DoF) matrix-multibody coupled backrest supported seated human anatomy model is established and validated to depict vertical and fore-aft head motion. Multi-objective genetic algorithm-based optimization has been used for model parameter identification by minimizing the error difference separating the experimental and model-derived seat to head transmissibility.

Keywords: Biodynamics; Matrix model; Multibody modelling; Optimization; Vibrations.

1. Introduction
Occupational vehicle drivers often suffer from back disorders for sufferings [1,2]. Vehicle drivers are subjected to immoderate lower-frequency whole body vibration (WBV) of substantial enormity demonstrated structural alterations within the lumbar region of the spine [3]. Exposure to WBV in the workplace is thus widely known to cause inconvenience, displeasure, well-being and safety hazards [4]. The establishment and validation of efficacious seated human anatomy biodynamic models’ utilization in seating and suspension vibro-isolation capability refinement demand comprehensive evaluation and characterizations of biodynamics of the human anatomy subjected to practical vehicular vibration disturbances. The seated human anatomy biodynamic responses subjected to WBV has been broadly investigated over the wide span of vibrational magnitude, frequency and postural circumstances. Research investigations have also revealed the greater incidence of lower back disruption for instance, smashing of lumbar lordosis, minuscule impairment of the intervertebral discs,
rise in muscular distress and intradiscal strain in professional operators subjected to whole-body vibration [5,6]. Also, greater health hazard of the spine, outlying veins, digestive system, nervous system, and vestibular system [7]. As a result, numerous afflictions, in particular, intervertebral disc prolapse, chondrosis, spondylarthrosis, osteochondrosis, and protrusion [8] are observed. The impact of vibration exposure on the human anatomy relies upon three primary elements: frequency, intensity and the duration of the involved vibrations [9–11]. The study of drivers exposed to whole-body vibrations requires biodynamic models of a suitable level of complexity and associated constraints. The vibrations transmitted from road tire interaction to the human anatomy depends on many factors such as road profile, vehicle and seat suspension cushion properties etc. These mathematical models will be beneficial to realize the biodynamics behavioral responses of the human anatomy in an extensive way, consequently contribute towards better seating and vehicle dynamics. The human anatomy mathematical models developed in the literature are classified as lumped parameter models [12], finite element models [13,14], multibody models [15–22] and matrix models [23]. Most of the developed models are one dimensional and constraint due to backrest support is usually ignored. The human anatomy in sitting posture acted upon vertical direction vibrations at the base, head exhibit motion in vertical and fore-and-aft directions. This vertical and horizontal motion called as direct vertical (DV) and cross axis fore-aft (CAFA). Coupled matrix-multibody model is developed in this research activity to represent the human anatomy seated with the backrest to represent two-dimensional head motion. This model can be used to investigate vehicle dynamics and human anatomy comfort assessment with integrating on a vehicle model.

2. Matrix-multibody modelling

In matrix model [23,24], associated human anatomy movement is considered together vertical and horizontal directions is included in the model development. The primary component which in particular enables this are coupled matrices of spring and damper coefficients. As a result, higher accuracy and simplicity can be accommodated in the human anatomy model. The limitations with matrix model are rotational moments in body joints cannot be investigated. The multibody dynamic models are made up of distinct inertial mass sections interconnected by kinematic joints, occasionally includes external force components. Such models have the required anthropometric standards to exemplify the human anatomy configuration. A biodynamic model of the body with the capabilities to represent the vibrational effects in a realistic way is an important concern in understating the human anatomy in a vibrational environment. Thus, accounting for modelling complexity and accuracy, 9 degrees of freedom (DoF) matrix-multibody model for the human anatomy is developed and presented in Fig. 1. The human anatomy considered to be in a sitting posture with pelvis and backrest supported. Each mass represents distinct parts of the human anatomy and has two degrees of freedom - in the sagittal plane. The biomechanical human anatomy model is constructed of four concentrated rigid masses 1-4, portraying the structure of thigh pelvis, lower-torso, upper-torso and head individually. The stiffness and damping matrices are formulated in place of the spring and damper coefficients to transmit the vertical vibrations in coupled direction - vertical and fore-aft. The pelvis and backrest interaction parameters with the seat are represented by $[K_B, C_B]$ and $[K_0, C_0]$ matrices. The neck joint is configured as a 3 DoF using translational $[k_{x_0}, c_{x_0}]$ and rotational $[k_{r_0}, c_{r_0}]$ spring dampers system. The additional rotational degree of freedom to the head is represented using $\theta_4$. 

2
The equations of motion can be represented by Eq. (1)-(3).

\[
M_i = \begin{bmatrix} m_1 & 0 \\ 0 & m_1 \end{bmatrix}; M_2 = \begin{bmatrix} m_2 & 0 \\ 0 & m_2 \end{bmatrix}; M_3 = \begin{bmatrix} m_3 & 0 \\ 0 & m_3 \end{bmatrix}; M_4 = \begin{bmatrix} m_4 & 0 \\ 0 & m_4 \end{bmatrix}
\]

(1)

\[
K_i = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}; K_2 = \begin{bmatrix} k_{21} & k_{22} \\ k_{31} & k_{32} \end{bmatrix}; K_p = \begin{bmatrix} k_{p1} & k_{p2} \\ k_{p3} & k_{p4} \end{bmatrix}; K_B = \begin{bmatrix} k_{B1} & k_{B2} \\ k_{B3} & k_{B4} \end{bmatrix}
\]

(2)

\[
C_i = \begin{bmatrix} c_{i1} & c_{i2} \\ c_{i3} & c_{i4} \end{bmatrix}; C_2 = \begin{bmatrix} c_{21} & c_{22} \\ c_{23} & c_{24} \end{bmatrix}; C_p = \begin{bmatrix} c_{p1} & c_{p2} \\ c_{p3} & c_{p4} \end{bmatrix}; C_B = \begin{bmatrix} c_{B1} & c_{B2} \\ c_{B3} & c_{B4} \end{bmatrix}
\]

(3)

The input excitation and mass displacement variables represented by Eq. (4).

\[
P_0 = \begin{bmatrix} x_0 \\ z_0 \end{bmatrix}; P_1 = \begin{bmatrix} x_1 \\ z_1 \end{bmatrix}; P_2 = \begin{bmatrix} x_2 \\ z_2 \end{bmatrix}; P_3 = \begin{bmatrix} x_3 \\ z_3 \end{bmatrix}
\]

(4)

The model parameters represented by Eqs. (5)-(6).

\[
x_{4j3} = x_z - l_{4j3} \theta_4 \\
z_{4j3} = z_4 + l_{4j3} \theta_4 \\
\dot{x}_{4j3} = \dot{x}_z - l_{4j3} \dot{\theta}_4 \\
\dot{z}_{4j3} = \dot{z}_4 + l_{4j3} \dot{\theta}_4 \\
f_{3j} = k_{r3} \theta_4 + c_{r3} \dot{\theta}_4
\]

(5)

\[
f_{3x} = k_{3x}(x_z - x_{4j3}) + c_{3x}(\dot{x}_z - \dot{x}_{4j3})
\]

\[
f_{3z} = k_{3z}(z_z - z_{4j3}) + c_{3z}(\dot{z}_z - \dot{z}_{4j3})
\]

(6)

The equations of motion can be represented by Eqs. (7)-(8).

\[
M_1 \ddot{P}_1 + C_p [\ddot{P}_1 - \ddot{P}_0] + K_p [P_1 - P_0] + C_1 [\dot{P}_1 - \dot{P}_0] + K_1 [P_1 - P_0] = 0
\]

\[
M_2 \ddot{P}_2 + C_1 [\ddot{P}_2 - \ddot{P}_1] + K_1 [P_2 - P_1] + C_2 [\dot{P}_2 - \dot{P}_1] + K_2 [P_2 - P_1] + C_3 [\ddot{P}_2 - \ddot{P}_0] + K_3 [P_2 - P_0] = 0
\]

(7)

\[
M_3 \ddot{P}_3 + C_3 [\ddot{P}_3 - \ddot{P}_2] + K_2 [P_3 - P_2] + \begin{bmatrix} f_{3x} \\ f_{3z} \end{bmatrix} = 0
\]
\[ m_\beta \ddot{x}_\beta = f_{3x} \]
\[ m_\gamma \ddot{x}_\gamma = f_{3x} \]
\[ I_\alpha \dot{\theta}_\alpha = (-f_{3x})l_{4j/3y} + f_{3x}l_{4j/3z} + f_{r3} \]

The Eqs. (7)-(8) gives rise to nine equations of motion representing the motion of masses in x-z directions and head rotation. The three-dimension head movement is expressed by Eq. (8). The expression for four masses 1-4 can be revised and formulated as \([M] \ddot{z} + [C] \dot{z} + [K]z = F\)

Here,

- **M** - Mass matrix (dimension 9 x 9)
- **C** - Damping coefficient matrix (dimension 9 x 9)
- **K** - Stiffness coefficient matrix (dimension 9 x 9)
- **F** - Input force excitation vector (dimension 9 x 1)

\(z, \dot{z}\) and \(\ddot{z}\) symbolize the displacement, velocity and acceleration response vector of each masses (dimension 9 x 1). These equations of motion are transfigured from the time domain into the frequency domain using Laplace transform for the purpose of representing frequency domain measured data. As the model is linear, frequency domain (FD) evaluation is performed to simplify the assessment of the behavioural response of the system. With the use of Laplace conversion, the equations of motion are processed from the frequency domain out of time domain to represent corresponding the experimental results. The model outcome considers solely the steady state behaviour of the system.

The coupled mass, stiffness and input excitation force vector are represented as follows. The damping coefficients matrix is similar to the spring stiffness matrix with corresponding damping elements.

\[ M = \text{diag}\{m_1, m_1, m_2, m_2, m_3, m_3, m_4, m_4, I_4\} \]

\[ K = \begin{bmatrix}
K_{11} + K_{31} & K_{12} + K_{32} & -K_{11} & -K_{12} & 0 & 0 & 0 & 0 & 0 \\
K_{13} + K_{33} & K_{14} + K_{34} & -K_{13} & -K_{14} & 0 & 0 & 0 & 0 & 0 \\
-K_{15} & -K_{16} & K_{15} + K_{35} & K_{16} + K_{36} & -K_{15} & -K_{16} & 0 & 0 & 0 \\
0 & 0 & -K_{21} & K_{22} + K_{41} & K_{23} + K_{42} & K_{24} + K_{43} & K_{25} + K_{44} & 0 & 0 \\
0 & 0 & -K_{23} & K_{24} & 0 & -k_{41} & 0 & -k_{42} & 0 \\
0 & 0 & 0 & 0 & -k_{43} & 0 & k_{44} & 0 & -k_{45} \\
0 & 0 & 0 & 0 & 0 & k_{43} & -k_{44} & 0 & -k_{45} \\
0 & 0 & 0 & 0 & 0 & 0 & k_{44} & k_{45} & -k_{46} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \]

\[ F = \begin{bmatrix}
C_{p2} \ddot{z}_0 + K_{p2} \dot{z}_0 \\
C_{p4} \ddot{z}_0 + K_{p4} \dot{z}_0 \\
C_{B2} \ddot{z}_0 + K_{B2} \dot{z}_0 \\
C_{B4} \ddot{z}_0 + K_{B4} \dot{z}_0 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix} \]

Seat to head transmissibility, also called as “through-the-body” biodynamic response function defined as a fraction of the response’s amplitude acceleration, velocity or displacement or of a model in steady-state vibrations, this simplifies the interpretation of the vibrational responses of the human anatomy. The vibrational transmissibility magnitude is represented as a function of the excitation frequency. Transmissibility measure helps the investigator in analysing the way vibrations
transmitting across the body, frequency at the moment excitation signal is resonated, peak in resonance frequency and amount of damping in respective resonance frequency across the range of interest. The magnitude of the maximum response is reciprocally proportionate to the human body sitting position and damping variables. The influence of the model variables on the transmissibility fraction facilitates the investigator to determine the crucial parameters those could be provided with higher significance in the interest to enhance human ride comfort. The peak in the transmissibility depicts excitations around frequency range, is magnified by a continuous building up of stored energy owing to frequent squeezing and expansion of buttocks-pelvis tissue and muscles. The seat to head transmissibility ratio measure functions (STHT), particularly direct vertical (DV) and cross axis foreAft (CAFA) are defined by Eq. (9)-(10).

\[ DVSTHT = \frac{z_4}{z_0} \text{or} \frac{\dot{z}_4}{\dot{z}_0} \text{ or} \frac{\ddot{z}_4}{\ddot{z}_0} \]  \hspace{1cm} (9)

\[ CAFASTHT = \frac{x_4}{z_0} \text{or} \frac{\dot{x}_4}{\dot{z}_0} \text{ or} \frac{\ddot{x}_4}{\ddot{z}_0} \]  \hspace{1cm} (10)

3. Parameter identification

Utilizing multi objective genetic algorithm and consequently, global optimization technique is used to obtain the model parameters. The flowchart to obtain model parameters is shown in Figure 2. There are two objective functions related to the direct vertical STHT and cross axis fore aft CAFA STHT are formulated using Eq. (11), whereby \( f \) in the equations represent frequency parameter. The indexes \( M \) and \( E \) symbolize the model outcome and experimental results [25], in each instance.

\[ J_1 = \sum_{i=1}^{N} (|DVSTHT_M(f_i)| - |DVSTHT_E(f_i)|)^2 \]  \hspace{1cm} (11)

\[ J_2 = \sum_{i=1}^{N} (|CFASTHT_M(f_i)| - |CFASTHT_E(f_i)|)^2 \]

To find the answer to the multi-objective problem, the global minimization technique is employed as specified by Rao [26]. The total deviation to be reduced is expressed as a summation of two deviations as formulated in Eq.(12).

\[ J_{Model} = \sum_{i=1}^{2} \left[ \frac{J_i - J_i^*}{J_i^*} \right]^2 \]  \hspace{1cm} (12)

The parameter values to different human body parts for instance mass and inertia components, are collected from the literature [27–29] and shown in Table 1.

| Table 1. Body parts mass values (mass kg, inertia kgm²). |
|--------------------------------------------------------|
| Body segment              | Mass (kg)  |
| Thighs-pelvis (\(m_1\))  | 26.67      |
| Lower torso (\(m_2\))    | 10.84      |
| Upper torso (\(m_3\))    | 24.64      |
| Head (\(m_4\))           | 6.31       |
| Head moment of inertia (\(I_4\)) | 0.022     |

The methodology for parameter optimization is illustrated in Figure 2.
Here $J_i^*$, $i = 1$ and 2 depict the minimal error at time the model parameters obtained with only one objective genetic algorithm. Following calculating $J_i^*$ through single objective genetic algorithm (GA), the total function deviation in both cases will be reduced concurrently by through Eq. (12). The GA tool of MATLAB is utilized and the simulation variables are presented in Table 2.

| Variable                        | value                      |
|--------------------------------|----------------------------|
| Population type                | Vector double              |
| Population size                | 200                        |
| Creation function              | Dependent constraint       |
| Function - Fitness scaling     | Rank                       |
| Function - Selection           | Uniform stochastic         |
| Reproduction                   |                            |
| Elite counts                   | 0.05*Population size       |
| Fraction crossover             | 0.8                        |
| Function - Mutation            | Dependent constraint       |
| Function - Crossover           | Dependent constraint       |
| Migration                      |                            |
| Direction                      | Forward                    |
| Fraction                       | 0.2                        |
| Period                         | 20                         |
| Stopping standard Function     | 1e-6                       |

The stiffness and damping coefficient values obtained after optimization procedure are given in Table 3.
Table 3. Optimized model parameter values (springs stiffness coefficient: N/m, damping coefficient: Ns/m, rotational stiffness: Nm/rad and rotational damping coefficient: Ns/m rad).

| Parameter | Value       | Parameter | Value       |
|-----------|-------------|-----------|-------------|
| $k_{P1}$  | 9.4545×10^4 | $c_{P1}$  | 2.5427×10^3 |
| $k_{P2}$  | 1.6739×10^4 | $c_{P2}$  | 4.7669×10^3 |
| $k_{P3}$  | 9.0533×10^4 | $c_{P3}$  | 2.0680×10^3 |
| $k_{P4}$  | 8.1751×10^4 | $c_{P4}$  | 8.9187×10^3 |
| $k_{B1}$  | 3.0910×10^4 | $c_{B1}$  | 3.6043×10^3 |
| $k_{B2}$  | 4.9002×10^4 | $c_{B2}$  | 710.3095    |
| $k_{B3}$  | 8.5312×10^3 | $c_{B3}$  | 357.9326    |
| $k_{B4}$  | 8.7159×10^3 | $c_{B4}$  | 7.1499×10^3 |
| $k_{11}$  | 6.6922×10^1 | $c_{11}$  | 1.4416×10^1 |
| $k_{12}$  | 1.8810×10^4 | $c_{12}$  | 1.8258×10^3 |
| $k_{13}$  | 3.4820×10^4 | $c_{13}$  | 7.0043×10^3 |
| $k_{14}$  | 3.1250×10^4 | $c_{14}$  | 7.8017×10^3 |
| $k_{21}$  | 5.3316×10^3 | $c_{21}$  | 33.0705     |
| $k_{22}$  | 9.1306×10^4 | $c_{22}$  | 3.5738×10^3 |
| $k_{23}$  | 2.7212×10^4 | $c_{23}$  | 1.5173×10^3 |
| $k_{24}$  | 5.3490×10^4 | $c_{24}$  | 6.8925×10^3 |
| $k_{4x}$  | 1.8771×10^1 | $c_{4x}$  | 7.4684×10^3 |
| $k_{4z}$  | 6.8078×10^3 | $c_{4z}$  | 2.1034×10^3 |
| $k_{rd}$  | 6.3116×10^4 | $c_{rd}$  | 553.5312    |

The direct vertical and cross axis fore and aft seat to head transmissibility for model-simulated and experimental results are illustrated in Figure 3. It can be observed that model results are in closely compliance with the experimental results.

![Figure 3](image-url)

Figure 3. Model vs experimental [25] seat to head transmissibility (a) direct vertical (b) cross axis fore-and-aft.

4. Conclusion
A detailed coupled matrix multibody human body model is established to represent direct and cross-axis motion of the human head, subjected to vertical axis seat excitations. With the integration of matrix and multibody modelling, one can obtain rotational moment in the neck region. Thus with 3 DoF neck joint configuration, detailed neck region investigations can be conducted. The model dynamical equations of motion are transferred from time response state to frequency domain to obtain model direct vertical and cross-axis head motion frequency response. The model variables are optimized utilising the genetic algorithm to represent experimental direct and cross-axis movement of the human head in the seating posture subjected to vertical axis seat disturbances. Thus, model accurately represents the experimental results. This developed model can be integrated with the
vehicle model for simulation of various crash conditions, to obtain seat suspension and cushion variables to improve drivers ride comfort level.

5. References

[1] Lings S and Leboeuf-Yde C 1998 Whole body vibrations and low back pain *Ugeskr. Laeger.* **160** 4298–301

[2] Desai R, Guha A and Seshu P 2021 Modelling and Simulation of Active and Passive Seat Suspensions for Vibration Attenuation of Vehicle Occupants. *Int. J. Dyn. Control* 1–21

[3] Sandover J and Dupuis H 1987 A reanalysis of spinal motion during vibration. *Ergonomics* **30** 975–85

[4] Bovenzi M and Hulshof C T J 1998 An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain. *J. Sound Vib.* **215** 595–611

[5] Diyana M Y A, Karmegam K, Shamsul B M T, Irniza R, Vivien H, Sivasankar S, Syahira M J P A and Kulanthayan K C M 2019 Risk factors analysis: Work-related musculoskeletal disorders among male traffic policemen using high-powered motorcycles. *Int. J. Ind. Ergon.* **74** 102863

[6] Ramalingam M and Jebaseelan D D 2019 The effect of vibration characteristics of an automotive seating system on ride comfort–A finite element study. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **233** 6588–601

[7] Seidel H and Heide R 1986 Long-term effects of whole-body vibration: a critical survey of the literature. *Int. Arch. Occup. Environ Health* **58** 1–26

[8] Dupuis H 1994 Medical and occupational preconditions for vibration-induced spinal disorders: occupational disease no. 2110 in Germany. *Int. Arch. Occup. Environ Health.* **66** 303–8

[9] Mansfield N J 2004 Human response to vibration (CRC press)

[10] Desai R, Guha A and Seshu P 2021 A comparison of different models of passive seat suspensions Proc IMechE Part D J Automob. Eng.

[11] Desai R, Guha A and Seshu P 2021 A Comparison of Quarter, Half and Full Car Models for Predicting Vibration Attenuation of an Occupant in a Vehicle. *J. Vib. Eng. Technol.*

[12] Wan Y and Schimmels J M 1995 A simple model that captures the essential dynamics of a seated human exposed to whole body vibration. *Adv. Bioeng.*

[13] Zhang X, Qiu Y and Griffin M J 2015 Developing a simplified finite element model of a car seat with occupant for predicting vibration transmissibility in the vertical direction. *Ergonomics* **58** 1220–31

[14] Desai R, Vekaria A, Guha A and Seshu P 2019 Seat pan angle optimization for vehicle ride comfort using finite element model of human spine. *Proceedings of the 26th International Congress on Sound and Vibration*, ICSV 2019

[15] Zheng G, Qiu Y and Griffin M J 2011 An analytic model of the in-line and cross-axis apparent mass of the seated human body exposed to vertical vibration with and without a backrest. *J. Sound Vib.* **330** 6509–25

[16] Desai R, Guha A and Seshu P 2020 Multibody modelling of the human body for vibration induced direct and cross-axis seat to head transmissibility. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*

[17] Desai R, Guha A and Seshu P 2020 Modelling and simulation of an integrated human-vehicle system with non-linear cushion contact force. *Simul. Model. Pract. Theory.* 102206

[18] Desai R, Guha A and Seshu P 2018 Multibody Biomechanical Modelling of Human Body Response to Direct and Cross Axis Vibration. *Procedia Comput. Sci.* **133** 494–501

[19] Desai R, Guha A and Seshu P 2020 Investigations on the Human Body and Seat Suspension Response Using Quarter, Half and Full Car Models. *Joint International Conference of the International Conference on Mechanisms and Mechanical Transmissions and the International Conference on Robotics.* vol 88 (Springer) pp 507–16
Desai R, Guha A and Seshu P 2019 Multibody Biomechanical Modelling of Human Body Response to Vibrations in an Automobile. *IFToMM World Congress on Mechanism and Machine Science* vol 73 pp 3–12

Desai R, Guha A and Seshu P 2020 Investigation of Internal Human Body Dynamic Forces Developed During a Vehicle Ride. *The International Conference of IFToMM ITALY* vol 91 (Springer) pp 85–93

Desai R, Guha A and Seshu P 2021 Multibody Modeling of Direct and Cross-Axis Seat to Head Transmissibility of the Seated Human Body Supported with Backrest and Exposed to Vertical Vibrations. *Lecture Notes in Mechanical Engineering* pp 119–34

Marzbanrad J and Afkar A 2013 A biomechanical model as a seated human body for calculation of vertical vibration transmissibility using a genetic algorithm. *J. Mech. Med. Biol.* 13 1350053

Marzbanrad J, Shakhlavi S J, Moghaddam I T and Afkar A 2018 Biomechanical Modeling of a Seated Human Body Exposed to Vertical and Horizontal Vibrations Using Genetic Algorithms. *J. Vib. Eng. Technol.* 6 417–26

Wang W, Rakheja S and Boileau P-É 2006 Effect of back support condition on seat to head transmissibilities of seated occupants under vertical vibration. *J. Low Freq. noise, Vib. Act. Control* 25 239–59

Rao S S 2009 *Engineering optimization: theory and practice* (John Wiley & Sons)

Gągorowski A 2010 Simulation study on stiffness of suspension seat in the aspect of the vibration assessment affecting a vehicle driver. *Logist. Transp.* 11 55–62

Winter D A 2009 Biomechanics and motor control of human movement (John Wiley & Sons)

Chandler R F, Clauser C E, McConville J T, Reynolds H M and Young J W 1975. *Investigation of inertial properties of the human body*