Research Article

The normal vehicle forces effects of a two in-wheel electric vehicle towards the human brain on different road profile maneuver

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Abstract

Noise, harshness and vibrations are a non-trivial aspect of ride or human comfort, and car manufacturers often sought to improve the aforesaid comfort level. In previous studies, human biodynamic model and vehicle model are often modelled separately. Human model is used to study human alertness level and health while vehicle model is used to study on the car vibration to specifically understand the impact of vibration towards the model independently. In this study, a twelve degrees of freedom (12 DOF) human biodynamic model is incorporated with a two in-wheel electric car model to investigate the effect of vertical vibration towards the human brain based on different types of road profile and maneuver. MATLAB simulation environment is used to carry out the investigation, and it was established from the present study that the proposed model is able to provide significant insights on the impact experienced by the human brain to the skull based on the given vertical input of different road profile. The impact on the human brain to the skull is often associated with human alertness while driving where vibration exposure towards human driver influence the sleepiness level, human reaction times and lapses of attention which may lead to road accidents.

Keywords Vibration · Electric vehicle · Human biodynamic model · Comfort

1 Introduction

The increasing usage of vehicle worldwide has motivated the car manufacturers to produce a vehicle that is safe, comfortable, optimized fuel consumption as well as have a minimal impact on the environment. Human beings are exposed to vibration through different mediums such as driving and working conditions amongst others in their daily life. It is worth noting that when travelling, both the driver as well as passengers are exposed to vibrations which originate primarily from the vehicle due to the interaction between the vehicle and the road. Studies have shown that prolonged vibrational exposure leads to harmful effects towards human health such as reducing the alertness level, increase in heart rate and also back problem [1, 2]. Moreover, sudden manoeuvre or braking also could cause injury and decrease the human comfort level when travelling [3, 4]. This is due to the vibration transmitted through the supported vibrated surface that, to some extent, affects the comfort level of the human body.

Researchers have developed human biodynamic models as a lumped masses that are connected with springs and dampers which represent the body joints and muscles to represent the human body in order to study the impact of vibration towards human health and comfort [5–7]. By using this model, the effect of vibration exposure towards human health and comfort can be obtained and verified. Similarly, the lumped mass approach has also been employed to vehicle models. Such models are able

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to provide insights on the ride comfort and road handling that could quantify the effect of different road profiles [8, 9]. In addition, a study by Sezgin and Arslan had demonstrated that the comfort level experienced by the driver or passenger is significantly reduced by travelling at rate a of 72 km/h for 5 to 6 h journey on a smooth road with passive suspension systems, suggesting that vehicular condition, as well as road profile, does affect its users [10].

More often than not, the study on human biodynamic models is investigated independently without coupling it with any vehicle model. Moreover, it has been reported in the literature that the vibration effect on the human body considers the vibration effect attained from the vehicle seat without considering the vehicle conditions on different road profile while travelling [1, 2, 7, 10]. In a recent study, the effect of vibration towards human comfort, particularly towards the brain was investigated by exciting the human model that consists of lumped masses with varying input values [11]. In addition, a two in-wheel electric car model that considers the effect of both lateral and longitudinal forces of the vehicle was investigated in [12]. The forces were computed by means of the Dugoff's model as the weight shift, and the tire stiffness are considered independently for both lateral and longitudinal directions. Therefore, this paper attempts to investigate the effect of vertical vibration towards the brain of twelve degrees of freedom (12 DOF) human biodynamic model [7, 13] coupled with the aforesaid two in-wheel electric car model.

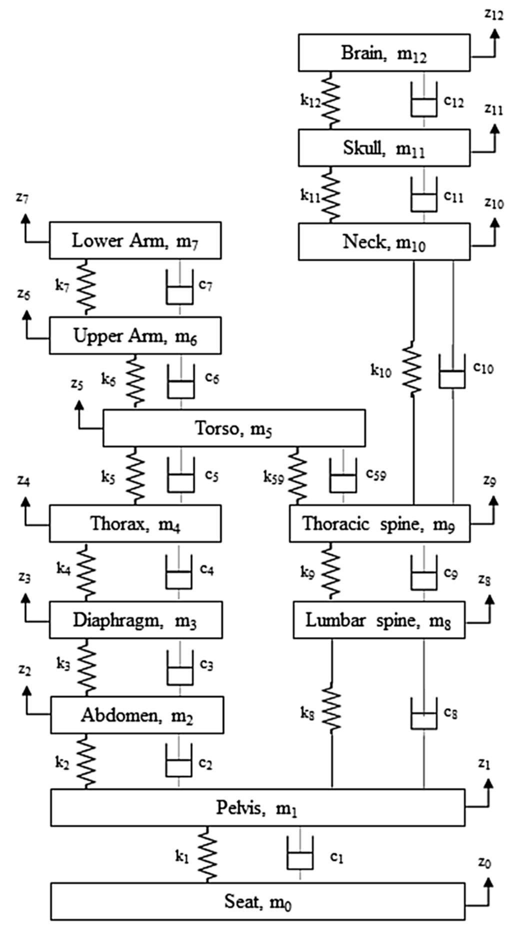

Fig. 1 Schematic of 12 DOF human biodynamic model [5, 7, 13]

2 Premilinary section

Figure 1 depicts a schematic of 12 DOF of the human biodynamic model. Eleven degrees of freedom (11 DOF) model [5, 7] which are commonly used in previous studies of the human model are added with a brain parameter [13] which represents the new 12 DOF model. The inclusion of the aforesaid parameter allows for the ability to investigate the effect of vibration towards the human brain. This evaluation is non-trivial as prolonged exposure of vibration has reported affecting human health [1, 14, 15]. The proposed linear model consists of lumped masses, m_i connected with springs, k_i and dampers, c_i that represents the mass of body parts, joints and muscles of the human body. Table 1 shows the lists of human biodynamic model parameters of the proposed 12 DOF model.

Figure 2 shows the two in-wheel electric car that used in this study. Number of sensors, namely encoders as well as accelerometers are placed at different locations on the vehicle. These sensors are used to record the rotational velocity of each tire and to measure the yaw rate as well as the vehicle's velocity at its center. Conversely, a phone IMU sensor is used to log the resultant data of the vehicle when travelling at different velocity. This compact electric vehicle velocity is limited to up to 20 km/h due to safety reasons and stability constraint of the vehicle. The vehicle parameters are used in the Simulink model as the vehicle model that is coupled with the 12 DOF human model. The non-linear vehicle model with the combination of both the lateral and longitudinal effect is used in this study as the weight shift is considered. Major forces acting on vehicle are generated by the forces and moments from the road through the tires of the vehicle.

The vehicle tire receives major forces and moments that acts on the vehicle. As the properties of tires are deformable, Dugoff's model (Eqs. 1–7) is employed as it considers the tire stiffness as independent values for both lateral and longitudinal directions. Thus, the forces acting on each tire can be determined independently and be used as the vibrational input on the 12 DOF human model. Besides that, this model is developed from force balance equation, which is analytically derived.

The longitudinal (F_x) and lateral (F_y) force equation are given as below

Table 1 12 DOF human biodynamic model parameter [5, 13]

Model	Mass (kg)	Damping (Ns/m)	Stiffness (N/m)
12 DOF	$m_1 = 27.174$, $m_2 = 5.906$ $m_3 = 0.454$, $m_4 = 13.626$ $m_5 = 32.697$, $m_6 = 5.470$ $m_7 = 5.297$, $m_8 = 2.002$ $m_9 = 4.806$, $m_{10} = 1.084$ $m_{11} = 3.500$, $m_{12} = 1.500$	$c_1 = 37.8$, $c_2 = 29.8$ $c_3 = 29.8$, $c_4 = 29.8$ $c_5 = 365.1$, $c_6 = 365.1$ $c_7 = 365.1$, $c_8 = 365.1$ $c_9 = 365.1$, $c_{10} = 365.1$ $c_{11} = 1\,800\,000.0$ $c_{12} = 156\,000.0$ $c_{59} = 365.1$	$k_1 = 2550.0$, $k_2 = 89.41$ $k_3 = 89.41$, $k_4 = 89.41$ $k_5 = 5364.0$, $k_6 = 6885.0$ $k_7 = 6885.0$, $k_8 = 5364.0$ $k_9 = 5364.0$, $k_{10} = 5364.0$ $k_{11} = 450.0$, $k_{12} = 340.0$ $k_{59} = 5364.0$

Fig. 2 Two in-wheel electric car

$$F_x = C_\sigma \frac{\rho}{1+\rho} f(\lambda) \tag{1}$$

$$F_y = C_\sigma \frac{\tan\alpha}{1+\rho} f(\lambda) \tag{2}$$

where ρ is tire slip ratio λ is given by

$$\lambda = \frac{\mu F_z(1+\rho)}{2\left[(C_\sigma \rho)^2 + (C_\alpha \tan(\alpha))^2\right]^{1/2}} \tag{3}$$

And

$$f(\lambda) = (2-\lambda)\lambda \quad \text{if } \lambda < 1 \tag{4}$$

$$f(\lambda) = 1 \quad \text{if } \lambda < 1 \tag{5}$$

where μ is the tire-road friction coefficient and F_z is the vertical force that are affected by the load transfer that acting on the tire. The value of μ is determined from Eqs. (6) and (7)

$$\mu = -1.05k[\exp(-45\rho) - \exp(-0.45\rho)], \quad \text{driving} \tag{6}$$

$$\mu = 1.1k[\exp(35\rho) - \exp(0.35\rho)], \quad \text{braking} \tag{7}$$

where k is the road constant.

Figure 3 illustrates the mass distribution and forces that act on the vehicle as well as the load transfer. The normal forces, F_z that acting on the vehicle is used as the vibration input on the human biodynamic model. The total mass of the vehicle is divided into two segments namely, m_r and m_f both for front and rear, respectively.

From the figure above, Eqs. (8)–(11) are used to determine the vehicle mass shift both in lateral and longitudinal acceleration of vehicle direction. This equation is the combination of vertical tire loads for static vehicle, longitudinal load transfer and load transfer during cornering since the cornering of the vehicle is being considered.

$$F_{zfl} = mg\frac{l_r}{l} + \frac{m_f a_y h_c}{l_w} - ma_x\frac{h_c}{l} \tag{8}$$

$$F_{zfr} = mg\frac{l_r}{l} - \frac{m_f a_y h_c}{l_w} - ma_x\frac{h_c}{l} \tag{9}$$

$$F_{zrr} = mg\frac{l_r}{l} + \frac{m_f a_y h_c}{l_w} + ma_x\frac{h_c}{l} \tag{10}$$

$$F_{zrl} = mg\frac{l_r}{l} - \frac{m_f a_y h_c}{l_w} + ma_x\frac{h_c}{l} \tag{11}$$

where $l = l_f + l_r$, $l_f = 0.53$ m, $l_r = 0.62$ m, $g = 9.81$ m/s^2, $m_r = 163.1$ kg, $m_f = 159$ kg, $l_w = 1.43$ m and $h_c = 0.105$ m.

The schematic of human–vehicle model shown in Fig. 4. This model combines both 12 DOF human biodynamic model with two in-wheel vehicle model to perform human–vehicle model. Tire deflection or tire stiffness [9] is added as to normalize the error present in the vehicle model before the normal forces, F_z acting on the tire used as the input on 12 DOF human biodynamic model. The simulation of this model was carried out by using MATLAB Simulink commercial software package, as shown in Fig. 5.

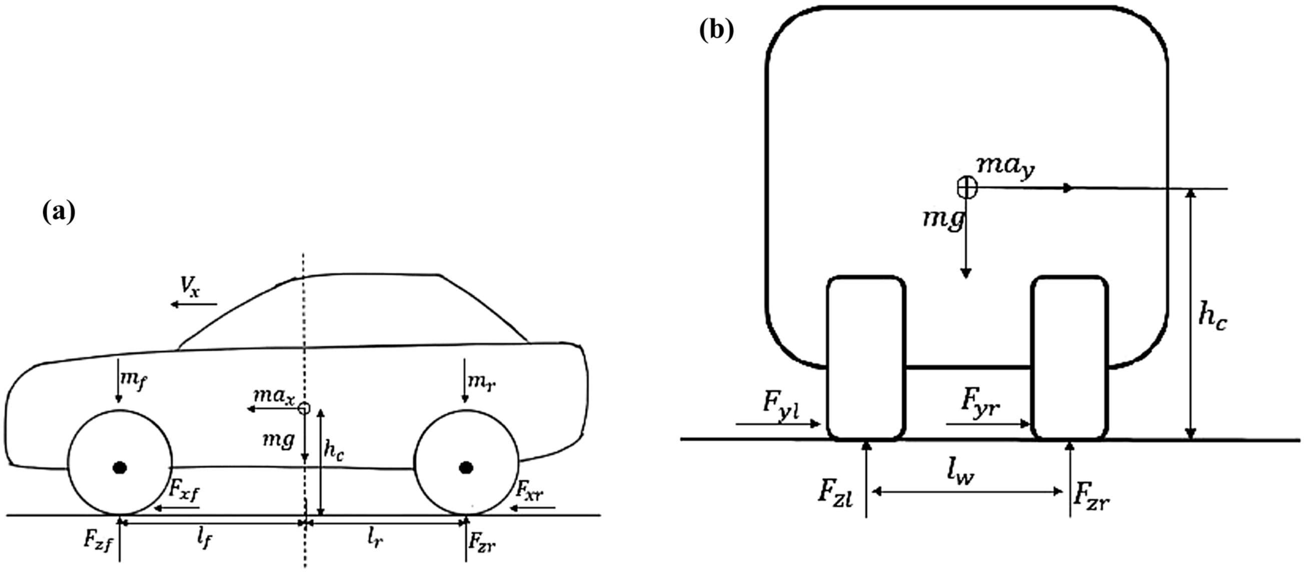

Fig. 3 **a** Mass distribution and forces acting on vehicle model, **b** load transfer on the vehicle model [12]

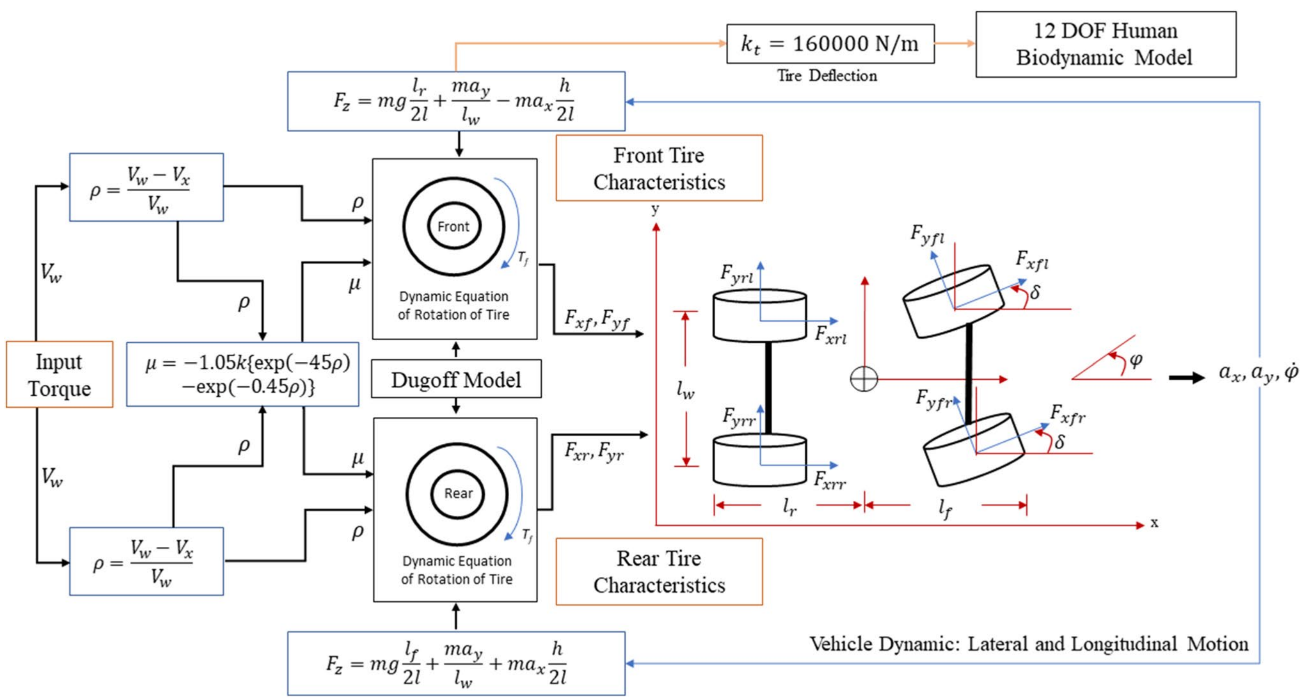

Fig. 4 Schematic of human–vehicle model

3 Result and discussion

From the human–vehicle model, Fig. 6 shows the wheel steering input and heading of the vehicle used in as an input in the model. Several steering inputs are used to observe the behaviour of the vehicle while travelling on different road profile manoeuver. Two road profile are used with different angle of steering input mimics the behavior of vehicle while cornering to the right and cornering to the left.

Figures 7 and 8 show the normal force, F_z that acting on each tire at rear and front of the vehicle based on steering input of road 1 and 2. When the cornering

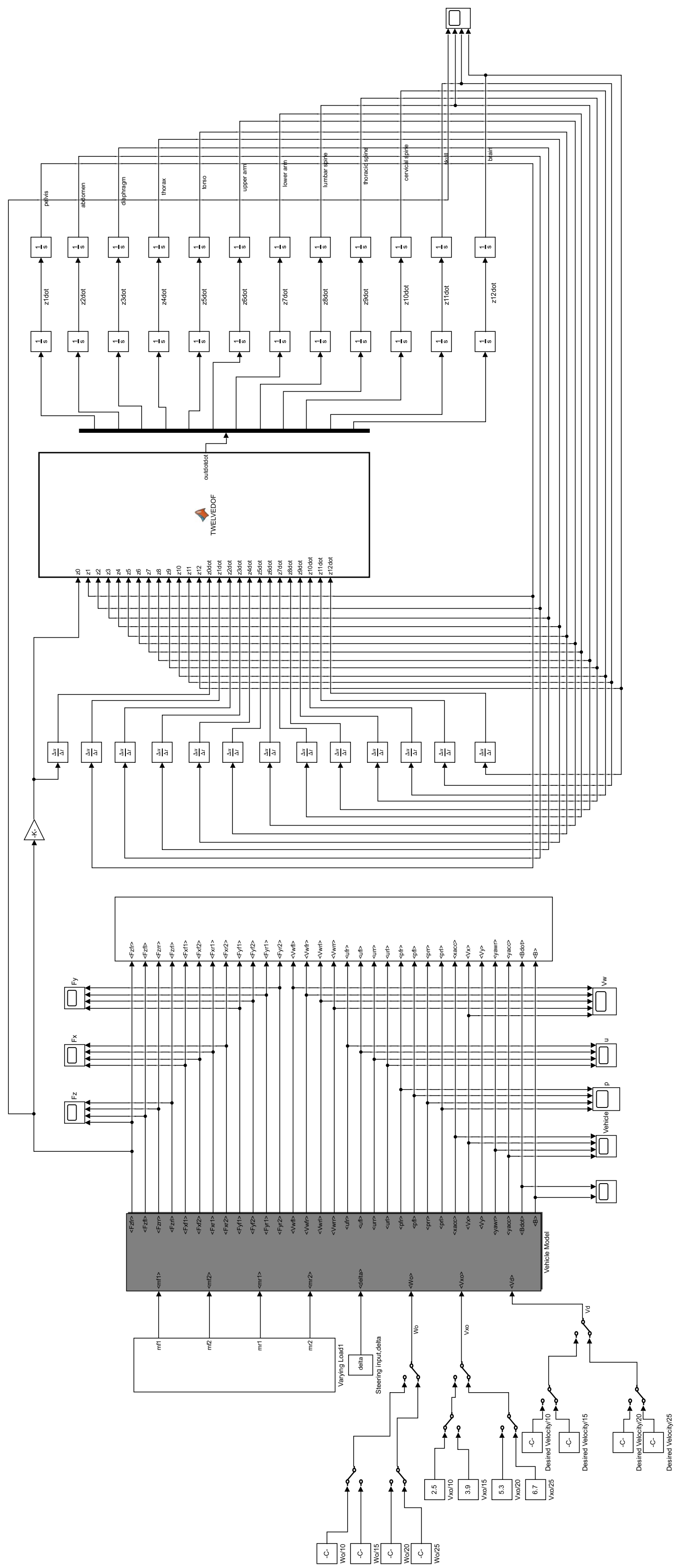

Fig. 5 Human–vehicle model environment in MATLAB Simulink

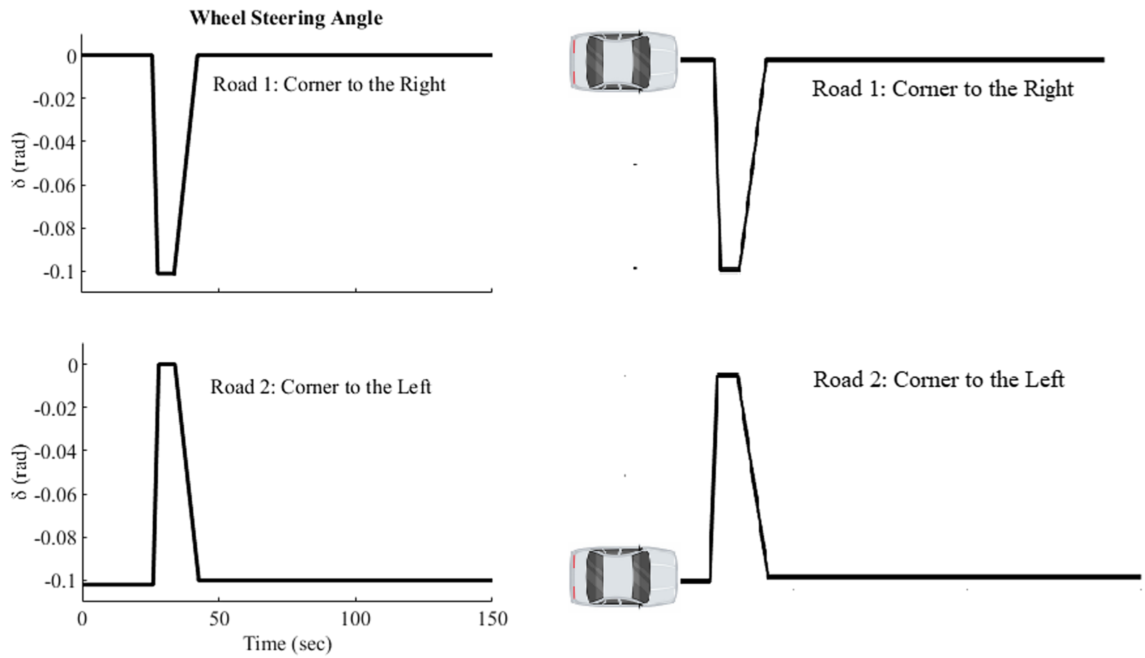

Fig. 6 Wheel steering input

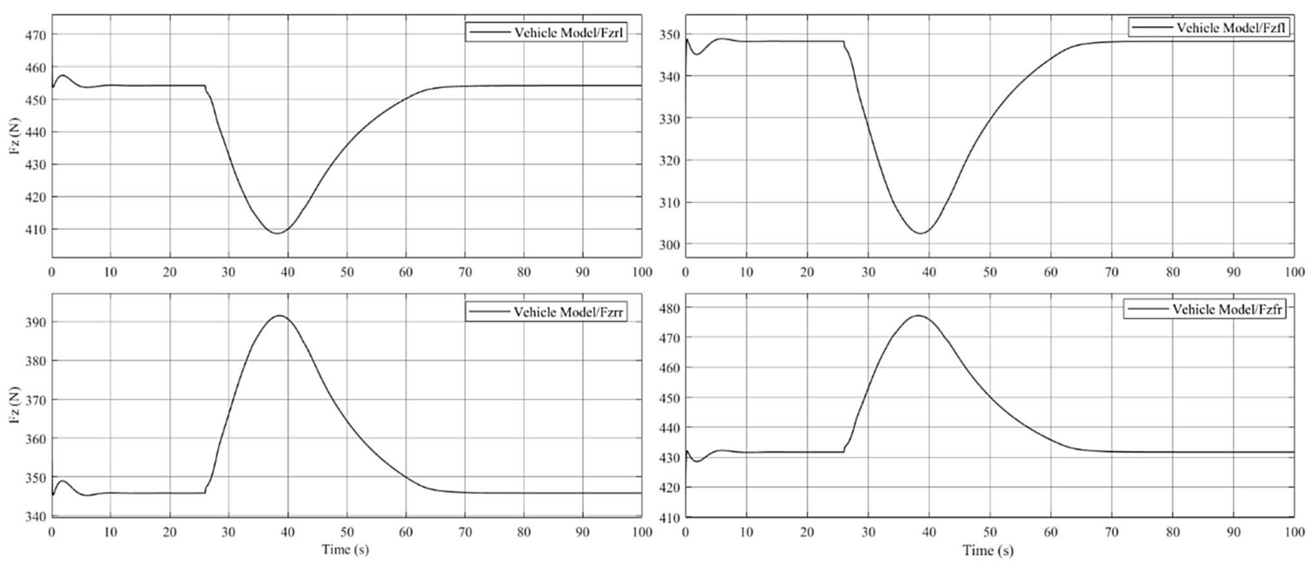

Fig. 7 Normal force, F_z that acting on each tire at rear and front of the vehicle based on steering input of road 1

mode was activated, rear and front tire shows different results as the forces moves based on the direction of the vehicle. The normal forces are changed according to the input of steering applied. Correspondingly, Figs. 9 and 10 show the result on the displacement response on human biodynamic model based on different road profile manoeuver. Displacement output from F_{zfr} of vehicle model were taken as the input for biodynamic model. This is due to the location of the driver that seat at the front right of the vehicle (right-hand drive).

The displacement of human body parts depends on the forces exerted on it. This observation is evident as shown in Figs. 9 and 10 where the displacement of skull and brain are based on the steering input. High excitation of displacement on the earlier part between 0 and 10 s is due to the vehicle movement from zero acceleration before

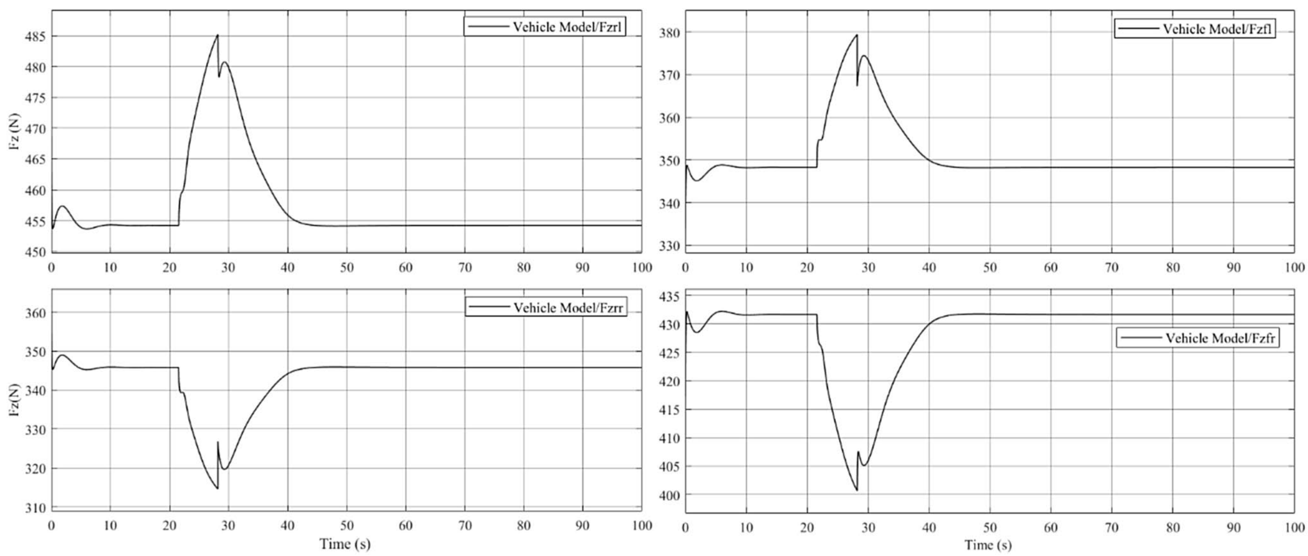

Fig. 8 Normal force, F_z that acting on each tire at rear and front of the vehicle based on steering input of road 2

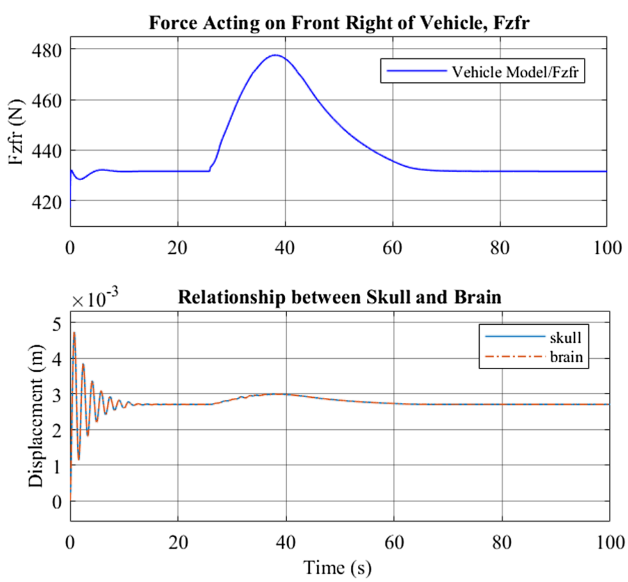

Fig. 9 Human–vehicle model result based on road 1 steering input

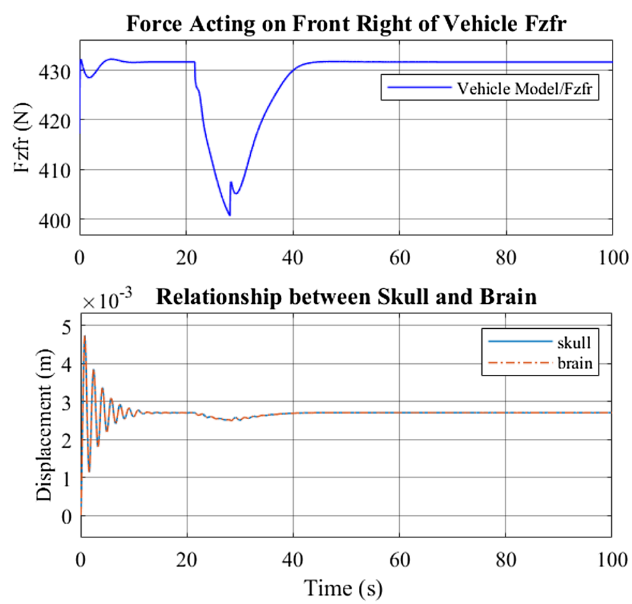

Fig. 10 Human–vehicle model result based on road 2 steering input

it comes to constant speed. The relationship between human biodynamic and vehicle model is apparent when force exerted on the vehicle when moving as shown in Fig. 11. It could be seen that the brain is displaced against the skull, suggesting that an impact or collision does transpire, albeit small. Nonetheless, it is noteworthy to mention, that such prolonged exposure could be detrimental. A study by Taha et al. [13], suggests that that the skull and brain collides due to phase difference, and such impact.

From the preliminary investigation, it could be established that the forces arising from different road profile conditions of a moving vehicle do affect parts of the human body to a certain extent. Although the value of displacement is small, nonetheless, upon prolonged exposure, it could pose detrimental effect towards the driver as well as the passengers [10, 15].

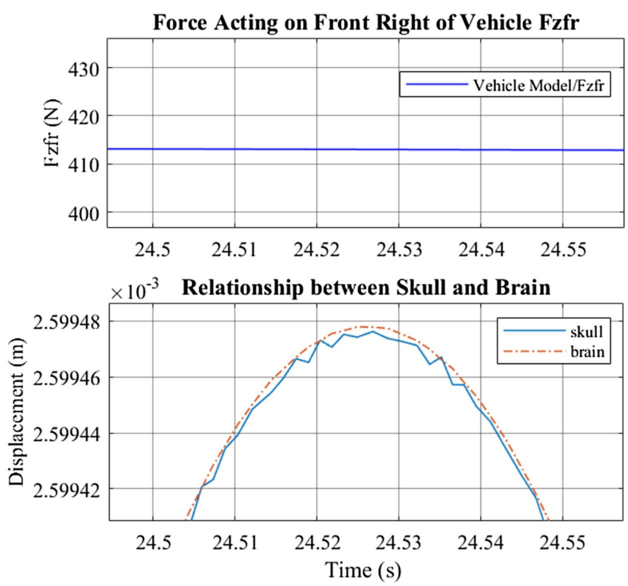

Fig. 11 Skull and brain displacement when force acting on F_{zfr}

4 Conclusion

In conclusion, the forces that acting of the vehicle tire does affect the parts of the human body to a certain extent when the vehicle is moving. This may reduce the comfort level of human while travelling at a prolonged duration which, in turn, could also affect human health in the long term. Further study on the effect of vertical vibration towards the human body due to the normal forces acting on different tires of the vehicle shall be investigated. Also the frequencies generated by the forces, shall also be scrutinized to observe, if the natural frequencies of the body parts or organs coincides as prolonged exposure could have an adverse effect on one's health.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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