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The Effect of Bumper Dimensions and Car Speed on Neck and Lower Back Forces

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Abstract: Vehicle vibrations significantly affect the health and comfort of the driver and passengers. The aim of this study is to analyze the effects of vertical vehicle vibrations caused by speed bumpers on the driver's lower back and neck in terms of forces. To achieve this goal, a human biodynamic model with 11 degrees of freedom was included in a half vehicle model with 5 degrees of freedom. This composite human vehicle model was subjected to half-sinusoidal shaped bumps of different sizes (heights and widths) and with different vehicle speeds. The equations of motion of the system were solved using MATLAB (R2021a) to find the forces acting on the lower back and neck joint. In this article, besides commenting on the speed of the cars passing through the bumps, the effect of the bumps on the driver's lower back and neck was tried to be deduced in terms of forces. The results are presented visually and comparatively in graphs. At the end of the article, it was concluded that the mentioned speed bumps should be designed considering human comfort and health. In addition, in biomechanical studies examining human-vehicle-road interaction, it was emphasized that the parameter values of the human body should be determined more realistically.

Keywords: Vehicle Vibration, Lower Back Pain, Neck Pain, Half Car, Human Vibration Model, Speed Bump

1. Introduction

The need for drivers to experience better driving comfort and safety in vehicles has recently become a concern and priority in the automotive industry. While the vehicle is being driven, vibrations arising from the roughness of the road and the vehicle's engine are transferred to the human body through every area that comes into contact with the vehicle, especially the seat. This type of vibration affecting the whole body is called whole body vibration [1]. Numerous studies have been conducted over the years to reduce the impact of vehicle vibrations on drivers [2–4]. These studies mostly focus on optimization of suspension parameters [5–7], new seat designs [8, 9] and different control strategies [10, 11].

Three different vehicle models are used in control systems, namely, the quarter car model, the half car model and the full car model. Quarter car models only take into account vertical vibrational motion without considering the roll and roll motion of the chassis and wheel. Generally, the left side and right side of the vehicles are symmetrical, so the physical model of the vehicle can be customized as a half-car model. Rather than a quarter-car system, the half-car model can express both vertical and inclined displacements of the vehicle. A complete model of a vehicle can be modeled with seven degrees of freedom. There are studies in the literature that can be done with the full vehicle model [12]. Considering the ease of application, it is seen that the half vehicle model, which includes vertical and tilt movements of the vehicle, is used in many applications [13, 14].

During the travel, human body tissues may be subject to mechanical damage due to vibration energy and the disruptive effects of the road. The effect of mechanical damage on the human body is mainly related to the frequency, magnitude and exposure time of the vibration [11]. Vibrations affecting the human body primarily affect the parts of the body that are connected by joints (arms, legs, head, spinal cord, etc.) not working properly. As a result, diseases such as joint pain, low back pain, occupational diseases and nervous system disorders occur [13]. Therefore, it is an important issue to comprehensively investigate the effect of vibration on the human body. In most of the studies in the literature, the evaluation of mechanical vibration effects on the human body has been made according to International Standard ISO 2631 and British Standard BS 6841 [10].

It may cause waist and neck injuries as a result of the transmission of the vibration caused by the vehicle and the disturbing effects of the road through the pelvis of the drivers and passengers sitting on the seats to their bodies. Long-distance drivers with lower acceleration levels of vibrations can cause injury to the waist and neck joint in people such as drivers passing speed bumps in short distances [2, 15–17]. In addition, since heavy equipment vehicles such as agriculture, construction, military and mining are operated on rough terrain, back and neck pain may occur as drivers using these vehicles are exposed to stronger vibration stimulation [16, 18–20]. A better understanding of the risk factors for these joints can provide important information about the prevention and management of this condition. In order to fully investigate the dynamic response of the lumbar and neck joints, the human body has been considered as a complex mechanical system in which different masses are interconnected by springs and damping elements. Simulation work with such mechanical models is simple and can avoid real experimental work with ethically regulated people [11].

It has developed various methods to reduce the undesirable consequences of speed for sensitive road users, especially on urban roads. Some of these methods are electronic detectors, warning signs and speed bumps. As a result of being easy and economical to apply, speed bumps are frequently preferred around the world. Speed bumps are named as speed bumper, speed humper, speed table and speed cushions according to their size and cross-sectional geometry. Due to the constant cross-section throughout the width of the road, humper and bumper decelerators are frequently preferred worldwide. However, the drivers in the vehicles may be adversely affected while passing over these speed breakers. Back and neck problems are at the forefront of the negative effects on drivers [2, 15, 21–23].

In this study, a model of a half car with its seat was built together with a human body model, and the effect of speed bumps used on highways on whole body vibrations and especially on human lower back and neck joints was investigated.

In the second part of this study, half car modeling and driver biomechanical model approaches are mentioned. Again, in this section, modeling of velocity hump profiles that cause forces in the waist and neck region of the study is presented. In the third part, simulation studies are given. Finally, the study was concluded by evaluating the results.

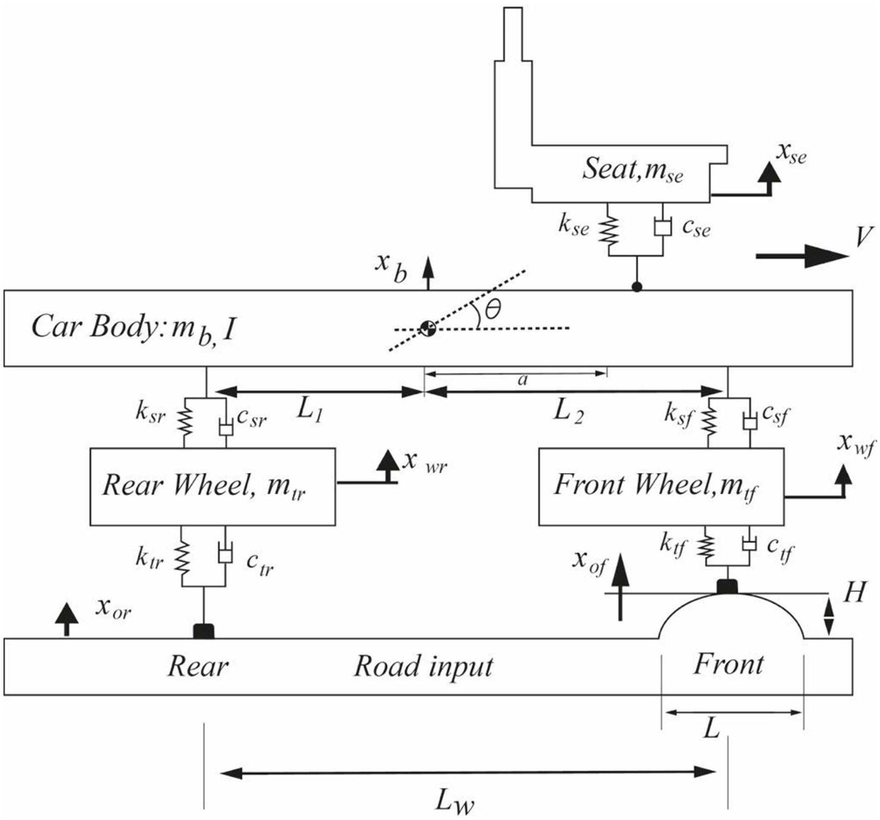

Figure 1. Half car model used in physical model [5].

2. Model

2.1. Half car Model

The physical system under investigation here considers the driver, the driver's seat, and the half-car model together. The physical model is considered as a mechanical system consisting of springs, segment masses and shock absorbers. As shown in Figure 1, the half car has 5 degrees of freedom with the driver's seat. In this way, the vertical displacement of the vehicle center of mass (x_b), the center of mass rotation axis (θ), the displacement of the center of mass of the front wheel system (x_{wf}), the displacement of the center of mass of the rear wheel system (x_{wr}), and finally the displacement of the center of mass of the seat replacement (x_{se}) can be determined. A car traveling along a straight road with a constant velocity (V) is considered to encounter a speed bump as shown in the figure.

The suspension system of the vehicle and the tires on the vehicle are modeled as linear spring and damper elements. In addition, the model assumes that the tires always remain in contact with the road surface. All parameters of the half vehicle model with five degrees of freedom including the driver's seat are taken from Abbas et al. [5] and their values are given in Table 1. During modeling, the small angle approach was applied, assuming that the movement of the vehicle body in the pitch direction moves at small angles.

Table 1. *Parameter values of half car and driver's seat [5].*

Parameter	Symbol	Value
Front tire stiffness (N/m)	k_{tf}	155
Rear tire stiffness (N/m)	k_{tr}	900
Front axle masses (Kg)	m_{wf}	28.58
Rear axle masses (Kg)	m_{wr}	54.3
Linear front and rear suspension damping Coefficients (Ns/m)	c_{sf}, c_{sr}	1828
Front and rear tire damping Coefficients (Ns/m)	c_{tf}, c_{tr}	0
Front and rear suspension stiffness (N/m)	k_{sf}, k_{sr}	15
Distance between the center of gravity and front axle (m)	L_1	1.098
Distance between the center of gravity and rear axle (m)	L_2	1.468
Distance between the center of gravity and seat (m)	a	0.7
Body mass (Kg)	m_b	505.1
Body mass moment of inertia (Kgm^2)	I	651
Seat mass (Kg)	m_{se}	35
Seat damping Coefficients (Ns/m)	c_{se}	150
Seat suspension stiffness (N/m)	k_{se}	15

2.2. Biomechanical Model

Some models have been introduced in the literature to represent the biodynamic properties of the human body. In these physical models, the human body was considered as masses representing different body parts connected by springs and shock absorbers [9, 24–26]. The biomechanical model of the driver used in this study has 11 degrees of freedom as seen in Figure 2. As seen in the model, the human back is divided into neck, thoracic spine and lumbar spine with the same spring and damping coefficients [24]. The displacement of the centers of mass of the human body parts is given as ($z_1, z_2, z_3, \ldots, z_{11}$). In addition, the masses of the sections of the model ($m_1, m_2, m_3, \ldots, m_{11}$), spring constants ($k_1$, k_2, k_3, …, k_{11}, k_{54} and k_{59}) and damping constants (c_1, c_2, c_3, …, c_{11}, c_{54} and c_{59}) and the parameter values of this model are presented in Table 2.

Table 2. *Biomechanical Model Parameters of the Driver [24].*

Mass (Kg)		Damping Coefficients (Ns/m)		Stiffness (N/m)	
m_{11}	5.445	c_{11}	3581.6	k_{11}	52621.0
m_{10}	1.084	c_{10}	3581.6	k_{10}	52621.0
m_9	4.806	c_9	3581.6	k_9	52621.0
m_8	2.002	c_8	3581.6	k_8	52621.0
m_7	5.297	c_7	3581.6	k_7	67542.0
m_6	5.470	c_6	3581.6	k_6	67542.0
m_5	32.697	c_{59}	3581.6	k_{54}	52621.0
		c_{54}	292.3	k_{59}	877.0
m_4	1.362	c_4	292.3	k_4	877.0
m_3	0.454	c_3	292.3	k_3	877.0
m_2	5.906	c_2	292.3	k_2	877.0
m_1	27.23	c_1	370.8	k_1	25016.0

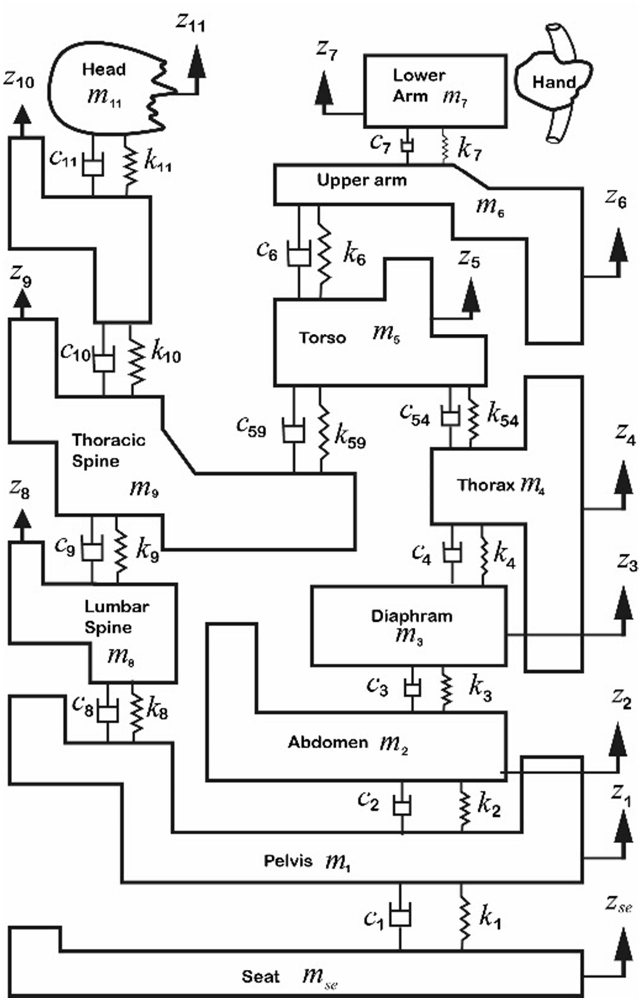

Figure 2. *Biomechanical Model of the Driver [24].*

Qassem et al [24] proposed a model in which they could express vibrations in both horizontal and vertical directions in their original model. In the literature, especially vertical model suggestions have attracted attention and have been the subject of some researches. In this article, only vertical vibrations are considered [9].

The most important aspect of this model proposal is that it offers the possibility to predict the forces acting on both the neck and the lumbar, as well as the vibrational interactions of the internal organs. Based on these calculations, predictions can be made about neck and low back pain in long-distance driving.

2.3. Mathematical Model

The mathematical model of the vehicle and driver system, whose physical model is explained above, is obtained using the Newton-Euler formulation. Since all masses except the car mass are expressed in point mass, it is sufficient to use Newton's second law of motion as

$$\sum F_{z,i} = m_i \ddot{z}_i \quad (1)$$

However, since the car body is modeled as a rigid body,

$$\sum M_G = I_G \ddot{\theta} \quad (2)$$

Thus, the mathematical expressions obtained are 16 second-order linear ordinary differential equations with constant coefficients. These equations are expressed in the form of state spaces as

$$\dot{\mathrm{x}} = \mathrm{Ax} + \mathrm{Bu} \quad (3)$$

$$\mathrm{y} = \mathrm{Cx} + \mathrm{Du} \quad (4)$$

where, matrices A, B, C, and D denote the system, input, output, and feedforward matrices, respectively. The x, u, and y vectors represent the state, input, and output vectors, respectively.

The matrix A is a 32×32 matrix, since the essence of the subject is to express 16 second-order differential equations with 32 first-order differential equations.

The input that disturbs the system is the sinusoidal road profile. Therefore, it can be considered as two disturbance to the system when the front and rear wheels, respectively, passes through a bumper at certain intervals. In this sense, the input matrix B is a 32×2 matrix.

2.4. Modeling of the Velocity Bump Profile

Depending on the road profile, the dynamic effects of the lower back and neck joints can be analyzed by the body acceleration of the driver and passengers in the vehicle. In this study, in the modeling study for the vehicle passing over a bump, the disturbing inputs coming from the ground are expressed as (x_{of}) for the front wheel and (x_{or}) for the rear wheel. These inputs are defined as system input elements due to the convenience of working in the state space equation. Figure 3 shows the velocity bump profile used in the study. The L in the figure indicates the curvature length, and the H denotes the curvature height.

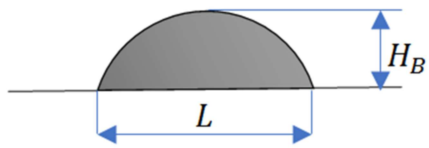

Figure 3. *Speed Bumper Profile.*

The road profile is modeled as a half-sinusoidal curvature and given with

$$x_{of} = H_B \sin(\omega t) \quad (5)$$

$$x_{or} = H_B \sin(\omega t + \tau) \quad (6)$$

where ω is the circular frequency (rad/s) of the path and is expressed as $\pi V/L$. There is also a time difference between the front and rear wheels, calculated with $\tau = L_w/v$.

The vector denoted by y here is optional as it is the output (in a sense solution) vector. Whatever is required from the system as a solution, such as the load on neck or lumbar of the head, can be expressed with this vector and its dimensions can be adjusted accordingly.

For the force generated in between head and neck.

$$F_N = k_{11}(z_{11} - z_{10}) + c_{11}(\dot{z}_{11} - \dot{z}_{10}) \quad (7)$$

and the force in between lumbar and pelvis.

$$F_L = k_8(z_8 - z_1) + c_8(\dot{z}_8 - \dot{z}_1) \quad (8)$$

can be written.

3. Simulation Results

The equations of motion of the system are simulated by using MATLAB (R2021a). Linear simulations (*lsim*) were carried out with the ready to use commands available in MATLAB.

While computing the forces, the speed of the car was kept constant at $v = 10$ m/s and the bump height was taken as $H_B = 3.5\,cm$ and the bump width was $L = 50\,cm$. Simulatied forces acting on both the neck and lumbar under these conditions are presented in Figures 4 and 5.

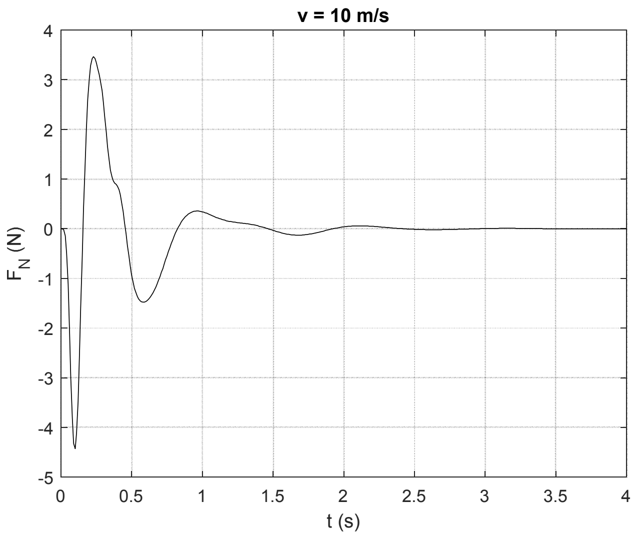

Figure 4. *Force generated on the neck for a constant speed.*

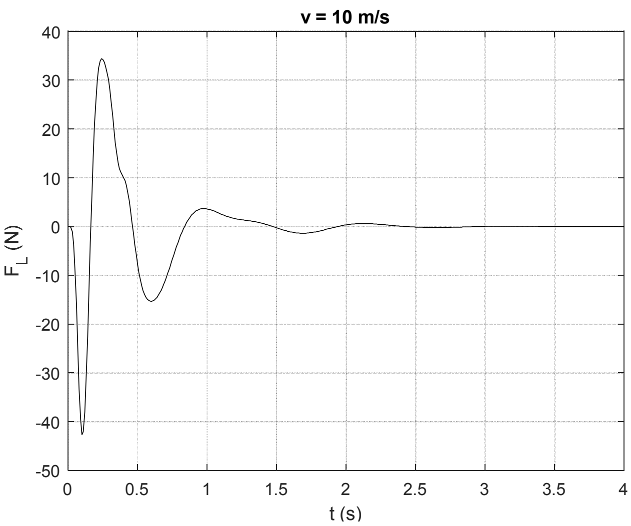

Figure 5. *Force generated on the lumbar for a constant speed.*

The forces acting on the neck and lumbar while the car is passing through the bumper are also calculated according to the changing car speeds and the maximums of the computed forces are given in Figure 6. The point that draws attention in the graph is that these maximum forces decrease as the car speed increases. This is because the damping forces in the model are considered proportional to the speed of segments ($F_d = cv$). The increase in the relative speed between the segments results in an increase in the damping force.

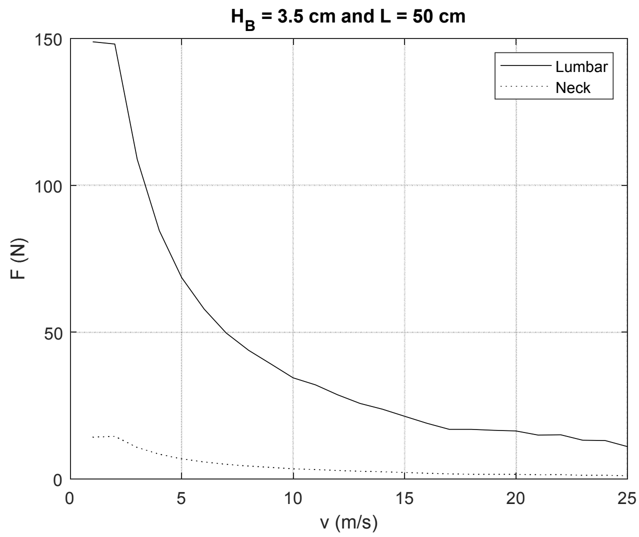

Figure 6. *Loads effecting neck and lumbar with changing car speed.*

The loads acting on the neck and lower back are computed for different bumper sizes. While keeping the car speed constant at 10 m/s, the calculations were repeated by changing the bump width between 10 cm and 100 cm and the bump height between 1 cm and 10 cm. The results obtained are presented in two different graphs for neck and lumbar loads (Figures 7 and 8).

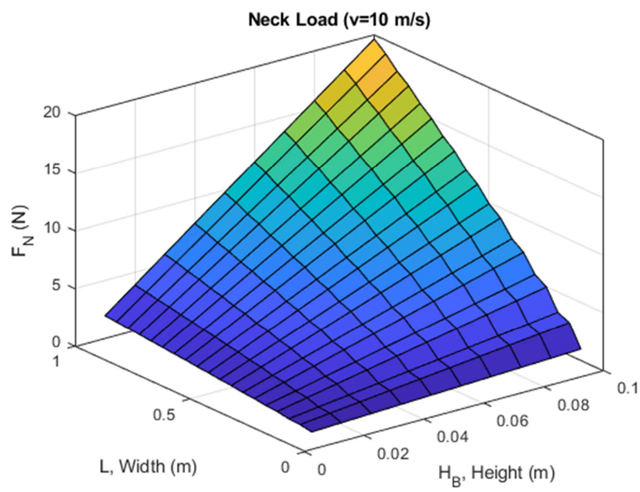

Figure 7. *Neck load for changing bumper dimensions (v = 10 m/s).*

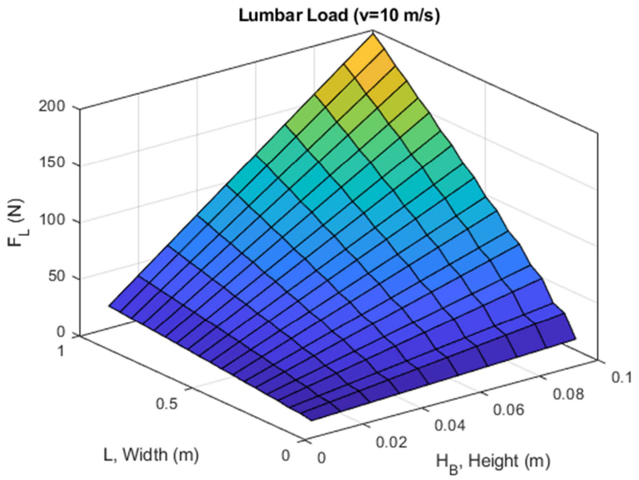

Figure 8. *Lumbar load for changing bumper dimensions (v = 10 m/s).*

4. Discussion

In this study, a half car with its seat and a driver on it are modeled. The model is a mechanical model consisting of a mass-spring-shock absorber. Simulations were made at different car speeds and different bump sizes, and the results were presented in the form of graphics.

First, the forces on the neck and waist were calculated by keeping the car speed and bump dimensions constant. Then, the simulations were repeated by changing the car speed and bump dimensions.

It has been observed that the forces acting on the neck and lumbar decrease depending on the increasing car speed. This is thought to be caused by modeling the damping force proportional to the velocity between the segments. Accordingly, it can be predicted that keeping the speed of the car around 30 km/h while passing through bumps is favorable for human health, but higher speeds will damage the mechanical parts of the car in particular and may have an impact on the passengers and the driver.

In the analyzes, it was also investigated how the forces acting on the neck and lumbar changed with the size of the bumper and it was observed that these forces increased with both the bumper height and the bumper width.

5. Conclusion

It should be noted that these results are calculated over the parameter values given for the biomechanical model of the car and human body in the literature. Therefore, the presented results are dependent on the car and human body biomechanical model parameters.

These used parameters of the human body mostly consist of values taken from cadavers. This does not fully reflect the real situation. Therefore, it is thought for a future study that these parameters should be obtained from the data obtained from the real system and noninvasively.

This study would also shed light on some other future studies. For example, it may be a favorable research to design a bump or suspension system so as not to cause neck and low back pain.

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