Experimental and Numerical Study on Ergonomic Evaluation of Automotive Seating Comfort

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Abstract. Automotive car seats play a vital role in providing optimum comfort to the occupants when it comes to vehicle comfort. The objective of this study was to perform an experimental and numerical investigation of the ergonomic evaluation of automotive seating comfort. A questionnaire survey was carried out on car drivers driving two different cars namely Tata Indica and Maruti Swift, to understand the perception of drivers on seating comfort. Posture monitoring techniques using Kinect camera and pressure mapping systems were used to analyze the sitting posture and sitting angle. A multibody dynamics analysis technique was used to evaluate the human body exposed to vehicle vibration. The vertical vibration transmissibility was measured from different body segments using this model. Also, with the help of a multibody dynamics simulation model, the results were compared and validated with existing literature. This study suggests suitable sitting posture and sitting angle derived with the help of multibody dynamics simulation along with the experimental investigation, which would reduce the fatigue of the driver when exposed to prolonged driving.

Keywords: Seating comfort, Multibody dynamics, Vibration transmissibility, Fatigue, Prolonged driving, Kinect technology, Pressure distribution mapping.

1. Introduction
Globally automobile industries are growing fast, and comfort is the main approach of customers. One of the most important elements for comfort is the car seat since the human body is directly in contact with the seat and exposes to vibrations coming from the base to the top [1]. One of the methods to measure vibrations is to check transmissibility from the base to the human body through seat [2].

The interest to purchase vehicle is associated with various consumer specifications such as performance, mileage, safety, luxury, comfort and cost. These specifications vary based on the subjective perception of the customer. The seat and car manufacturers commonly highlight safety and seating comfort, to attract a larger number of customers and thereby beat the tough competition. As it is important to consider the safety of the occupants, the car manufacturers give extra care to the seats and sitting postures segment. The seating comfort is highly correlated to vehicle vibration due to varying road conditions, sitting postures, vehicle conditions, and so on [3]. Figure 1 shows the sitting postures (correct and bad) of the driver during driving. It is seen that each class of vehicle has a
different seating position according to the specific cabin design and dimensions. The number of vehicles on the road is increasing drastically every day. The number of light commercial vehicles (LCVs) is rather higher than heavy commercial vehicles (HCVs). Therefore the LCVs are considered for the research. It is seen that each class of vehicle has a different seating position according to the specific cabin design and dimensions. The number of vehicles on the road is increasing drastically every day. The number of light commercial vehicles (LCVs) is rather higher than heavy commercial vehicles (HCVs). Therefore the LCVs are considered for the research.

![Figure 1](image) Sitting postures of driver in a car while driving.

The constant vibration, induced by vehicle structure due to traveling in different road conditions at different speeds is seen as a major factor for discomfort to the occupants in the car. These external vibrations are transmitted to occupants through the vehicle seat structure. Many studies show that the human body reaction to vehicle seat vibrations varies depending on the dynamic performance of the seat structure as well as the characteristics of the human body. Several studies have shown that the human body discomfort is significantly influenced by vibrations in frequencies of 0.5–80 Hz. Also, the resonance frequencies for the unoccupied and occupied vehicle seat structures lie mainly in the frequency range of 10–60 Hz [4]. It can be amplified depending on the frequency function of the combined human body and seat. Hence, it is essential to study the relationship between the vehicle seat and the occupant body at frequencies where the human body is highly susceptible to vibration since the dynamic characteristics of occupants are also highly susceptible to the seat structural dynamic responses. But the difficulty in analyzing the dynamics behaviour of the occupied seat is primarily due to the presence of non-linearity and the complex coupling between the seat of the vehicle and the human body.

The multibody dynamics is one of the reliable numerical modeling methods which can be used for analyzing the comfort of the seat and driver. The multibody dynamics simulation model is used to evaluate the effects of deformations in the rigid and flexible bodies with high computational efficiency. Therefore, for this research, the multibody dynamics model is used to simulate the effects on the seat and the occupants in real time conditions.

Kumbhar et al. [5, 6] proposed three-seat model hard seat, seat with cushion, seat with cushion, and base suspension. After numerical analysis for transmissibility between the car seat and human body, they concluded that optimizing cushion material and base suspension stiffness and damping coefficients can increase seating comfort. Kim et al. [7] established a human body sitting posture model for assessing the vibration transmissibility on head and apparent mass on vertical vibrations. For this, they tested various eight models and selected the best-suited model after putting experimental data.

Automobile seat plays an important role in any vehicle as it deals with the comfort and safety of the occupant during a long journey as it imposes a lot of physical and mental stress upon the driver; which would result in fatigue of the driver and gradually an accident. The exposure to vibration during prolonged driving in an automobile is associated with seating discomfort, increased prevalence of low back pain, and other musculoskeletal disorders [8]. This can be avoided by using a better seat model. In recent days, the preference of the customer is increased towards comfort. Since the field tests for assessing seating comfort with participants are time-consuming, the laboratory static and motion simulators can be utilized with suitable medical and ethical precautions. Computer based simulation models can also be used to assess human–seat interface.
Considering these issues faced by the occupant, the research focuses on determining the proper sitting postures and angles. The sitting posture and sitting angle were observed using Kinect technology and the pressure mapping system [9-10].

With regards to that, vibration analysis has to be done and frequency response function (FRF) is to be obtained by simulation software to find the induced vibration on the vehicle seat and the occupants. This has to be validated using an experimental setup consisting of a set of accelerometer pads fitted on different points of the seat. The above studies would provide enough data from which proper sitting postures and seating comfort are analyzed to reduce the fatigue induced on the driver due to prolonged driving.

2. Materials and Methods

2.1. Multibody Dynamics Analysis

Whole-body vibration in sitting posture on a car seat is taken up in this study. Since the human body is directly in contact with the car seat, vibrations are exposed from the seat to the human body. For this purpose, data from Kumbhar et al. [5, 6] and Kim et al. [6] were used which is based on experimental measurements and by using these data we run vibration analysis using multibody dynamics simulation software MSC ADAMS for the seat to body vibration transmissibility. For this study, vibration analysis is performed for three car seat models: hard seat, seat with a cushion but no seat suspension, and seat with cushion and base suspension. Assumptions include, all model parts are assumed as rigid bodies and their flexibility is defined through stiffness and damping coefficients. In the car seat, backrest support transfers a large amount of vibrations to the human body, so it is considered at an angle of 230° with a vertical plane. The biomechanical properties of the human body segments and car models are taken from Kumbhar et al. [5, 6]. The running condition of the vehicle is taken as ideal.

2.1.1 Hard Seat

In Figure 2, a human model is seated on a hard seat. The seat cushion and backrest cushion are also ignored in this model. There is nothing in this seat to protect the human body from vibrations. Thus, all vibrations are exposed to the human body directly [11]. The system (human model coupled with the seat model has 14 degrees of freedom) receives feedback directly from the floor.

2.1.2 Seat with a Cushion but No Seat Suspension

A human model is seated on a seat with cushion without suspension (Figure 3). In this case, any vibrations, as a consequence of cushion stiffness, are isolated. The stiffness of each cushion is extremely non-linear. Nevertheless, for convenience, they are assumed to be linear, in this study. With regard to its contact surface, each cushion has one horizontal motion and one vertical motion. The total number of degrees of freedom in this model is 18.

2.1.3 Seat with Cushion and Base Suspension

Figure 4 shows a human model placed on a seat with cushion, and suspension. Using such links, which serve as seat suspension, the seat is attached to the vehicle body floor. This seat has one horizontal and one vertical movement for which the vehicle body floor receives input. Thus, given the seat’s two degrees of freedom, the cushions’ two degrees of freedom, and the human model’s 14 degrees of freedom, the total number of degrees of freedom in this model is 20.
2.2. Vibration Analysis

Vibration analysis is used to measure transmissibility from the vehicle floor to various human parts. The multibody dynamics simulation software MSC ADAMS was used to perform vibration analysis on three car seat models to get transmissibility magnitude and frequency. The seat parameters can be optimized with the maximum magnitude of transmissibility and its frequency to reduce discomfort [12, 13].
2.3. Questionnaire Survey

This questionnaire survey was conducted to estimate the driver discomfort in a different kind of passenger car driver seat and to describe the nature of sitting discomfort. The specifications of the seat have been chosen using anthropometric data such as thigh and buttocks, and seat design standards like seat length, seat width, etc. [14].

| Table 1. Anthropometric data of the participant. |
|-------------------------------------------------|
| Variable                                    | Range          | Mean             |
|                                              | Tata Indica Car | Maruti Swift Car |
|                                              | Tata Indica Car | Maruti Swift Car |
| Age (Years)                                 | 26 - 55        | 22 - 60          |
| BMI (kg/m²)                                 | 18.14 - 25.95  | 20.07 - 27.92    |
| Height (m)                                  | 1.66 - 1.70    | 1.60 - 1.75      |
| Weight (kg)                                 | 50 - 75        | 55 - 80          |

In this study, the brief subjective method of evaluating the driver’s seat discomfort questionnaire is designed to cover all the major parameters on it. The survey was taken from 100 males, each professional passenger’s car drivers in Chennai city. All the participants are from the Tata Indica and Maruti Swift car drivers alone. Table 1 shows anthropometric data obtained from the participants. The seats of Indica and Swift are shown in Figure 5. The participants were categorized into four groups based on their age groups. Group 1 consists of drivers whose age lies in between 26-30 years; Group 2 consists of drivers whose age lies in between 31-35 years; Group 3 consists of drivers whose age lies in between 36-40 years; and Group 4 consists of drivers whose age lies in between 41-55 years.

Cronbach’s alpha test is used to measure the internal consistency (reliability) of the questionnaire. In this questionnaire survey, the design is validated to be reliable with Cronbach Alpha score. (Cronbach's alpha > 0.070 is significant).

The scale selection is foremost important in any subjective method of evaluation. Based on that only the responses to be collected and analyzed. In this study, a 5 point Likert scale is used in this questionnaire survey. The driver’s seat is to rate as [negative]-2 to +2 [positive] (Table 2).
Figure 5. Seat of Indica car (Left) and Swift car (Right).

Table 2. Scale to measure seating comfort.

| Discomfort | Little Discomfort | Neutral | Little Comfort | Comfort |
|------------|-------------------|---------|----------------|---------|
| -2         | -1                | 0       | +1             | +2      |

2.4. Pressure Mapping System

The force sensitive resistor pressure sensor is used in this study (Figure 6). The sensors are arranged in a form of a 4x4 matrix (i.e., 16 sensors in all). They are joined with an Arduino Board and it is programmed and calibrated in such a way that with appropriate force, an appropriate reading is observed. Two different driver seats of Tata Indica and Maruti Swift were acquired for the study. Both seats are of cars that are extensively used in the range of commercial cars and by major Taxi aggregators, such as OLA and UBER.

Figure 6. Pressure mapping system using force sensitive resistor pressure sensors.
In this pressure sensing system, the participants were asked to position themselves just above the seat having their back rested in a relaxed position. Before having them seated in the position, the arrangements of the apparatus had been done and they were asked to sit comfortably on the seat as prescribed with their hands resting on their laps. Ultimate care was taken so that the apparatuses were not moved while positioning the participants over the mat and throughout the whole reading procedure. No obstructions such as a wallet or a mobile phone are allowed to be kept on the buttock region while seated on the seat. Then the participant was asked to sit and then multiple reading was taken and recorded for less error and higher chances of convergence. The participants were asked to sit on the seat for about 30-40 seconds about 5 times. As the readings were a voluminous form of data, it was carefully settled down by taking an average at a particular instance. A total of 5 participants were considered for the study of different BMI ratings.

2.5. Kinect Sensor - Skeletal Mapping System
The Kinect is an RGB-D sensor providing skeletal mapping images with synchronized color and depth. This system uses IR camera that takes reading in the form of recordings and the snapshots of the recording are taken. A Kinect used here is in the virtue of obtaining the skeletal map of a body, and through it, can be obtained the stress levels that are exerted by the body after prolonged driving/sitting in a particular position [10]. The participants can use their arms at a distance, range of 1.2 m to 3.5 m.

As soon as the participant gets in front of the camera, the camera starts detecting the participant. The Kinect takes readings in the form of camera recordings and snapshots of the recording are taken. The angles of the participants are measured manually by KLONK image measuring software. All these processes are carried out by asking the participant to position on rigid car seats. These images of the skeletal tracked body were then used to find the sitting posture of those participants while driving the automobile. The participants were the only participants in the vicinity of the Kinect so that there are no miscalculations by the device. The entire process was conducted for approximately 60 seconds. Angles involving the lumbar region and the knees region were manually found out using KLONK Image measuring software.

3. Results and Discussion
Figure 7 shows the vibration analysis results of transmissibility for all body part segments from the hard seat model. Results show graphs for transmissibility magnitude versus frequency. We can obtain peak transmissibility value with its respective frequency from these results. For the hard seat model, where no vibration isolation happens, vibrations are transferred to the body directly through feet and seat contact with the body. Results show frequencies for all body segments are between 4 to 10 Hz. Figure 8 shows the vibration analysis results of transmissibility for all body part segment from the seat with a cushion but no base suspension. In the case of the second model, where only cushions are provided, vibrations isolated through cushions are not transferred to body parts directly. So frequency and magnitude are decreased as compared to the hard seat model. Results show transfer function frequencies for all body parts are approximately 2 to 3 Hz. The vibration analysis results of transmissibility for all body part segment from the seat with cushion and base suspension is depicted in Figure 9. In this model, where cushions and base suspension have been provided, vibrations are isolated through cushions and base suspension and are not transferred to body parts directly. So frequency and magnitude are decreased as compared to the hard seat model. Results show transfer function frequency for all body parts is approximately 2 Hz. Table 3 shows multibody dynamics simulation results for all three car seat models compared to results obtained from Kumbhar et al. [5]. The comparison for transmissibility magnitude and their respective frequencies are compared for three models; frequency values are approximately same and have some differences in transmissibility.
Table 3. Validation of results of the three car seat models.

| Car Seat Model | Body Segment | Proposed Multibody Dynamics Simulation Model | Results from Kumbhar et al. [5] |
|----------------|--------------|---------------------------------------------|---------------------------------|
|                |              | Transmissibility Magnitude | Frequency (Hz) | Transmissibility Magnitude | Frequency (Hz) |
| Hard seat      | Thigh        | 1                           | 1.85             | 1.1                          | 2.5             |
|                | Hip          | 1.59                        | 5                | 1.5                          | 5.2             |
|                | Back         | 1.7                         | 5.1              | 1.15                         | 5.2             |
|                | Head         | 1.58                        | 5                | 1.2                          | 5.2             |
|                | Viscera      | 3.6                         | 5.97             | 2.9                          | 5.7             |
| Seat with a cushion without suspension | Thigh | 1.62 | 3.07 | 1.35 | 3.45 |
|                | Hip          | 1.32                        | 2.08             | 1.1                          | 2               |
|                | Back         | 1.02                        | 2.09             | 1.53                         | 2               |
|                | Head         | 1.02                        | 3.07             | 1.24                         | 2.8             |
|                | Viscera      | 1.68                        | 3.08             | 1.36                         | 2.78            |
| Seat with cushion and base suspension | Thigh | 1.46 | 1.85 | 1.2  | 2.2  |
|                | Hip          | 1.9                         | 2                | 1.25                         | 2.2             |
|                | Back         | 1.6                         | 2                | 1.2                          | 2.2             |
|                | Head         | 1.53                        | 2                | 1.2                          | 2.2             |
|                | Viscera      | 2.35                        | 2                | 1.7                          | 2.2             |

Table 4. Comfort Scores of Head, Lumbar, Backrest, and Overall for Tata Indica and Maruti Swift.

| Age Group (Years) | Car          | Comfort Score |
|-------------------|--------------|---------------|
|                   |   | Head | Lumbar | Backrest | Overall |
| 26-30             | Tata Indica | -0.3235 | -0.4412 | -0.625 | -0.8137 |
|                   | Maruti Swift | 0.1256 | 0.0272 | -0.1033 | 0.1014 |
| 31-35             | Tata Indica | -0.3547 | -0.4231 | -0.5385 | -0.8846 |
|                   | Maruti Swift | 0.1634 | 0.0735 | -0.1618 | -0.0239 |
| 36-40             | Tata Indica | -0.2731 | -0.5021 | -0.6508 | -0.8583 |
|                   | Maruti Swift | 0.1471 | 0.0478 | -0.1407 | -0.0392 |
| 41-55             | Tata Indica | -0.1589 | -0.1641 | -0.3047 | -0.6667 |
|                   | Maruti Swift | 0.1068 | 0.0197 | -0.1038 | -0.0405 |
Figure 7. Transmissibility results for hard seat.

Figure 8. Transmissibility results for the seat with a cushion but no suspension.

Figure 9. Transmissibility results for the seat with cushion and base suspension.

From the survey study, it can be seen that the comfort level of the Tata Indica seats was much lower compared to that of Maruti Swift seats. Figure 10 shows the relation between two seats with their respective comfort scores of different age groups. Table 4 shows the comfort levels of different seat segments concerning the different age groups. It is seen that the comfort levels of Tata Indica lack behind the comfort levels of the Maruti Swift for all age groups. The pressure mapping system gives the contour images of the seat pressure distribution obtained from Tata Indica and Maruti Swift cars. The contour images are taken for each seat on the following categories: Underweight participants; Healthy participants; and Over-weight participants (Figure 11).
The final result that is obtained is that the buttock region has been stressed the most as corroborated with the study investigated by Rosaria et al. [15]. Also, a flexible back angle should be given to reduce the stress exerted by the participant. Moreover, there is no padding or support for the calves of the legs and the stress can be reduced if the padding supports the calves’ region of the driver. All these lead to a conclusion that the comfort of the driver doesn’t depend on a single parameter but multiple factors. The stresses in the buttock regions can be obviated by designing the seat appropriately and with proper material. Three participants (underweight participant, healthy participant, and over-weight participant) were made to sit on both the seats, and data were captured using the Kinect sensor – skeletal mapping system (Figure 12). The Kinect camera helps to find the angle that is made by all body parts of a participant driving the car. This method proved to enable us to
find the optimal angle and where a body is strained the most and thus, posture can be improved. The result obtained by the Kinect camera is very close to the benchmark except for the hip joint angle and torso angle because all the procedure is carried out on a rigid car seat.

Figure 12. Skeletal image of participant captured using the Kinect camera system. (a) Underweight participant, (b) Healthy participant, and (c) Over-weight participant. (Blue – Tata Indica and Green – Maruti Swift).

4. Conclusion
In this study, the experimental and numerical investigation of human-car seating models was carried out and validated. The study reveals that by changing model parameters like spring stiffness, damping coefficients, and seat part masses, we can reduce vibration transmissibility can be reduced and thereby enhance more seating comfort. The pressure sensors produced accurate results of where is the most stressed part of the human body on the seat while the participant sits on it. It is seen that the buttock region has been stressed the most. The Kinect camera system helped to find the optimal angle and
where a body is strained the most and thus, sitting posture can be improved. The stress felt on the buttock region of the participant while seated can be obviated by designing the seat with suitable cushion material. Also with thus, the seats could be given a smart option to adjust the seats with small degrees, as per the driver’s requirement, manually or automatically.

5. References

[1] Fard M, Lo L, Subic A and Jazar R 2014 Effects of seat structural dynamics on current ride comfort criteria *Ergonomics*, 57(10), pp. 1549-1561.

[2] Lean Lo, Fard M, Subic A and Jazar R 2013 Structural dynamic characterization of a vehicle seat coupled with human occupant *Journal of Sound and Vibration*, 332(4), pp. 1141-1152.

[3] Tang A H, Tian J P and Liao Y H 2014 Analysis for ride comfort evaluation of passenger car traveling on roads with generalized road profiles and conventional speeds *Advanced Materials Research*, 926-930, Trans Tech Publications, Ltd., pp. 877-880.

[4] Mansfield N J (2005), *Human Response to Vibration*, First Edition, CRC Press, Florida, pp. 1-244.

[5] Kumbhar P, Xu P and Yang J 2013 Evaluation of human body response for different vehicle seats using a multibody biodynamic model *SAE Technical Paper*, 2013-01-0994, pp. 1-14.

[6] Kumbhar P, Li N, Xu P and Yang J 2014 Optimal seat dynamic parameters determination for minimizing virtual driver's fatigue *SAE Technical Paper*, 2014-01-0877, pp. 1-13.

[7] Kim T H, Kim Y T and Yoon Y S 2005 Development of a biomechanical model of the human body in a sitting posture with vibration transmissibility in the vertical direction *International Journal of Industrial Ergonomics*, 35(9), pp. 817-829.

[8] Jagannath M and Balasubramanian V 2014 Assessment of early onset of driver fatigue using multimodal fatigue measures in a static simulator *Applied Ergonomics*, 45(4), pp. 1140 – 1147.

[9] Paul S, Basu S and Nasipuri M 2015 Microsoft Kinect in gesture recognition: A short review *I J C T A*, International Science Press, 8(5), pp. 2071-2076

[10] Napolia A, Glass S, Ward C, Tucker C and Obeid I 2017 Performance analysis of a generalized motion capture system uses microsoft kinect 2.0 *Biomedical Signal Processing and Control*, 38, pp. 265-280.

[11] Wang X, Savonnet L, Theodorakos I, Beurier G and Duprey S 2019 Biomechanical human models for seating discomfort assessment In: S. Scataglini and G. Paul (Eds.) *DHM and Posturography*, Academic Press, pp. 643-656.

[12] Ittianuwat R, Fard M and Kato K 2014 The transmission of vibration at various locations on vehicle seat to seated occupant body. In: *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Melbourne, Australia, pp. 2062-2073.

[13] Toward M G R and Griffin M J 2011 The transmission of vertical vibration through seats: Influence of the characteristics of the human body *Journal of Sound and Vibration*, 330(26), pp. 6526–6543.

[14] Smith D R, Andrews D M and Wawrow P T 2006 Development and evaluation of the Automotive Seating Discomfort Questionnaire (ASDQ) *International Journal of Industrial Ergonomics*, 36(2), pp. 141-149.

[15] Rosaria C, Alessandro N and Chiara C 2020 Comfort seat design: Thermal sensitivity of human back and buttock *International Journal of Industrial Ergonomics*, 78, p. 102961.

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