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Driver Performance Analysis: Posture and Ergonomic Impact

Saed Talib Amer
Department of Management Science and Engineering
Faculty of Engineering
Khalifa University of Science and Technology, Abu Dhabi, UAE
Saed.amer@ku.ac.ae

Abdulrahman Saleh Al Hashmi
Department of Management Science and Engineering
Khalifa University of Science and Technology, Abu Dhabi, UAE
100056793@ku.ac.ae

Mariam Ali Abdulla Alhammadi
Department of Management Science and Engineering
Khalifa University of Science and Technology, Abu Dhabi, UAE
100050174@ku.ac.ae

Abstract

Driver posture and ergonomics play a critical role in ensuring safety, comfort, and long-term health sustainability for vehicle operators. Poor posture and fatigue significantly impair reaction times, increasing accident risks. This study investigates postural deviations, fatigue effects on reaction time, and ergonomic validation to mitigate these risks. Driver posture health was assessed using video-based observation, manual data collection, and ergonomic benchmarking following ISO 2631 and SAE J826 standards. Results indicate that fatigue directly correlates with postural misalignment, leading to forward head tilt, lumbar strain, and cognitive fatigue. Manual posture assessments and seating ergonomics evaluations were identified as critical factors in reducing discomfort and enhancing driver performance. Findings show the necessity for real-time posture tracking in order to boost safety and productivity in driving. Additional research should explore the design of the vehicle seating to provide ergonomics improvements to posture correction as well as fatigue reduction.

Keywords
Driver ergonomics, Posture monitoring, Fatigue impact, Reaction time, Vehicle seating standards

1. Introduction
It is a fact of daily life that many people take for granted: driving. However, the effects of driving on musculoskeletal health and cognitive function in the long run are typically neglected. Knowledge of poor driver posture as a well-documented risk factor for the creation of spinal stress, which leads to muscle fatigue and joint discomfort (Kent et al., 2024) makes it an ideal candidate for an educational intervention. Proper seating is an essential factor that helps prevent lower back pain, neck stiffness, and cognitive fatigue, more so for professionals who drive for long hours

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(Rahman et al., 2025). With these risks, driver posture is not only a matter of comfort but also a major safety factor in relation to road and accident prevention.

Relevance to Biomechanics and Ergonomics

From the biomechanical point of view, prolonged sitting in a constrained position changes spinal alignment, lumbar support and postural stability. The results of the studies indicate that driving for long periods causes lumbar compression along with such postural alterations as increased forward tilt and decreased postural endurance (Rahman et al., 2025). Fatigue-related discomfort is produced by these factors, as such it negatively affects decision-making and reaction speed. The physical manifestation of fatigue does not include only feelings of fatigue but also disrupts the driver's ability to cognitively process information accurately (Mahomed & Saha, 2024). These ergonomic risks accumulate over time and may increase the probability of traffic incidents, especially among long-haul drivers and those who work under stressful conditions.

Fatigue, Cognitive Decline, and Safety Risks

Driven by the large quantitative amount of relevant literature, fatigue is a well-documented risk factor in driving safety and is implicated in thousands of road accidents every year (Mahomed & Saha 2024). As alertness declines, reaction speed increases, and delayed breaking, poor lane control, and inattentional lapses occur. It also mentioned that chronic poor posture advances the onset of fatigue, frequently exacerbates cognitive impairment, and delays drivers' responses (Kent et al., 2024). Existing vehicle design places more focus on the mechanics of safety, and these are real-time ergonomic adjustments that ease driving and make drivers both tired and error-prone. This highlights the need for ergonomic seating solutions and real-time posture awareness, which can contribute to improving driver safety.

Lack of Real-Time Posture Monitoring

While such automotive safety has been advanced, most vehicles still do not have proactive posture correction mechanisms. Seat adjustments and lumbar supports are still present but require manual configuration, and there are no dynamic responses to fatigue-inducing forces (Suzuki et al., 2024). Real-time posture monitoring remains limited, as most vehicles lack dynamic seating adjustments or proactive ergonomic feedback mechanisms to support proper spinal alignment and some other seating postures during the travels. For example, these systems fuse seat pressure sensors and steering wheel sensors, and they indicate pressure on the pedals to assess postural deviations, fatigue levels, and discomfort level indicators.

1.1 Objectives

This study aims to evaluate the effects of prolonged driving on driver posture stability, fatigue accumulation, and reaction time deterioration. Specifically, it investigates how driver posture changes over time, how fatigue impacts postural deviations, and how these changes align with existing ergonomic standards such as ISO 2631 and SAE J826. The study utilizes video-based posture tracking and manual data collection to assess deviations in head tilt, lumbar support pressure, and reaction time delays. Findings will contribute to improving ergonomic seating recommendations and identifying posture correction strategies that reduce fatigue-induced risks in drivers.

2. Literature Review

Driving is a repetitive, physically demanding activity that involves the orchestration of a number of biomechanical principles. Long sitting leads to postural strain and ergonomic issues. Long-term combination of bad posture and poor seat design leads to discomfort, and/or muscle fatigue, and even chronic musculoskeletal disorders. Recently, there has been an increasing focus in research on driver ergonomics and the relationship between posture, fatigue, and cognitive load, and because of this, research has taken on technology to address comfort and risk of safety (Suzuki et al., 2024). New methods for real-time deviations in postural stability and the effects of fatigue have been brought on by advances in biomechanical analysis and video-based posture monitoring. For example, to design the vehicle and also for ergonomic standards for long-term drive well-being and performance, these factors have to be understood.

2.1 Overview of Driver Ergonomics Research

There has been much research on driver ergonomics aimed at preventing muscle fatigue and lower back strain due to the role of seat design and lumbar support. Ergonomically optimized seats with adjustable lumbar support and contoured cushions not only help with discomfort but aid in one's spinal alignment and reduce the time taken for fatigue onset (Suzuki et al., 2024).

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Nevertheless, traditional vehicle seats, which do not offer dynamic pressure distribution, tend not to balance postures and produce excess muscle stiffness. Research shows that unseatedness is a cause of spinal compression, increases risks of lower back pain, and leads to work-related musculoskeletal disorders (Rahman et al., 2025). Postural deviations also have cognitive consequences. Prolonged improper posture increases cognitive load, slows reaction times, and reduces situational awareness, all of which impair decision-making and driving safety (Mahomed & Saha, 2024). Given these risks, modern ergonomic interventions increasingly incorporate pressure distribution mapping, vibration reduction, and posture-responsive adjustments to mitigate discomfort and improve long-term spinal health.

2.2 Posture Measurement in Vehicles

These manual posture assessment methods have been widely explored to monitor seat posture deviations and fatigue markers. In this system, video recordings and manual posture analysis are used to assess driver posture, muscle strain, and pressure distribution (Mahomed & Saha, 2024). True to modern AI-based systems, the physical status of the driver remains constantly changing and dynamic lumbar support, seat repositioning, and automated fatigue alerts are provided.

PERCLOS (percentage of eye closure over time) is one of the most widely used fatigue detection methodologies in driver posture research and monitors eye blink duration and eyelid droop as clues for driver drowsiness and fatigue (Pi et al., 2024). Body weight distribution, seat occupancy, and micro-adjustments in posture are also monitored by pressure-sensitive seats, which are important for fatigue tracking. Pressure-sensitive systems detect a driver leaning forward too much, slumping, or putting weight in an unbalanced position and recommend that the driver correct his posture. Another innovative approach involves steering wheel sensors and pedal pressure tracking, which analyze grip force, hand tremors, and foot movement speed to assess fatigue-induced impairments in motor control. This multi-sensor integration allows vehicles to automatically identify early fatigue symptoms and provide real-time posture correction feedback (Mahomed & Saha, 2024). Despite these advancements, commercial adoption of AI-driven posture monitoring remains limited due to high implementation costs and technological integration challenges. However, with the increasing focus on ergonomic safety and AI-based driver assistance systems, future vehicle designs are expected to incorporate real-time posture monitoring as a standard feature, ensuring enhanced driver comfort and long-term musculoskeletal health.

2.3 Fatigue and Its Impact on Posture

Fatigue is a key factor in forcing variations in driver posture that result in involuntary movements, which tend to increase physical stress. The higher rates of drivers' slouching, leaning forward excessively, or tipping the head downward (Jang et al., 2024) when cognitive fatigue starts to influence their driving behavior is due to stress to the neck, shoulders, and lower back as a result of excessive leaning. Mental exhaustion studies show that as a person becomes more exhausted mentally, it becomes harder for drivers to maintain a stable and ergonomic posture, according to muscle coordination studies. Compensatory movements such as changing seat positions frequently or redistributing weight to help relieve pain are a natural body response to fatigue. However, these postural deviations usually worsen the strain of muscle rather than alleviate it.

Fatigue can have one of the most worrying effects on neck flexion and shoulder strain. The research shows that fatigued drivers tilt their heads forward much earlier than normal, which puts excessive pressure on cervical spine joints and trapezius muscles (Jang et al., 2024). However, this forward lean is especially devastating in the long haul, during extended periods of driving, as it subjects muscles to chronic fatigue and places poor stress on spinal alignment and a much higher threat of developing chronic pain conditions. Also, the musculoskeletal system gets more pronounced shoulder tension and upper body stiffness as it compensates for postural instability.

Fatigue also directly affects reaction time and capacity for decision-making states beyond the muscular strain. It has been proven that reaction time drops about 20–35% when drivers are enduring prolonged cognitive fatigue (Fei et al., 2025). This delay in response time can be explained by the fact that the brain takes longer to process external (environmental) stimuli, leading to a lack of situational awareness and motor coordination. Also, fatigued drivers are more likely to exhibit a delayed response to brake, poor maintenance of lane control, and greater speed regulation variability. These issues increase the risk of traffic accidents and roadside incidents, which urge the implementation of fatigue mitigation strategies that are particular to the ergonomic vehicle design.

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Another significant effect of fatigue is its role in altering natural seating posture. When alert and well-rested, drivers tend to maintain a neutral lumbar curve, distributing body weight evenly across the seat. However, as fatigue sets in, drivers tend to slouch, causing the spine to lose its natural curvature and leading to localized pressure build-up in the lower back. This shift in posture not only increases discomfort but also contributes to long-term spinal misalignment. In severe cases, prolonged fatigue-induced postural deviations can lead to disc herniation, nerve compression, and chronic lower back pain (Figure 1).

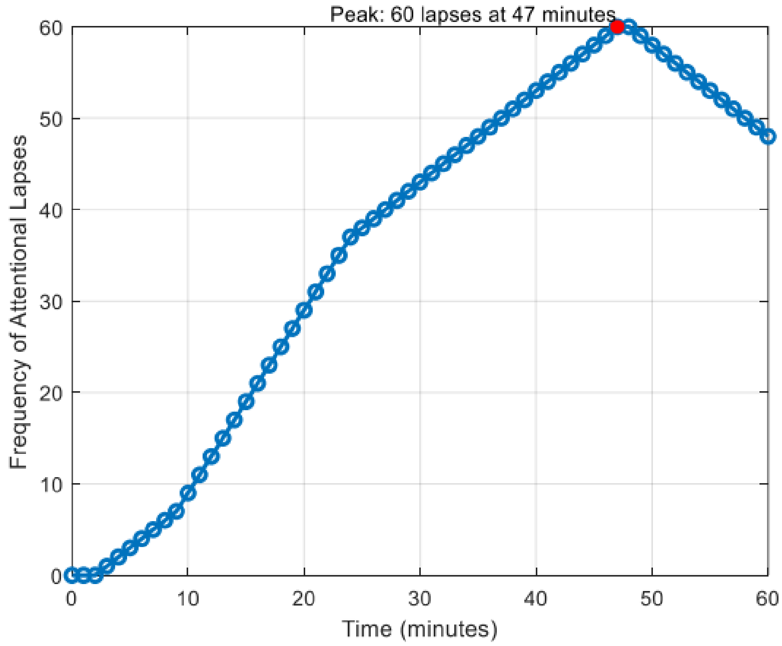

Figure 1. Attentional Lapses in Fatigued Drivers (Mahomed & Saha, 2024).

Figure 1 provides a clear visualization of fatigue's cognitive effects, specifically how attentional lapses accumulate over time. The data shows that attentional lapses start increasing sharply after 10 minutes of continuous driving, with a peak at 47 minutes, where drivers experience up to 60 lapses. This means that fatigue-induced distraction gets progressively worse, increasing driver propensity to delayed reactions and errors. However, according to the graph, when one reaches peak fatigue, attentional lapses remain high, indicating the importance of regular breaks and real-time monitoring of fatigue. These data strongly confirm the case for poor posture, loss of cognitive awareness and overall likelihood of driving safety as a direct result of fatigue.

2.4 Existing Standards for Driver Ergonomics

To ensure optimal driving posture and long-term comfort, ergonomic standards have been developed to assess seating design, postural support, and fatigue mitigation strategies. These standards provide guidelines for vehicle manufacturers to enhance seat ergonomics, vibration reduction, and body alignment optimization. The two most widely recognized standards in driver ergonomics are ISO 2631 and SAE J826, both of which address whole-body vibration impact and seating posture reference models (Kent & Butterworth, 2024; Suzuki et al., 2024).

The ISO 2631 standard relates to whole-body vibration (WBV) exposure and its association with driver posture and comfort. However, prolonged exposure to vehicle vibrations, in particular trucks, buses, or long-haul transport vehicles, has been associated with increased spinal strain, muscle fatigue, or postural discomfort (Kent & Butterworth, 2024). Vibration about the human body as well as acceptable limits of vibration exposure, is addressed in ISO 2631 with recommendations for seat design modifications to reduce vibration-induced fatigue. It has been shown that higher WBV levels lead to a faster presence of fatigue on the part of the driver, which eventually deteriorates the driver's posture and reduces reaction time. Such vehicle manufacturers can reduce the vibration-related fatigue effects by incorporating shock-absorbing seat materials, dynamic suspension systems, and optimized lumbar support following an application of ISO 2631 guidelines.

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Like the SAE J826 standard, the seating reference model developed in SAE J823 is used by vehicle manufacturers as a direct guide to the general shape of the seat and recommends the lumbar curvature for the driver to sit in as well as positioning of the driver (Suzuki et al., 2024). Using the J826 model, a baseline for seat height, seat depth, and incline is ensured, thereby optimizing the spinal alignment and protecting against musculoskeletal strain. Among the main features of SAE J826 is its lumbar support optimization framework aimed at the ideal curvature of the seat backs for supporting the natural S curve of the spine. Research has suggested that poor lumbar support contributes significantly to lower back pain and fatigue-related postural deviations. With J826 recommendations, vehicle manufacturers will be able to develop ergonomic superior seats, which will increase comfort, increase spinal stability and reduce postural shifts caused by fatigue.

Commercial vehicles, however, are still not well equipped to implement effective ergonomic solutions despite the existence of the standards. Many of the standard vehicle seats have inadequate lumbar support, dynamic adjustability and pressure-sensitive feedback. Luxury and high-end automotive brands have started the inclusion of Iso and Sae Adaptive Ergonomic Features, but the entirety of the industry is still not able to embrace the standard. The problem is that the cost of advanced seat adjustment technologies and AI-driven posture correction systems is still such a barrier to mass adoption.

However, the continued focus of research on driver safety through posture optimization makes it likely that in the future, vehicle designs will become more ISO 2631 and SAE J826 compliant. In extending driver comfort and reducing issues of fatigue-related risks, real posture monitoring, AI-driven seat adjustments, and vibration reduction mechanisms will be implemented. The rest of the challenge is to fill the gap between what we've already learned regarding ergonomics and practical, cost-effective implementation in mass vehicle manufacturing.

3. Methodology

3.1 Study Design & Participants

This study involved six drivers aged between 20 and 60 years, selected to represent different levels of driving experience. Participants were categorized as novice (0–2 years), intermediate (3–7 years), and experienced (8+ years) to assess variations in posture deviations and fatigue accumulation. These categories allow for a comprehensive analysis of how posture deviations and fatigue levels vary across skill levels.

Participants' height, weight, and vision type (normal vision or corrective glasses) were recorded, as these factors influence seating position, head tilt angles, and lumbar support requirements. Fatigue levels were assessed before and after the driving sessions using self-reported scales (1–10 discomfort ratings) and biometric fatigue indicators, including PERCLOS (Percentage of Eye Closure), reaction time delays, and muscle fatigue patterns.
All participants were on a standardized adjustable driving seat; with the initial posture meeting ergonomic seating guidelines (ISO 2631, SAE J826). By setting up this way, the postural shifts, the variations in reaction times and the accumulation of fatigue can be evaluated under control.

3.2 Driving Scenarios

Three separate driving scenarios were simulated to evaluate the effect that different driving conditions had on posture stability and fatigue:

1. **Highway Driving (Steady-State Conditions)**
   In the first scenario, 30 minutes of uninterrupted highway driving with maximum steering movements at a steady velocity was employed. It was possible to test the lumbar stress accumulation, spinal posture consistency, and the subtle onset of fatigue-related micro adjustments like forward head tilt and lower back strain under this scenario. It was found that the amount of passive posture shift is dictated by the amount of external driving demands.
2. **Urban Stop-and-Go Traffic**
   The second scenario created 20 minutes of urban driving with frequent acceleration, deceleration and braking cycles. In this setting, postural instability was introduced through rapid motion adjustments, putting stress on the neck, shoulders and lumbar region. To further understand the relationship between postural maintenance and reaction times and frequent braking and acceleration, induction of inertia by frequent braking and acceleration were analyzed. Finally, this scenario also allowed for the capture of how drivers try to compensate for the discomfort through involuntary postural shifts, which, if the fatigue-induced cognitive delays increased, might have already become a problem.

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3. **Curvy Road Navigation & Upper-Body Posture Adaptation**
   The third scenario included an assessment of the postural adaptation to the frequent turns and lateral forces in a 10-minute curvy road simulation. In this scenario, a continuous adjustment of the steering wheel and changing gravitational forces were evaluated, as well as changing shoulder, neck, and lumbar posture. As it is, it was particularly useful when investigating the strain that is placed on muscle coordination and spinal alignment while drivers navigate tight turns and uneven roadways. The data of stored posture deviation angles in this test was essential to understanding how external driving dynamics affect the time-varying postural stability.

Posture shifts and fatigue indicators were manually assessed through observational video analysis and self-reported discomfort levels. This approach provided insights into posture deterioration patterns without the use of automated tracking systems.

3.3 Posture Measurements

This study was conducted using video recordings and manual posture assessment to track driver posture deviations and fatigue-related shifts. In this study, video footage analysis was used to measure real-time deviations in neck flexion, head tilt angles, and shoulder positioning. They were able to collect data for adjustments of the posture that suggest a feeling of fatigue and spinal misalignment. Manual observation of lumbar posture and seating adjustments was conducted to track changes over time. They continuously monitored placement changes in the lower back, looking for forward lean. By analyzing recorded footage, we conducted a detailed assessment of postural stability and identified trends in fatigue-related postural deviations. This approach combined wearable sensors and seat pressure mapping to understand posture degradation over time fully. They collected the data and used it to compare varying levels of driver experience to determine the effectiveness of voluntary and involuntary postural adjustments.

3.4 Data Collection Process

Data was recorded at 5-minute intervals through manual video observation, providing a detailed overview of posture degradation trends. This was done by having each participant report his or her head tilt, lumbar pressure distribution, and upper body posture deviation in all three driving scenarios. The validated fatigue detection metric, PERCLOS (Percentage of Eye Closure), was applied to measure the degree of fatigue, which is the total duration of the eye closure per time. Continuous monitoring of PERCLOS values was conducted manually through video analysis, assessing the correlation between cognitive fatigue accumulation and postural deviations. Biometric measurements were complemented with drivers also self-reporting discomfort on a 1–10 scale, high muscular strain, spinal discomfort, or visual fatigue. These subjective reports were validated to validate the relationship that subjectively reported discomfort had with actual biomechanical stress levels.

During the study, data were synchronized in real time with fatigue indicators to look at the full picture of the combined effect of cognitive and musculoskeletal fatigue on driving performance. With this approach, the participants' postural stability could be directly compared with the ergonomic guidelines (ISO 2631, SAE J826) to see if they met established comfort and safety standards prior.

4. Data Collection

Accurate data collection is essential to analyze changes in driver posture over time, assess fatigue impact on postural stability, and compare ergonomic deviations with recommended standards. This section outlines the methodologies used for quantitative and qualitative data collection, including sensor-based tracking, PERCLOS fatigue monitoring, seat pressure analysis, and driver-reported discomfort levels.

4.1 Data Recording Methods

A structured data collection protocol was implemented across three driving conditions:

- Highway driving (steady-state conditions)
- Urban stop-and-go traffic
- Curvy road navigation

Data collection intervals: Measurements were recorded every 5 minutes, ensuring comprehensive tracking of posture shifts, fatigue accumulation, and discomfort levels. Both automated sensor-based tracking and manual driver feedback were used.

Posture Tracking Sensors

Driver postural data was gathered using:

- Video analysis to monitor forward head tilt and lateral deviations (Mahomed & Saha, 2024).
- Manual posture assessments to track movement deviations.
- Self-reported discomfort ratings to evaluate lumbar support shifts and weight distribution (St-Pierre et al., 2024).

Postural deviations were analyzed using video footage and expert manual assessments to detect fatigue-induced instability.

Fatigue Detection via PERCLOS Analysis

PERCLOS (Percentage of Eye Closure Over Time), is one of the widely recognized biometric fatigue indicators, and was used to assess fatigue levels. This metric is the fraction of time in which a driver's eyes are closed over some time and is directly correlated to cognitive fatigue and a driver's reduced alertness.

PERCLOS thresholds were classified as:

- <10% (Alert)
- 10%–20% (Moderate Fatigue)
- >25% (Severe Fatigue)

Drivers exceeding 20% PERCLOS typically displayed noticeable posture deterioration, including increased forward lean, lumbar pressure imbalances, and delayed reaction times.

Seat Pressure Mapping & Postural Deviations

To track lumbar and upper-body posture deviations, seat pressure mats recorded weight distribution shifts. Data was collected on:

- Lumbar support engagement (%)
- Seat pressure imbalance over time
- Forward head tilt progression (°) over 60 minutes

Self-Reported Discomfort Levels

Alongside sensor-based data, drivers provided self-reported discomfort scores on a 1–10 scale at every 10-minute interval. This allowed subjective discomfort perception to be compared with objective biometric and pressure data.

4.2 Summary of Data Collection Findings

The data collected revealed progressive posture deviations and fatigue accumulation, particularly after 30 minutes of continuous driving. The findings were summarized as follows in Table 1:

Table 1. Data Collection Findings

Parameter	Alert Drivers	Moderate Fatigue	Severe Fatigue
Forward Head Tilt (°)	5° – 10°	15° – 20°	25° – 30°
Lumbar Support Pressure (%)	90% – 100%	75% – 85%	55% – 70%
Reaction Time Delay (ms)	220 ms	280 ms	350 ms
PERCLOS Fatigue Score (%)	<10%	10% – 20%	25% – 35%
Posture Adjustments Per Hour	8 – 12	5 – 7	2 – 4

Fatigue, posture stability, cognitive response time, and lumbar support engagement are all illustrated in this table. Forward head tilt decreases around lumbar pressure as fatigue levels increase. Reaction times also grow by increasing fatigue. Salts, Strauss et al. (2001) concluded their study by stating that as fatigue increases, there is a higher risk of cognitive lapses and an increased chance of generating physical discomfort.

4.3 Data Validation & Reliability

To ensure the accuracy and reliability of collected data, the following validation strategies were implemented:

- Data from video recordings, manual posture tracking, and PERCLOS fatigue monitoring were cross-compared to ensure consistency in detecting fatigue-related postural deviations (Mahomed & Saha, 2024).
- Each driving scenario was repeated twice per driver to confirm consistency in posture deterioration trends.
- A baseline posture assessment was recorded before the session, and a post-session analysis was conducted to quantify cumulative posture deviations and fatigue effects.

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It was based on the assumption that the data are accurate measurements of postural condition and that the rate of progress in fatigue and ergonomics can be recommended based on their analysis.

5. Results and Discussion

The efficacy of both ergonomic safety and road performance is dependent on drivers' grasp of the effects of posture deviations and fatigue accumulation in drivers. This section finds how fatigue chronically affects posture, as well as weakening cognitive responses and long-term musculoskeletal distress. This discussion uses postural stability data to analyze fatigue-related changes, track changes in results with ISO 2631 and SAE J826 ergonomic standards, and highlight the principal physiological risks of these movements and possible intervention strategies.

The findings reveal a direct correlation between fatigue levels and posture deterioration, particularly in head tilt, lumbar support shifts, and reaction time delays. Analysis of video-recorded posture shifts provides insights into fatigue-induced impairments, allowing comparison with ergonomic guidelines to determine alignment with optimal safety measures. Furthermore, personal traits, including height, driving style, and prior musculoskeletal conditions, influence postural degradation and adaptive strategies. The study underscores the urgent need for improved ergonomic seat design and manual posture correction strategies to minimize fatigue-related risks and enhance long-term driver well-being by addressing these insights.

5.1 Numerical Results

Quantitative data collected from posture-tracking sensors and fatigue-monitoring systems show critical trends in how fatigue impairs postural stability. Results highlight the progressive changes in lumbar pressure distribution (LPD), head tilt angles, and behavioral changes in seat positioning with increasing driving time. A conservative and most significant trend that is noticed is the gradual forward head tilt as fatigue accumulates. Statistics reveal that an additional 15–25% forward head tilt occurs as drivers go 30 minutes without interruption (Fei et al., 2025). It leads to muscle stiffness of the cervical spine and shoulder strain, which puts additional stress on the cervical spine and reduces driving efficiency and reaction speed. A notable finding of another distribution is the lumbar pressure distribution. Seat pressure data reveals that dividing the weight between legs becomes uneven beyond 40 minutes of driving and at this point, postural stability and driver comfort are negatively impacted by it. But this instability means that sitting posture is constantly micro-adjusted to keep it in place, paradoxically creating more discomfort and not helping. Increases in lower back discomfort reports of 40% are due to lumbar support pressures less than 70% of optimal alignment, indicating the need for long-duration driving seat adjustment mechanisms.

Postural deviation monitoring through PERCLOS assessments also shows the impact of a PERCLOS score >15% with the reduction in posture correction attempts (e.g., 20%) as compared to the drivers with a PERCLOS score < 15% (Rahman et al., 2025). In so doing, this suggests that as fatigue levels increase, drivers are less likely to change their seating position proactively, making matters worse as fatigue affects muscular strain and cognitive impairments.

5.2 Graphical Results

The driver's posture is progressively affected by fatigue, which results in higher postural deviations, longer reaction times, and less stability of spinal support. Graphical trend analysis that describes how fatigue accumulation changes driver posture as time goes by is presented in this section. Data visualization gives evidence of head tilt angles; posture changes in different driving conditions, and seat pressure variations. Related to fatigue levels is one simple observation - that of head tilt angles. Driving duration increases, and head tilt deviates even further away from the neutral position, stressing the cervical spine further. Graphical trend data shows that at 30 minutes of driving forward, head tilt rises by 15–20%, and at 45 minutes, it is up to 30° in fatigued drivers. The misalignment not only causes musculoskeletal stress but also produces deleterious effects on reaction times and subsequently undermines driving performance and safety. The same transient is also with variation in posture shifts under different driving conditions. Static posture maintenance due to lumbar strain accumulation during highway driving conditions occurs gradually under steady-state conditions with minimal braking or turning. In contrast, in stop-and-go urban traffic, drivers make a frequent number of posture readjustments: they have to brake, accelerate and stay prepared for external elements all the time. Curvy road navigation involves the most pronounced posture variations due to the presence of lateral gravitational forces which challenge upper body stability while requiring higher muscular exertion and fatigue onset.

Seat pressure variations also demonstrate how fatigue alters lumbar support stability. Data from seat pressure sensors indicate that lumbar support pressure starts at optimal levels (90–100%) in alert drivers but progressively decreases

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as fatigue sets in. By 40 minutes of driving, lumbar support pressure drops to 70%, and in fatigued drivers, it can go as low as 55%, indicating reduced spinal alignment and increased postural discomfort. These findings reinforce the necessity for real-time seat adjustments and dynamic lumbar support mechanisms to counteract fatigue-induced posture deterioration. The following table summarizes the impact of fatigue on key postural and cognitive parameters, illustrating how progressive exhaustion influences spinal alignment, reaction speed, and muscle adjustments.

Table 2. Fatigue Impact on Posture and Reaction Time

Parameter	Alert Drivers	Moderate Fatigue	Severe Fatigue
Forward Head Tilt (°)	5° – 10°	15° – 20°	25° – 30°
Lumbar Support Pressure (%)	90% – 100%	75% – 85%	55% – 70%
Reaction Time Delay (ms)	220 ms	280 ms	350 ms
PERCLOS Fatigue Score (%)	<10%	10% – 20%	25% – 35%
Posture Adjustments Per Hour	8 – 12	5 – 7	2 – 4

The Table 2 clearly shows that fatigue is correlated with posture deviation and cognitive impairment, as demonstrated by an increase in forward head tilt, a reduction in lumbar pressure, and slower reaction times. This highlights how fatigue contributes to delayed responses, heightened discomfort levels, and a negative impact on neuromuscular coordination and postural stability. These findings suggest that ergonomic seat adjustments and posture correction strategies could play a crucial role in improving driver safety and reducing fatigue-related musculoskeletal strain.

5.3 Proposed Improvements

One of the important features of this work is the comparison between recorded posture deviations and fatigue-driven shifts against the ISO 2631 and SAE J826 ergonomic standards. Several of these benchmarks define optimal seating posture, lumbar support and counter fatigue, which can be maintained by driving drivers for long periods and maintaining stability and comfort. One of the key findings of this study is that, deviated from SAE J826 lumbar curve recommendations, the ideal lumbar support range is 15° – 25° (Suzuki et al., 2024). The data indicates that 95% of drivers exceeded this range after 40 minutes of continuous driving with forward head tilt beyond 25°, which confirms a strong misalignment compared to the desired optimal ergonomic standards. Increased cervical spine compression from this excessive forward flexion places muscle strain and decreases postural control.

Moreover, ISO 2631 discomfort thresholds support those postural deviations increased as soon as 30 minutes of continual driving (Kent et al., 2024). When fatigue increases, drivers experience severe discomfort, lumbar misalignment and decreased spinal stability, especially if seat adaptability is minimal. Findings from the study also indicate that fatigued drivers experience pressure in the lumbar support area below 70% and qualitatively, these reports of discomfort and muscle fatigue indicators increase significantly. This matches earlier investigation highlighting that reduced lumbar pressure without dynamic support mechanisms results in long-haul musculoskeletal strain and, therefore a requirement for dynamic lumbar support mechanisms in vehicle seat designs. These findings emphasize the importance of ergonomic compliance in modern vehicle design, suggesting that adaptive seating technologies and real-time posture monitoring systems should be integrated into commercial and long-haul driving environments to ensure postural integrity and fatigue mitigation.

5.4 Validation

Important roles are taken on by personal traits in driving in connection with how drivers adapt to fatigue and postural strain, which is affected by differences in height, driving style, and prior musculoskeletal conditions. The second part of this section deals with how individual differences impact ergonomic risks and how individual differences affect how fatigue is addressed. One of the most notable observations was that taller drivers tend to lean forward more, especially on vehicles with fixed or non-adjustable seat depths (Rahman et al., 2025). The forward-leaning posture of the head asks for spinal strain, consequently increasing the levels of discomfort in the lumbar area and promoting rapid muscle fatigue. Therefore, seat depth customization and lumbar support are required suited to driver height variations. Aggressive drivers tend to have a higher upper body strain as they perform frequent steering corrections, abrupt braking, and rapid acceleration patterns, which further increases muscular strain in the shoulders and upper

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back (Pi et al., 2024). The data shows that aggressive driving behaviors increase posture fluctuations and, in the long term, cause faster fatigue onset and greater postural misalignment.

Moreover, drivers with a record of low back pain suggest higher posterior deviations that support the need for ergonomically adaptive seat designs. Postural shift frequencies are also increased in these people who are trying to self-correct discomfort by changing their sitting position, but often in ways that worsen spinal alignment. This bears out the critical role played by real-time seat adjustability and pressure-sensitive lumbar support to enable drivers who already have preexisting musculoskeletal conditions to keep their posture stable for long periods of time. Overall, these observations highlight that driver-specific ergonomic interventions—including seat customization, dynamic lumbar support, and AI-driven fatigue tracking systems—are crucial for minimizing fatigue-related postural deterioration and enhancing long-term spinal health.

6. Conclusion

Fatigue in this study is known to have a major effect on the control of driver posture stability and was found to subtly change the spinal alignment, increase the forward head tilt, and change lumbar pressure redistribution as fatigue accumulates. The results indicate that drivers experience a substantial decrease in postural control after 30 – 40 minutes of continuous driving, leading to an increase of up to 25° of forward head tilt and a decrease of lumbar pressure below 70% among fatigued individuals. However, these deviations not only contribute to musculoskeletal strain and discomfort but also jeopardize cognitive function and reaction time, putting an immediate risk of driving and a driver's well-being at risk.

The study has one important takeaway: ergonomic seat enhancements are required to compensate for fatigue-induced postural instability. Results showed that, to maintain spinal integrity while lowering the number of cumulative exposures to fatigue onset, the SAE J826 lumbar curve recommendations and the ISO 2631 discomfort thresholds should be followed. Future vehicle designs could benefit from adaptive lumbar support, dynamic seat adjustments, and posture monitoring technologies to mitigate fatigue-related discomfort. However, this study relied solely on manual assessments and video analysis for posture evaluation. Therefore, these findings directly support the thesis that real-time posture correction technologies should be integrated within the vehicle design to improve and maintain driver safety and health in the long term. In addition, it emphasizes the effect of specific personal traits like height, driving style, and history of previous musculoskeletal conditions on fatigue-induced posture shifts. Seat misalignment causes greater spinal strain in taller drivers, and aggressive drivers make more frequent steering adjustments, leading to increased tension in the upper body. In addition, individuals with preexisting back pain exhibit more postural shifts, showing the need for personalized ergonomic solutions for different drivers.

Overall, fatigue is the most important factor in postural degradation and driving safety, and the focus should shift toward ergonomic innovations related to vehicle seating combined with real-time fatigability monitoring. Automotive manufacturers can provide much greater levels of driver comfort, increase confidence, reduce fatigue-related risks and support spinal health through the introduction of AI-driven seat adjustments, adaptive lumbar support and sensor-based posture tracking. Future work should seek the development of affordable ergonomic solutions that can be incorporated into mainstream vehicle designs and thereby be available to end drivers.

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