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Can seat suspensions mitigate motion sickness and enhance vibration comfort while being driven? A subjective assessment of the K-Seat☆

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ABSTRACT

Prolonged exposure to whole-body vibration (WBV) is a key contributor to motion discomfort in vehicles, including motion sickness and ride comfort. This issue becomes more compelling in automated vehicles, where occupants are expected to frequently engage in non-driving-related activities and will expect high comfort levels. Hence, enhancing seat design to mitigate WBV is essential for improving ride comfort across vehicle types. Therefore, this study, which primarily addresses vertical accelerations, optimized an existing seat suspension (K-Seat) and subjectively assessed discomfort using 24 participants (13 males and 11 females) exposed to a 29-minute driving session. The experiment was conducted with a conventional Toyota Yaris seat in a driving simulator, where a K-Seat model was used to emulate the effect of the seat suspension. Thus we evaluated the K-Seat, which has shown great promise for attenuating low-frequency vibrations; however, it had never been tested on human participants. The results show an overall reduction of 50% in reported motion sickness using the motion illness symptoms classification scale (MISC). Subjective discomfort was also alleviated for head and upper back. In addition, perceived discomfort was analyzed based on gender, illustrating a greater effectiveness of the K-Seat in enhancing lower neck comfort for females than for males.

1. Introduction

Comfort while being driven is a highly complex concept, affected by environmental, physical and psychological factors (Peng et al., 2024; Pham Xuan et al., 2025). The physical comfort layer considers driving dynamics that lead to vehicle kinematics and proxemics (Dillen et al., 2020), and whole-body vibrations (WBV) affecting ride comfort (Papaioannou et al., 2023, 2025) and motion sickness (MS) (Diels and Bos, 2016), which can be affected by environmental and traffic influences (route geometry (Beggiato et al., 2019), road roughness, other road users), and interior design (Da Silva, 2002; De Looze et al., 2003). This paper will focus on a potential solution that can increase physical comfort through MS mitigation and ride comfort improvement.

Ride comfort and MS are strongly affected by the transmission of motion from the seat to the head, which varies with factors such as seat compliance, posture, and individual characteristics (Papaioannou et al., 2023, 2025). Meanwhile, head motion, in particular angular velocities and accelerations, plays a critical role in motion comfort (a term encompassing MS and ride discomfort symptoms), as it can diverge substantially from vehicle motion and directly influences motion perception, perceived comfort and sickness accumulation through its interaction with sensory systems (vision and vestibular), which are head referenced. All of the above underscore the necessity to design systems for conventional vehicles around ride comfort and MS. This is critical especially due to the rapid introduction of AVs. Engagement in non-driving related activities (NDRAs) is the main driver for the adoption of AVs, however it has proven to provoke discomfort and MS to occupants due to the lack of anticipation of the upcoming motion and the increased body motion (Papaioannou et al., 2025) among others. Hence, special focus on comfort is needed to secure the wide acceptance of automated driving.

To minimize MS and discomfort in AVs, motion planning algorithms are employed to reduce abrupt vehicle motions, such as sharp turns and abrupt accelerations and design them with regards to comfort and MS (Htike et al., 2021; Jain et al., 2023). Approaches such as curve tilting effectively decrease lateral body load and improve postural stability, offering additional comfort benefits (Zheng et al., 2022), particularly in situations lacking an external view (Wada et al., 2012). The excessive reduction of speed through motion planning for MS mitigation may negatively impact traffic flow and user satisfaction by extending travel times. Therefore, solutions that avoid increasing journey durations should also be considered. Optimization of passive suspensions with regards to ride comfort has also been explored with

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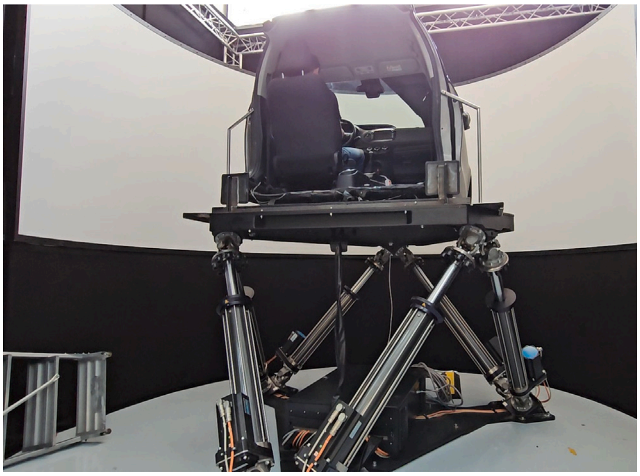

Fig. 1. Delft Advanced Vehicle Simulator (DAVSi) (Khusro et al., 2020).

regards to their impact on MS under different postures (Papaioannou et al., 2021). However, the design of passenger seats to isolate the WBV to enhance comfort and mitigate MS has been limited.

Comfort in seating is influenced by two main factors: static comfort and dynamic comfort, both of which affect the occupants' perceived discomfort (Ebe and Griffin, 2000). Static comfort is influenced by elements such as seat shape (Baucher and Leborgne, 2006), dimensions (Grieco, 1986; Kolich and Taboun, 2004), and materials (Maradei et al., 2017). Dynamic comfort, on the other hand, is mainly determined by the vibrations transmitted through the seat, which are dependent on vehicle and road conditions (El Falou et al., 2003). To improve ride comfort and minimize the impact of WBV on passengers, seat suspension systems are utilized particularly in commercial vehicles, where prolonged exposure to vibrations can have severe effects on occupants' health (e.g., musculoskeletal problems, and others) (Krajnak, 2018; Liang and Chiang, 2006). Seat suspensions are often optimized to improve dynamic comfort (i.e., ride comfort), although this can sometimes compromise static comfort (Cao et al., 2011; Pereira et al., 2023). Despite attempts to optimize passive seat designs, their performance in commercial seats has nearly reached its potential (Drehmer et al., 2015; Rahman and Kibria, 2014; Shangguan et al., 2017). Although semi-active and active suspension systems (Ahn et al., 2014; Ning et al., 2016) are increasingly gaining attention in both industry and academia, they tend to be more expensive, more complex, difficult to adjust to individual mass, anthropometry and preferences and less reliable than passive systems, which limits their widespread application. This has led to increased interest in alternative designs, such as those incorporating negative stiffness elements (Atindana et al., 2023; Ni et al., 2023; Papaioannou et al., 2020a,b), which have great capabilities in isolating the MS-provocative low-frequency vibrations. Such systems have been designed, but not yet validated with human participant experiments.

Focusing on ride comfort, Le and Ahn (2011) developed a passive vibration isolation system utilizing negative stiffness, which was subsequently enhanced by incorporating an active damper (Ahn et al., 2014). These systems were designed (Le et al., 2013), but not validated with human trials to assess the perceived ride comfort and potential benefits on MS. Other designs with negative stiffness elements have been introduced by Yan et al. (2015), who proposed a nonlinear seat suspension system designed using cam-roller-spring mechanisms for off-road vehicles. The design of the system was experimentally tested regarding its isolation capabilities but without human participants. Papaioannou et al. (2020a,b) designed the K-Seat for application in passenger seats. The results used mostly objective, but validated, metrics demonstrating great performance in isolating low-frequency vertical accelerations which could be critical for mitigating MS. However, there was no subjective testing with participants.

The ability of commercial seat suspensions to enhance ride comfort is widely discussed in the literature (Kia et al., 2021; Kim et al., 2018), but their effectiveness in mitigating motion sickness (MS) remains uncertain. On one hand, Kia et al. (2021) compared three commercial seats in terms of ride comfort and MS during non-driving-related tasks but did not observe any measurable improvement in task performance or MS reduction. On the other hand, Papaioannou et al. (2022) developed the Active K-Seat – a seat suspension system with a PID controller designed to follow the K-Seat reference – and compared it with other models using simulation studies. The simulation results demonstrated significant improvements in both ride comfort and motion sickness mitigation under vertical vibration exposure. However, these findings were not validated through human participant testing. This paper addresses that gap by conducting human trials to evaluate the ability of the K-Seat to (A) enhance ride comfort and (B) mitigate motion sickness symptoms.

2. Experiment design

A within-subject design was employed to evaluate the effectiveness of the K-Seat in enhancing ride comfort and mitigating motion sickness. Between subject analysis was also conducted for gendered conclusions. In total, 24 participants experienced two conditions in a cross-randomized order to counterbalance potential learning or adaptation effects.

Condition 1 (*Without K-Seat*)**.** The simulator setup included a passive Toyota Yaris seat mounted directly on the motion platform of the Delft Advanced Vehicle Simulator (DAVSi) (Fig. 1) (Khusro et al., 2020). Condition 1 served as the reference, capturing the participants' experience of ride comfort and motion sickness with the conventional seat configuration.

Condition 2 (*With K-Seat*)**.** As in Condition 1, the same Yaris seat was used; however, this condition simulated the presence of the K-Seat mechanism integrated below the existing seat. The K-Seat dynamics were emulated by modifying the platform's vertical motion to represent the isolated movement of the seat base as predicted by the K-Seat model offline. This approach allowed for a realistic evaluation of the K-Seat's vibration isolation without physical hardware changes.

2.1. Excitation

Each experimental condition involved a sequence of two excitations (Fig. 2) applied as inputs to the DAVSi. First, a 4-minute wide band noise was used, followed by a 25-minute road profile. The wide-band noise excitation is used to explore the impact of the K-Seat on human body dynamics in the relevant frequency range while participants were engaged in non-driving-related activities (NDRAs). This is part of future work to understand the seat-to-head transmissibility under different conditions. The second excitation, the road profile, was used to explore the differences of the two seat conditions on the accumulation of MS and discomfort while being driven and engaged in NDRAs for 25 min.

Details for each condition are provided below:

- Condition 1 (Without K-Seat): A wide-band noise excitation was designed, by considering a frequency bandwidth of 0.1–12.0 Hz and 0.3 m/s^2 rms power (Mirakhorlo et al., 2022). This signal was applied to the Delft Advanced Vehicle Simulator (DAVSi) in three axes (vertical, fore-aft, and lateral), each with a 60-second duration plus 5-second fade-in and fade-out to avoid abrupt transitions. The DAVSi's motion cueing algorithm significantly attenuated motion above 5 Hz. These three directional

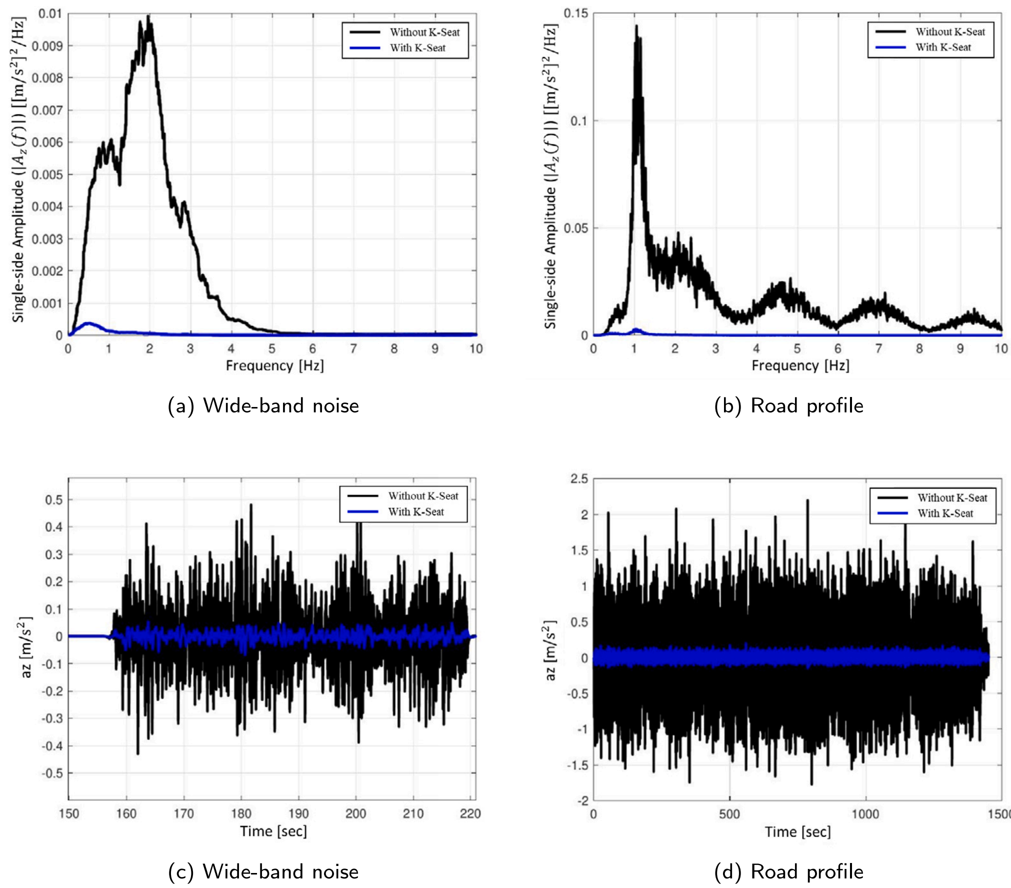

Fig. 2. Power spectral density in [m/s^2]^2/Hz (a and b) and time domain response (c and d) of the vertical acceleration signals for Conditions 1 and 2.

excitations were concatenated sequentially into a single continuous signal to ensure uninterrupted exposure. Then, for the road profile, the vehicle vertical acceleration response ($\ddot{z}_s$ in Appendix, Fig. 8) was used as excitation directly to DAVSi for the vertical direction only (Fig. 2(b), Without K-Seat). To generate the vehicle motion, a conventional passenger vehicle was simulated in IPG CarMaker, driving on a 17 km road (Papaioannou et al., 2022) of Class C road roughness profile based on ISO-8608 (International Organization for Standardization, 1995). The vehicle drove along this profile at a maximum velocity of 50 km/h.

- Condition 2 (With K-Seat): The same motions as in Condition 1 (wide-band noise followed by road profile) were now used as input to the mathematical model of K-Seat to extract the seat vertical acceleration ($\ddot{x}$ in Appendix, Fig. 8). This response was applied as an excitation to DAVSi for the vertical direction. We applied the same fore-aft and lateral signals as Condition 1, since K-Seat could not have isolated vibrations in these directions.

The seat is rigidly mounted to the simulator's motion platform, meaning there is no intermediate suspension or damping mechanism to alter the transmitted vibrations. This configuration ensures that the platform excitation is indeed directly applied to the seat. Therefore, the dynamic stimulus applied at the seat level can be considered consistent and is clearly illustrated in Fig. 2 via the time- and frequency-domain figures. Additionally, according to previous work by the authors conducted in this seat base (Mirakhorlo et al., 2022), vertical vibration transmission gains up to around 2 Hz are close to one with little variance between participants. This means that body accelerations at pelvis, trunk and head are close to the accelerations applied at the seat base. At higher frequencies more variation is seen with some amplification of pelvis acceleration around 5 Hz which is indeed related to seat and body compliance and which indeed relates to individual body size and other factors.

Table 1
Aw values of the input signal in Condition 1 and 2 as assessed according to ISO-2631 (ISO 2631-1:1997 en, 1997) by applying no filter (Aw), and w_d and w_f filters for z accelerations (Aw_{wd} and Aw_{wf} respectively).

Condition 1: Without K-Seat		
	Wide-band	Road profile
Aw (m/s^2)	0.054	1.019
Aw_{wd} (m/s^2)	0.044	0.831
Aw_{wf} (m/s^2)	0.004	0.031
Condition 2: With K-Seat		
	Wide-band	Road profile
Aw (m/s^2)	0.008	0.124
Aw_{wd} (m/s^2)	0.004	0.071
Aw_{wf} (m/s^2)	0.004	0.026

The characteristics of the excitations are compared in Table 1 using ISO-2631 (ISO 2631-1:1997 en, 1997), where Aw values of the input signal in Conditions 1 and 2 as assessed according to ISO-2631 (ISO 2631-1:1997 en, 1997) by applying no filter (Aw), and w_d and w_f filters for z accelerations (Aw_{wd} and Aw_{wf} respectively). The w_d and w_f filters are used to weight the acceleration for the human sensitivity on ride comfort and motion sickness respectively. According to Table 1, the excitation of Condition 2 is greatly isolated through K-Seat. More specifically, the Aw_{wd} was labeling the road profile case as uncomfortable in Condition 1, which is changed to not uncomfortable in Condition 2.

2.2. Ethics statement

The experiment was conducted in accordance with the Declaration of Helsinki. The study was approved by the Human Research Ethics Council of Delft University of Technology (Delft, The Netherlands; application number 4006). All participants gave their written informed consent before participating in the study. Participants received a compensation of 10 €.

2.3. Participants

This study involved 24 healthy volunteers (11 females, 13 males, mean age: 22.4 years, range: 19–30 years). The male population has mean body mass: 78.1 kg, mean height: 180.8 cm, mean body mass index: 23.8. The female population has mean body mass: 62.9 kg, mean height: 169.6 cm, mean body mass index: 21.8. None of the participants were aware of the exact research objectives and the sequence of the excitations.

Participants were recruited via university mailing lists, posters, and word of mouth within the TU Delft campus. The inclusion criteria required participants to be healthy adults more than 18 years old, with normal or corrected-to-normal vision, and without any physical impairments that would affect sitting posture or the use of the simulator. The exclusion criteria included self-reported history of severe motion sickness, vestibular disorders, neurological or musculoskeletal conditions, recent injuries affecting posture or movement, pregnancy, and current use of medications known to affect balance or induce drowsiness. Participants were screened based on a short pre-screening questionnaire to ensure eligibility prior to scheduling the test sessions.

2.4. Procedure

Prior to scheduling, all participants were provided with an overview of the experimental procedure and instructed to refrain from eating at least one hour before each session. On each test day, the experimental setup was checked in advance to ensure safety and hygiene. Upon arrival, participants were welcomed and briefed again on the procedure. They were informed that the study involved two separate sessions. Given the cumulative nature of motion sickness (Dużmańska et al., 2018; Irmak et al., 2021), participant's sessions were spaced at least one day apart to minimize carryover effects between conditions. Participants gave written informed consent before beginning the study.

Before the start of the experiment, participants completed a pre-drive questionnaire for their body measurements (e.g., segment lengths and circumferences) as recorded to calibrate the XSENS suit (used to capture 3D body motion) and the motion sickness assessment questionnaire (MASQ) (Golding, 1998, 2006). The anthropometric measurements were collected during the first session. After the pre-drive questionnaire, they wore the XSENS suit and assisted the experimenters with its calibration. Following this, the participants were guided into the simulator and were provided a tablet for them to engage in a NDRA (sports video watching). The video was edited by adding events (large dots/balls) in random timings of the video, and the participants were requested to count them and report them. The engagement in the NDRA urged the participants to have a head-down posture blocking their view to the non-natural environment of the simulator. Therefore, their perception of comfort was not affected by the environment setup. Before starting the experiment, participants were shown how to maintain a correct erect posture (Fig. 3), ensuring consistent body positioning across sessions. They were also reminded of their right to stop the experiment at any point for any reason.

The experiment began with the first excitation, a 4-minute wide-band noise profile. Upon completion, participants paused the video and filled in the Intermediate-drive questionnaire while remaining seated in the simulator. The Intermediate-drive questionnaire questioned the motion sickness level using the motion sickness assessment questionnaire (MSAQ), overall perceived discomfort and discomfort per body segment after the initial part of the motion exposure (wide band noise excitation). Once finished, they resumed the video, and the 25-minute road profile excitation was initiated. During both excitations, the participants were asked to rate their current level of MS every minute using the 11-point scale motion illness symptoms classification scale (MISC) (Reuten et al., 2021), a widely used and validated single-item metric that enables high-frequency monitoring of momentary sickness intensity in simulator and vehicular environments (Bos et al., 2005; Harmankaya et al., 2024; Reuten et al., 2021; de Winkel et al., 2022). To ensure the reliability of participants' responses across these repeated sessions, we employed validated and widely used subjective measures. Both MSAQ and MISC have both demonstrated strong test-retest reliability and internal consistency in prior studies on motion sickness and whole-body vibration exposure (Golding, 1998, 2006; Irmak et al., 2021; Papaioannou et al., 2025; de Winkel et al., 2022). These validated tools ensure consistent and dependable assessment of subjective discomfort and motion sickness over time, making them suitable for our within-subject design. If a participant reported a MISC score of 7 or higher, the experiment was immediately terminated in accordance with ethical safety guidelines.

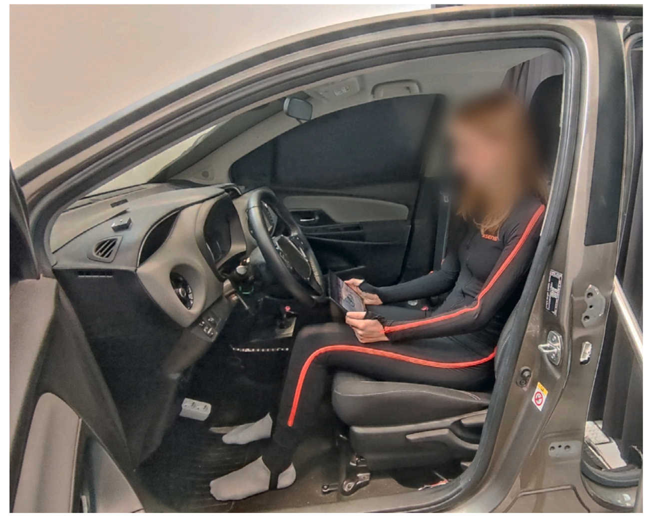

Fig. 3. A participant in the DAVSi.

At the end of the session, participants exited the simulator and completed the post-drive questionnaire. The Post-drive questionnaire duplicated the Intermediate, by capturing the MS level using MSAQ, overall perceived discomfort, discomfort per body segment and perceived head motion. In addition participants reported the number of counted visual events and answered an open-feedback question about the experimental process. However, the latter was not analyzed in this paper. Regarding the counted visual events, several participants misunderstood the instruction and recorded the condition number instead of the count. Hence, this data is not reported. To ensure the validity of the participants' feedback, all the questionnaires were explained according to their original publications.

2.5. Dependent variables

The dependent variables were selected to assess MS and discomfort in both Conditions, with the following metrics:

- For motion sickness: max MISC, MISC vs. time during the exposure, MSAQ-Pre and MSAQ-Post drive;

• For perceived discomfort: Overall and Body segment (Intermediate and Post-drive - lower neck, upper back, lower back, and buttocks) discomfort and perceived head motion (Intermediate- and Post-drive);

2.6. Independent variables

The primary independent variable in this study was the seat condition—specifically, whether the K-Seat mechanism was active (With K-Seat) or not (Without K-Seat). This variable was manipulated using a within-subjects design, meaning that all participants experienced both conditions in a randomized order to control for order effects. In addition to seat condition, time was included as a secondary within-subject factor in certain analyses, particularly when assessing changes between Intermediate and Post-drive responses (e.g., in discomfort ratings and MSAQ scores). Furthermore, participant gender (male/female) was treated as a between-subjects factor for exploratory purposes, enabling the analysis of gender-related differences in perceived discomfort.

2.7. Statistical analysis

The Wilcoxon signed-rank test, a non-parametric alternative to the paired t-test, was used to compare two related samples (within-subject comparisons). This test evaluates whether the median of the paired differences differs significantly from zero and is appropriate for ordinal data or non-normally distributed variables. The Wilcoxon signed-rank test was applied to assess the effects of the K-Seat on maximum MISC, MSAQ scores at all experimental stages, and discomfort ratings (overall and per body segment) at the Intermediate and Post-drive stages. For between-subject comparisons (male vs. female participants), the Mann–Whitney U test was employed. This non-parametric alternative to the independent samples t-test is suitable for independent groups when data are ordinal or not normally distributed. The test assumes independence of observations and similar distribution shapes between groups, without requiring normality or homogeneity of variances (McKnight and Najab, 2010; Nachar et al., 2008). Specifically, the Mann–Whitney U test was applied to examine gender differences in overall and body-segment discomfort ratings within each condition.

In addition to the non-parametric analyses, a linear mixed-effects (LME) model was fitted using the `fitlme` function in MATLAB to examine the longitudinal evolution of motion sickness (MISC) over time. MISC scores from both conditions were structured in long format, with each participant contributing repeated measurements across 29 time points. The model included fixed effects for *Time*, *Condition*, and *Gender*, as well as all corresponding two-way interactions (*Time* × *Condition*, *Time* × *Gender*, and *Condition* × *Gender*). The three-way interaction was not retained in the final model to maintain parsimony, as it did not significantly improve model fit. A random intercept for each subject was included to account for individual baseline differences and to model the within-subject correlation inherent in the repeated-measures design.

$$\begin{aligned}\text{MISC} \sim & \text{ Time} + \text{Condition} + \text{Gender} \\ & + \text{Time:Condition} + \text{Time:Gender} \\ & + \text{Condition:Gender} \\ & + (1|\text{Subject})\end{aligned} \quad (1)$$

This model allows for the estimation of main effects and two-way interactions while adjusting for the inherent correlations within the repeated-measures structure of the data.

All analyses were performed with MATLAB 2022. A significance threshold of $p = 0.05$ was considered for all of them.

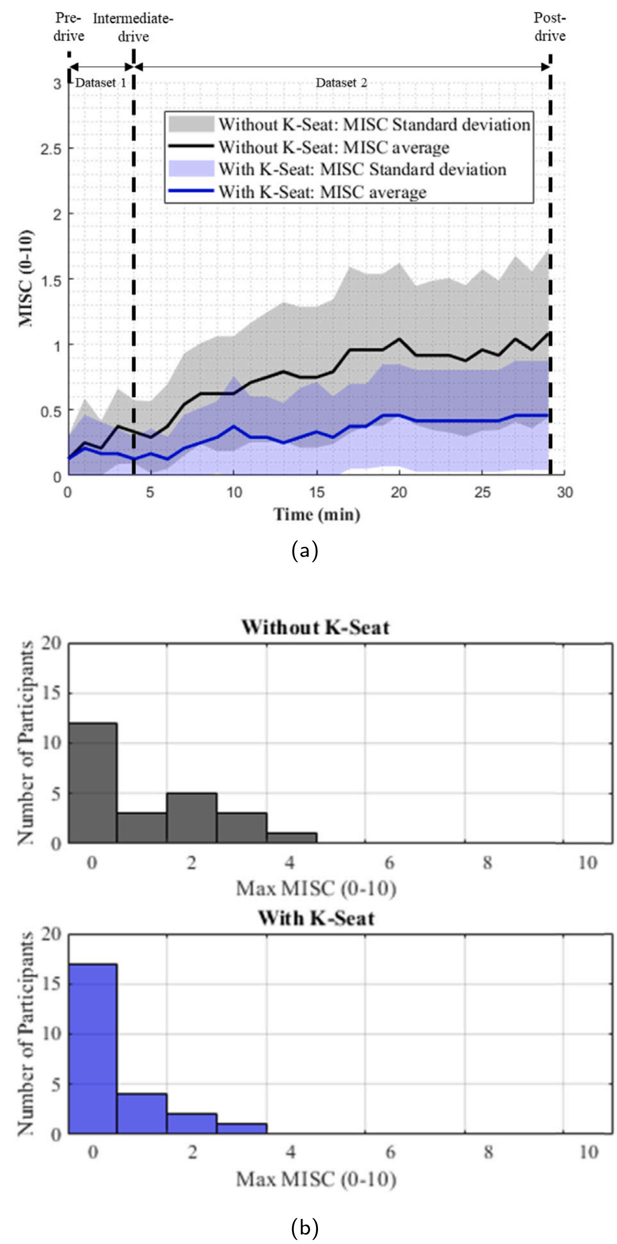

Fig. 4. MISC over time (a) and Maximum MISC (b) for the two conditions.

3. Results

All participants successfully completed both sessions of the experiment reaching at most MISC=4. This section will discuss the results on the subjective assessment of discomfort and motion sickness.

Motion sickness over time is reported using MISC (Fig. 4). According to the results, the 24 participants displayed a substantial variance in MISC (Fig. 4(a)) with 12 participants reporting no sickness symptoms (MISC=0) in Condition 1 and 15 participants reporting no sickness with K-Seat (Condition 2). The MISC results in both conditions show the expected increase over time (Fig. 4), but the effect of time over MISC was not significant ($p = 0.901$) in both conditions. The condition had a significant effect on MISC ($p = 0.002$), illustrating that the K-Seat provided significantly lower MISC levels to the participants over the duration of the exposure. However, there was no significant interaction for time and condition ($p = 0.936$). According to Fig. 4(b), the mean value of MISC for Condition 1 (Without K-Seat) (MISC = 1.4)

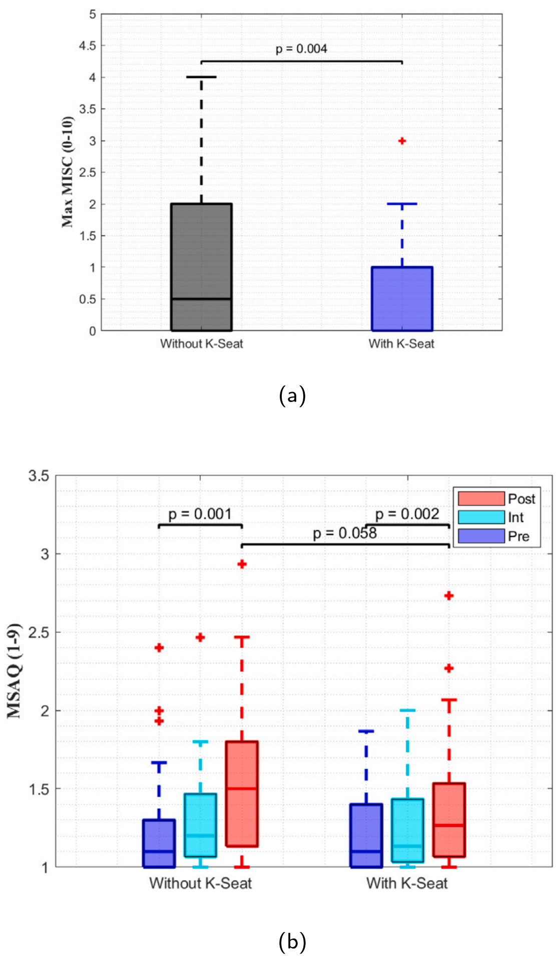

Fig. 5. Boxplots of the (a) maximum (final) MISC and (b) MSAQ recorded before, within and after the experiment for each participant, including the p-values based on the Wilcoxon signed-rank tests. The central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol.

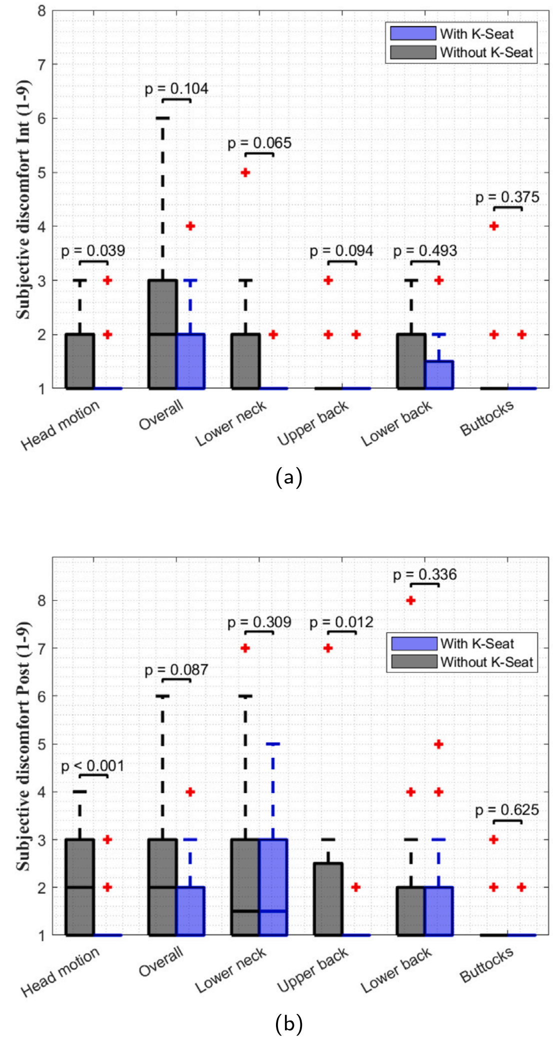

Fig. 6. Boxplots showing the results for perceived head motion and the overall and per body segment perceived discomfort in the (a) Intermediate- and (b) Post-drive, including the p-values based on the Wilcoxon signed-rank tests. The central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' marker symbol.

was decreased by 50% in Condition 2 (With K-Seat) (MISC = 0.7). The boxplots also demonstrate these differences in Fig. 5(a), where the maximum MISC is compared across cases and has a significant difference (p = 0.004). In addition, based on the linear mixed model, neither the gender (p = 0.187) not its interaction with time (p = 0.352) or condition (p = 0.524) had a significant effect on MISC.

According to the MSAQ results (Fig. 5(b)), Pre- and Post-drive results were significantly different in Condition 1 (Without K-Seat) and Condition 2 (With K-Seat) (p = 0.001 and p = 0.002, respectively). Meanwhile, post results between Conditions 1 and 2 were not significant. The median MSAQ illustrated a trend of decrease around 9%. A similar insignificant difference in medians was captured between the Intermediate MSAQ scores of the conditions.

When looking at the overall and body segment related subjective discomfort (Fig. 6), both the intermediate and post results include significant differences in perceived discomfort between Condition 1 (Without K-Seat) and Condition 2 (With K-Seat). The overall perceived discomfort, and the perceived discomfort in the lower neck, the lower back and the buttocks did not illustrate significant differences between the two conditions either in the Intermediate or Post-questionnaire. However, the perceived head motion discomfort displayed a significant difference between the two Conditions in the Intermediate- (p = 0.039 for head motion) and Post- (p < 0.001 for head motion) drive results. The perceived discomfort in the upper back became significantly different in the Post-questionnaire (p = 0.012). This implied that K-Seat significantly affect these two aspects.

Fig. 7 illustrates Post-drive differences between male and female participants in overall and per body segment perceived discomfort, and perceived head motion. Across the different body sections, males and females reported similar discomfort with no significant differences, except for the discomfort in the lower neck region in the Post-drive results (p = 0.025). This outcome may be attributed to different anthropometric characteristics, as for example females generally have a lower average mass and height than males refer to Section 2.3 (Yao et al., 2023). However, this is not depicted in the other body segment perceived discomfort. For the males, the mean post-drive discomfort rating in Condition 1 (Without K-Seat) is 1.84, while in Condition 2 (With K-Seat), it is 1.61, indicating a 14% reduction in discomfort with the K-Seat, which is not significant (p = 0.130). Similarly, for the

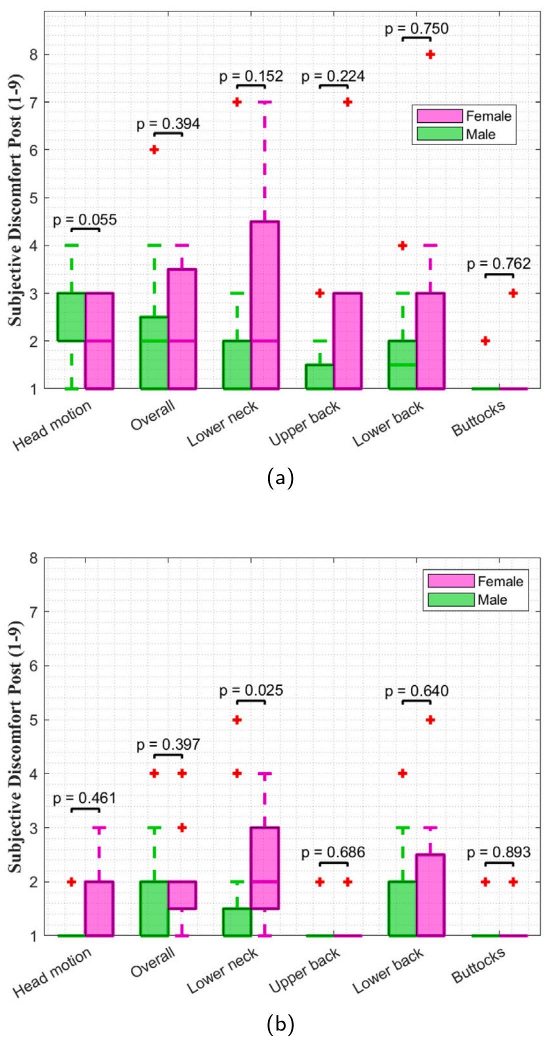

Fig. 7. Boxplots showing the results for perceived head motion and the overall and per body segment perceived discomfort between Males and Females in the Post-drive questionnaire (a) Condition 1 (Without K-Seat) (b) Condition 2 (With K-Seat), including the p-values based on the Mann–Whitney tests. The central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' marker symbol.

females, the mean post-drive discomfort rating in Condition 1 (Without K-Seat) is 3, whereas in Condition 2 (With K-Seat), it is 2.45, reflecting a 25% reduction in discomfort with the K-Seat, which is also not significant (p = 0.110).

4. Discussion

This study was motivated by contradictory results in the literature about the ability of seats to mitigate motion sickness while being driven. More specifically, the rationale for this study was to experimentally assess how a redesigned passive seat suspension system (K-Seat) impacts occupants' ride comfort and motion sickness under dynamic driving conditions.

The significant difference in maximum MISC scores along with the absence of high MISC values (above 3) in the K-Seat condition, reflects a clear reduction in motion sickness events. Furthermore, the K-seat was able to increase the number of participants who experienced no sickness symptoms by 20%. These findings support the K-Seat's potential as a countermeasure for road vibration-induced sickness over time, contradicting Kia et al. (2021), reporting that different seats do not affect motion sickness (Kia et al., 2021). However, there are a few differences between the studies. Our excitation was five times more intense in Condition 1, comparing our Aw values with Kia et al. (2021), whereas Condition 2 was less intense by almost 50%. Meanwhile, Kia et al. assessed motion sickness only with MSAQ. We also did not find significant main effects of seat using MSAQ, but did find significant effects using MISC (p=0.004, Fig. 5). Furthermore, the 9% improvement in post-MSAQ medians and the 50% reduction in average MISC scores for the K-Seat compared to the Without K-Seat condition underscore its effectiveness in reducing motion sickness intensity and improving discomfort after prolonged exposure to road vibrations. The motion sickness alleviation may be associated with head stabilization, as vestibular and visual sensory pathways rely on head position. Improved comfort for those who did not get sick was evidenced by the significant improvements in perceived discomfort for specific regions (head and upper back) with the K-Seat, highlighting its potential to reduce head discomfort. Further work is in progress to explore the differences in the seat-to-head transmissibility in the frequency domain.

The comparison of subjective discomfort across different body segments – head, lower neck, upper back, lower back, and buttocks – between the K-Seat and the conventional seat revealed significant differences only in the perceived head motion and the upper back perceived discomfort. These differences were present in the intermediate (4th-minute) and post-experiment (29th-minute) measurements. Additionally, the increase in reported discomfort was most pronounced for the upper back during the post-drive questionnaire, while perceived head motion was significant different for both the intermediate and post-experiment questionnaires. The absence of significant differences in overall discomfort, lower neck, lower back and buttocks areas suggests that the K-Seat primarily influences upper-torso stability. Similarly, Lampe and Deml (2023) highlighted the importance of upper-body stability and controlled movement in seating systems, showing that engaging upper-body muscles can improve comfort and reduce discomfort over time (Lampe and Deml, 2023). These findings in Lampe and Deml (2023) contrast with Kia et al. (2021) where participants engaged in a similar non-driving task with a comparable posture. Their study reported increased discomfort across multiple body regions, including the low back, mid back, gluteal region, legs, neck, and shoulders, following 25 min of vibration exposure. The most pronounced increases were observed in the gluteal region, neck, and shoulders. Furthermore, Kia et al. (2021) found that different seat suspension types did not significantly affect discomfort levels, which partially aligns with our findings that the K-Seat had limited influence on lower neck, lower back, and buttocks discomfort. Nevertheless, a review of studies investigating musculoskeletal pain in professional drivers reported that musculoskeletal pain is most prevalent in the lower back (53% meta-prevalence), followed by the neck (39.2%) and upper back (25.5%) (Joseph et al., 2020). Given this, the K-Seat's ability to reduce discomfort in the upper back is particularly relevant, as it addresses one of the most frequently affected body regions when being seated for prolonged periods in a car.

Another interesting observation was the significant (p = 0.024) discomfort difference in the lower neck region reported by females compared to males for Condition 2 (With K-Seat) which could suggest that gender-specific physiological factors may influence seat design efficacy (Fig. 7(b)). This observation aligns with findings from Golding (2006), Kennedy et al. (1995), which indicated that females were generally more susceptible to motion-related discomfort. The lower inertia associated with reduced body mass could make the females more susceptible to whole-body vibration, which aligns with the observed greater discomfort reduction (Papaioannou et al., 2025). According to the literature (Dewangan et al., 2018) the vibration power absorption is affected by gender for subjects of comparable anthropometric dimensions, while it was correlated with the body mass, lean body mass and body fat. However, no significant differences were observed in other body parts, likely due to the nature of the stimulus (vertical road vibrations). Further investigations using a broader range of stimuli and body postures are needed to gain deeper insights into gender-specific factors affecting seat discomfort.

5. Conclusion

The main findings of this study indicate that the K-Seat significantly improves occupant comfort and reduces motion sickness symptoms under vertical vibration exposure. Employing 24 participants (13 males, 11 females), the K-Seat led to a 50% reduction in average MISC scores, demonstrating a clear reduction in motion sickness severity. These improvements were especially evident in real-time MISC evaluations, reinforcing the K-Seat's effectiveness under prolonged exposure. However, gender-based analysis of discomfort and motion sickness was inconclusive. On one hand, the results revealed that the K-Seat was more effective in reducing discomfort for female participants in the lower neck region. This suggests the K-Seat may offer greater benefits for female users, possibly due to anthropometric differences that influence vibration sensitivity. On the other hand, there was no interaction effect of gender and condition on MISC, indicating that K-Seat decreased MISC regardless the gender.

CRediT authorship contribution statement

Farzam Tajdari: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chrysovalanto Messiou:** Writing – review & editing, Resources, Investigation, Data curation. **Riender Happee:** Writing – review & editing, Supervision, Funding acquisition. **Georgios Papaioannou:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this paper the authors used ChatGPT to check grammar, spelling, references, and clarity. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. K-Seat design

A.1. K-Seat model

From Papaioannou et al. (2020b), the K-Seat design is illustrated in Fig. 8 and consists of a mass (m) which is supported by two parallel linear coil springs (K_s and K_v) and a damper (C). The damper (C) and the spring (K_v) are also connected to a smaller mass (m_d). The negative stiffness can be achieved by a set of two symmetrical linear horizontal springs (K_h) which support the internal mass (m_d) by means of a modular mechanism. L_0 is the initial length of undeformed springs K_h. The static equilibrium position of the system corresponded to u_0 is illustrated in Fig. 8 under the effect of gravity only, where x is the displacement of m, z_s is the displacement of the vehicle, and y is the displacement of m_d from u_0. The disturbed position after applying the excitation of the spring-mass is shown in Fig. 8 along with the necessary notes on the various system shifts.

The final set of equations of motion from Papaioannou et al. (2020b) include:

$$m\ddot{x} + C(\dot{x} - \dot{y}) + 2K_s(x - z_s) + K_v(x - y) = 0 \tag{2}$$

$$\begin{aligned} &m_d\ddot{y} - C(\dot{x} - \dot{y}) - K_v(x - y) - \\ &2K_h\left(1 + c_I\frac{1}{\sqrt{1 - \frac{(u_0+y-z_s)^2}{b^2}}}\right)(u_0 + y - z_s) + \\ &2K_h\left(1 + c_I\frac{1}{\sqrt{1 - \frac{u^2}{b^2}}}\right)u_0 - c_p(\dot{z}_p - \dot{x}) - k_p(z_p - x) = 0 \end{aligned} \tag{3}$$

$$X_{st} = \frac{(m + m_d)g + 2K_h\left(1 + c_I\frac{1}{\sqrt{1-\frac{u^2}{b^2}}}\right)u_0}{2K_s} \tag{4}$$

where, $c_I = \frac{L_0 - a_0}{b}$, and $-c_p(\dot{z}_p - \dot{x}) - k_p(z_p - x)$ in (3) corresponds to forces applied to the seats by the pelvis where z_P is the pelvis displacement.

A.2. Optimization problem formulation

The main conflict in the seat suspensions implies that the increasing initial deformation of the system (X_{st} reflects the 'static comfort') leads to better isolation of the accelerations ($\ddot{x}$) and a more comfortable seat ('dynamic comfort'). However, due to the limited space in a vehicle, a minimized X_{st} is targeted which competes with the acceleration isolation represent the comfort. To address the competition, finding the optimized values of the K-Seat model's parameters ($P = [a_0, L_0, b, C, K_s, K_e, K_h]$) is a solution. Accordingly, a weighted cost function is then designed as below to further determine the optimum relation between the X_{st} and RMS of $\ddot{x}$:

$$J(\beta_1, \beta_2, P) = \beta_1\frac{r(P)}{\bar{r}} + \beta_2\frac{X_{st}(P)}{\bar{X}_{ST}} \tag{5}$$

$$r(P) = \frac{\mathrm{RMS}(\ddot{x}(t, P))}{\mathrm{RMS}(\ddot{z}_s(t))} \tag{6}$$

where $\ddot{x}$ is the generated acceleration from the seat designed based on the K-Seat which is implicitly dependent on P. The $\ddot{z}_s$ belongs to the acceleration response of the original passively damped seat or in this case, the Yaris seat that is inside the Delft Advanced Vehicle Simulator (DAVSi). The ratio (r) is the fraction of the output RMS of the generated acceleration over the original acceleration. β_1 is weight for the dynamic term and β_2 belongs to the static term. Note that the results of the optimized variables are used in Papaioannou et al. (2022) as the initial condition for the variables, and, r and X_{ST} are

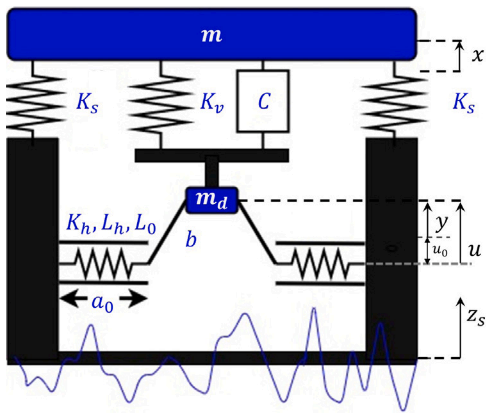

Fig. 8. Schematic of the K-Seat suspension (Papaioannou et al., 2020b).

Table 2
Design variables for K-seat.

Parameters	Work in Papaioannou et al. (2022)	our method
a_0 [m]	0.219	0.217
L_0 [m]	0.217	0.220
b [m]	0.240	0.162
C_v [N.s/m]	436	437
K_s [N/m]	12,073	24,144
K_v [N/m]	39,207	39,387
K_h [N/m]	39,207	7,347
β_1	–	0.6
β_2	–	0.4

normalized by $\bar{r}$ and $\bar{X}_{ST}$. Similarly, $\bar{r}$ and $\bar{X}_{ST}$ are resulting parameters using the optimized variables in Papaioannou et al. (2022). Due to the normalization features, the weights are designed such that $\beta_1 + \beta_2 = 1$.

To ensure that the K-Seat is more efficient than the Yaris seat, in terms of reduced acceleration the following constraint is applied:

$$r < 1. \tag{7}$$

Thus, the optimal problem is formulated as:

$$\min J(\beta_1, \beta_2, P) \ \text{S.t} \ r < 1 \tag{8}$$

A.3. Optimization K-Seat

We used the optimal parameters in Papaioannou et al. (2022) available in Table 2 to design our parameters. From Table 3 in Papaioannou et al. (2020b) we know that $c_p = 378$ [N.s/m], $k_p = 25500$ [N/m]. The parameters in Papaioannou et al. (2022) were considered as the initial condition for the parameters in our optimal problem. In addition, by implementing the parameters in Papaioannou et al. (2022) on the dataset corresponding to Condition 1 (Conventional seat), we found that $\bar{r} = 0.138$ and $\bar{X}_{ST} = 0.0416$ [m]. A MATLAB script is used to solve this optimization problem, primarily using the `fmincon` function.

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