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Doctoral Thesis

Development of a Motion Seat System for Reduction of a Driver's Passive Task-Related Fatigue

Seunghoon Lee (이 승 훈)

Department of Industrial and Management Engineering

Pohang University of Science and Technology

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운전자 Passive Task-Related 피로 저감을 위한 동적 승객석 시스템 개발

Development of a Motion Seat System for Reduction of a Driver's Passive Task-Related Fatigue

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by

Seunghoon Lee
Department of Industrial and Management Engineering
(Human Factors and Ergonomics Program)
Pohang University of Science and Technology

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Approved by

Dr. Heecheon You (Signature)

Academic Advisor

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Seunghoon Lee

The undersigned have examined this dissertation and hereby certify that it is worthy of acceptance for a doctoral degree from POSTECH

06/22/2020

Committee Chair	Heecheon You	(Seal)
Member	Chi-Hyuck Jun	(Seal)
Member	Kwangsoo Kim	(Seal)
Member	Seikwon Park	(Seal)
Member	Kihyo Jung	(Seal)

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ABSTRACT

Driver fatigue can cause traffic accidents by degrading the driver's alertness and performance. Driver fatigue is an impaired state of mental alertness, negatively affecting cognitive and psychomotor functions such as visual–spatial ability, memory, information processing, and rapid reaction required for driving tasks. Driver fatigue can be classified into active task-related (TR) fatigue in cognitive overload and passive TR fatigue in cognitive underload. For example, active TR fatigue can occur in a high workload situation such as driving in high-density traffic or poor visibility environment, while passive TR fatigue in a low workload situation such as driving on a monotonous highway or in a partially autonomous vehicle. Existing studies have reported that 20% ~ 35% of road accidents are due to driver fatigue.

The objective of the present study is to develop a motion seat system for the reduction of driver's passive TR fatigue. The specific objectives are as follows: (1) development and evaluation of statistical estimation models for hip locations (HLs) and eye locations (ELs) of the driver, (2) development of the motion seat system and its motion profiles to reduce passive TR fatigue during monotonous driving, (3) examination of the passive TR fatigue reduction effects of the motion seat system through simulation driving in a lab environment, and (4) validation of the passive TR fatigue reduction effects of the motion seat system in an on-road driving environment.

First, the statistical models for prediction of a driver's HL and EL were developed using anthropometric dimensions, joint angles, and seat configurations.

Driving postures of 23 Korean drivers (10 females and 13 males) were measured in a seating buck while simultaneously changing the fore-aft seat position, seat height, seatback recline angle, and seat cushion angle from the preferred seat configuration. The HLs, ELs, joint angles, and seat configurations of the participants were collected by a motion capture system. The HL and EL prediction models based on the driving postures and seat configurations were developed by stepwise regression. The proposed prediction models showed high accuracy in the prediction of HL and EL in terms of adj. R^2 ($M \pm SD$ = .83 ± .14) and *RMSE* ($M \pm SD$ = 19.3 ± 4.1 mm) on average. The performance difference between the posture- and seat configuration-based models were not statistically significant.

Second, the motion seat system was constructed using the power-adjustable driver seat, electronic control unit of the driver seat, controller area network interface device, and PC-based seat control system. The motion seat system which provides coordinated motions of backrest recline, cushion tilt, and lumbar support inflation/deflation was developed to induce the stretching and flexion of the whole body with two types (bow and wave) of motion profile with a particular time interval (e.g., 1 min). The EL correction algorithm, which compensates the eye location change due to backrest recline and cushion tilt motions, was applied to the motion seat system using developed EL prediction models. Seating comfort and driving safety for the established motion profiles were checked through a preliminary experiment conducted with seat evaluation experts (n = 10).

Third, the effectiveness of a motion seat system on the driver's passive TR fatigue was examined in a lab-based driving simulation. Standard deviation of lane position (SDLP), brake reaction time (BRT), percentage of eyelid closure rate (PERCLOS), standard deviation of NN interval (SDNN) and ratio of low frequency power to high frequency power (LF/HF) of electrocardiography signals were measured while 17 Korean drivers with more than two years of driving experience performed a 90-min. monotonous driving task in the static seat condition during the first half of the driving session and then in the static (static-static, SS) or motion seat (static-motion, SM) condition during the second half of the driving session. While

10.4% ~ 40.0% of significant increases in SDLP, BRT, and PERCLOS for the SS condition were identified in the second half of the driving session compared to the first half, there were no significant differences between the driving sessions for the SM conditions. In addition, significantly lower subjective state changes were identified for overall fatigue, mental fatigue, passive TR fatigue, driving safety, drowsiness, and degradation in concentration, but not for physical fatigue and active TR fatigue, in the SM conditions than those in the SS condition.

Lastly, the effectiveness of a motion seat system on the driver's passive TR fatigue was validated by using automotive and physiological sensors those applicable to the on-road driving environment. 20 drivers with more than two years of driving experience participated in an on-road experiment with two driving conditions: static–static (SS) and static–motion (SM) conditions. The SM condition showed significantly lower passive TR fatigue by 4.4% ~ 56.5% compared to the SS condition in terms of the standard deviation of velocity, PERCLOS, and LF/HF of electrocardiography signals. The drivers rated significantly lower subjective state changes of overall fatigue, mental fatigue, passive TR fatigue, drowsiness, and decreased concentration in the SM condition than those in the SS condition.

The motion seat system developed in the present study can contribute to mitigating passive TR fatigue by increasing mental alertness during monotonous driving. The findings of the passive TR fatigue reduction of the motion seat system can be used to help the driver reduce the degradation of alertness in a partially autonomous vehicle or a long-haul transportation vehicle. Next, the motion seat system which does not provide secondary tasks to the driver can be preferred to existing interactive technologies because it is less distracting during driving.

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Chapter 1 INTRODUCTION

1.1. Problem Statement

Driver fatigue can cause traffic accidents by degrading the driving capability of the driver. Driving is a complex task requiring cognitive and motor functions such as visual-spatial processing, attention, and reaction (Shinar, 1993). Driver fatigue decreases the capabilities of sensorimotor functions, information processing, physiological arousal, and reaction, impairing the capability of the driver to effectively avoid accidents (Williamson et al., 1996; Kaplan & Prato, 2012; Tzamalouka et al., 2005). Studies have reported that 20% ~ 30% of road accidents are attributed to driver fatigue (Balkin et al., 2011; MacLean et al., 2003); for example, Hartley (2004) reported that driver fatigue is attributable to 35% of all fatal crashes in rural areas and 12% of those in urban areas driver fatigue.

Driving fatigue can occur even under a low workload situation such as a monotonous or partially automated driving environment. Desmond & Hancock (2001) classified driving fatigue into active task-related (TR) fatigue in a high workload condition and passive TR fatigue in a low workload condition. For example, active TR fatigue can occur in a high workload situation such as driving in heavy traffic or severe weather conditions, while passive TR fatigue can occur in a low workload situation such as driving on a monotonous highway or in a partially autonomous vehicle (Desmond & Hancock, 2001; Gimeno et al., 2006). Oron-Gilad et al. (2008) proposed a driver's workload model of driver state and situational demand to explain that the driver workload can vary depending on a driver's state

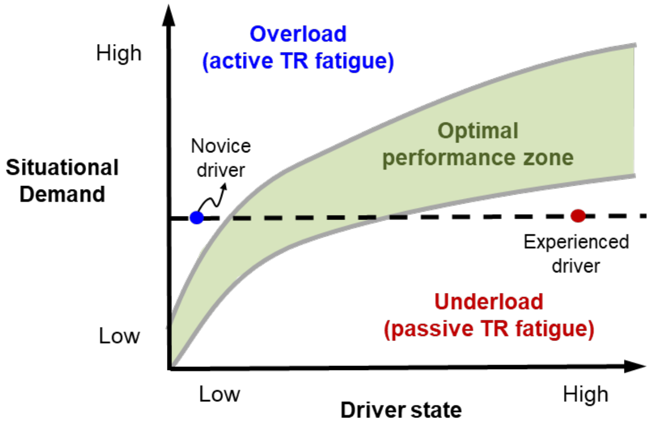


Figure 1.1. Driver workload and types of task-related (TR) fatigue by driver state and situational demand

for a particular level of situational demand. For example, Figure 1.1. shows that a partially automated driving condition requiring a relatively low situational demand compared with a manual driving condition may cause passive TR fatigue to an experienced driver due to the underload condition, but active TR fatigue to a novice driver due to the overload condition. Note that driver state is determined by various personal factors including driving experience, personality, and motivation.

Previous studies have reported that secondary tasks and sensory stimulation, which have been developed to increase the situational demand/cognitive workload of a driver, would be effective countermeasures to mitigate passive TR fatigue during monotonous driving. In terms of secondary tasks, Verwey & Zaidal (1999) demonstrated that an attention-demanding secondary game such as the card game '21' or Tetris on a speech-controlled game box system increased subjective alertness and task engagement compared to the normal driving condition. Oron-Gilad et al. (2008), Gershon et al. (2009), and Song et al.

(2017) have reported that an interactive cognitive task (ICT) such as trivia was effective in preventing passive TR fatigue by increasing the physiological arousal, vehicle control stability, and ratings of subjective motivation. However, Reid (1997) reported that the driver might miss events hazardous to driving safety if the secondary task requires excessive attention from the driver. Therefore, Oron-Gilad et al. (2008) stated that the development of secondary tasks that increase the overall demand on the driver without distracting the driver from the primary driving task is needed. In terms of sensory stimulation, the effectiveness of various countermeasures such as thermal stimuli, haptic stimuli, and postural change to mitigate passive TR fatigue by increasing mental alertness during monotonous driving has been examined. For example, Schmidt et al. (2019) reported that 15°C thermal stimuli directed to the face of a driver from the air vents of the center fascia increased the pupil diameter and significantly decreased the sleepiness level by 0.5 ~ 0.6 points using the 9-point Karolinska Sleepiness Scale (Shahid et al., 2011). Gasper et al. (2017) confirmed that the haptic stimuli by vibration pulses on the left and right sides of the driver's seat cushion improved driving performance in terms of lane departure and vehicle stability under the 45-min of sleep deprivation driving condition. Varela et al. (2017) reported that fore-aft seat movement, cushion tilt, and backrest recline motions could improve the awakening, alertness, and concentration of the driver through debriefing performed after 60-min of simulated driving.

The effectiveness of a motion seat system, which was developed by a research group including the authors to reduce driving monotony under low workload situations, needs to be evaluated in terms of passive TR fatigue reduction. The motion seat system changes its

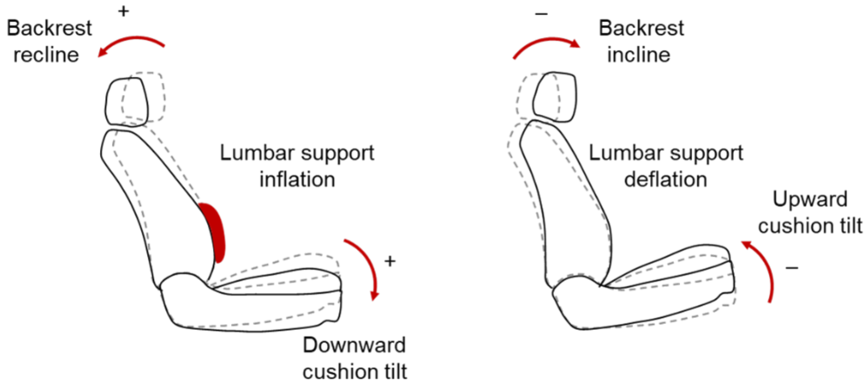


Figure 1.2. A motion seat system for continuous posture variation (illustrated)

backrest recline, cushion tilt, and lumbar support inflation/deflation by a proprietary control protocol as illustrated in Figure 1.2 to increase the level of situational demand for the driver in the seat during monotonous driving. Existing studies have examined the effectiveness of a seat having dynamic features in terms of biomechanical measures such as lumbosacral force and torque, seating pressure distribution variation, lumbar discomfort, and buttock numbness, but not in terms of passive TR fatigue measures such as driving performance, physiological response, and alertness. For example, Van Geffen et al. (2010) identified that cushion tilt motion was highly correlated ($r^2 > 0.8$) with lumbosacral force and torque estimated by the seating pressure distribution of the backrest interface, which supports the applicability of cushion tilt motion to reduction of lumbar discomfort in a prolonged static sitting. Aota et al. (2007) found that lumbar support inflation/deflation motion reduces buttock numbness by 37% by increasing the pressure distribution variation of the human-seat interface. Based on a questionnaire taken by participants after 45 minutes of sitting, Van

Veen et al. (2015) reported that cushion tilt and backrest recline motions made the drivers significantly more active, energetic, stimulated, and pleasantly surprised.

On-road driving evaluation is needed to ensure the validity of the passive TR fatigue reduction effect of interactive technology. A driving scenario with low variability in roadside scenery and traffic flow is administered in a lab experiment to induce passive TR fatigue from the driver (Thiffault & Bergeron, 2003; Oron-Gilad et al., 2007; Ting et al., 2008; Larue et al., 2011; Gastaldi et al., 2014). However, it is challenging to cause passive TR fatigue in an on-road experiment because on-road driving often requires a high level of vigilance from the driver or various environmental factors such as a sudden change in traffic or weather can affect the level of vigilance by acting as external stimuli (Nilsson et al., 1997; Oron-Gilad & Ronen, 2007; Song et al., 2017). For example, Philip et al. (2005) reported that inappropriate line crossing was increased by prolonged driving in the simulation driving condition, but no significant changes in driving performance could be observed in the first 2 h of on-road driving because the driver might allocate more attention to possible hazardous events. Lastly, de Winter et al. (2012) discussed that simulated driving environments might induce demotivation or unrealistic driving behaviors from participants due to lacking fidelity.

1.2. Objectives of the Study

The present study is to achieve four specific objectives as follows: (1) development and evaluation of statistical estimation models for hip locations (HLs) and eye locations (ELs) of the driver, (2) development of the motion seat system and its motion profiles to reduce

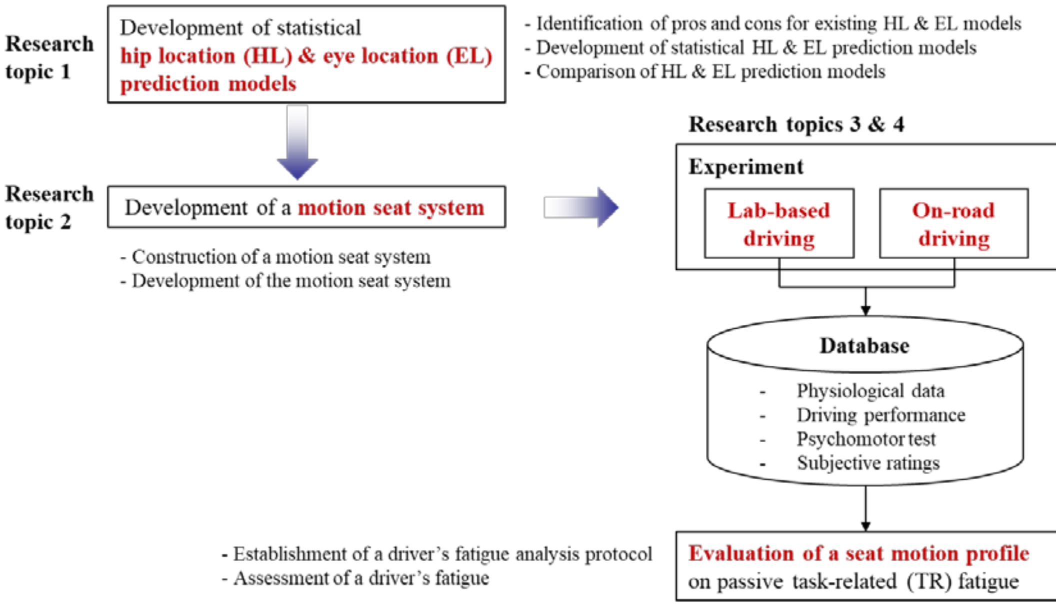


Figure 1.3. Research framework

passive TR fatigue during monotonous driving, (3) examination of the passive TR fatigue reduction effects of the motion seat system through simulation driving in a lab environment, and (4) validation of the passive TR fatigue reduction effects of the motion seat system in an on-road driving environment.

First, the present study is intended to develop regression equations which estimate a driver's HL and EL using anthropometric variables, joint angle, and seat adjustment variables. Measurements of HLs, ELs, and seat configurations of participants in a driving simulation seating buck were collected using a motion capture system. Multiple regression analysis was adopted to develop the statistical HL and EL estimation models using anthropometric information of the driver, driving posture, and seat adjustment variables such as fore-aft seat position and backrest angle. The proposed HL and EL models were compared with existing models in terms of adjusted R^2 and root mean square error (*RMSE*).

Second, a motion seat system and its motion profiles were developed to increase the level of situational demand for the driver in the seat during monotonous driving. The motion seat system was constructed using the driver seat and PC-based seat control system developed in this study. Next, two types of motion profiles (bow and wave) that provide coordinated motions of backrest recline, cushion tilt, and lumbar support inflation/deflation were developed to induce the stretching and flexion of the whole body. The eye location correction algorithm was applied to motion profiles to fix the eye position during the driving task using statistical HL and EL estimation models developed in the present study.

Third, the present study examined the passive TR fatigue reduction effects of the motion seat system in terms of driving performance, physiological response, and subjective fatigue through simulation driving in a lab environment. A driving scenario on a 130-km long monotonous highway was planned to induce passive TR fatigue on a driver. Standard deviation of lane position (SDLP), brake reaction time (BRT), heart rate variability (HRV), and percentage of eyelid closure rate (PERCLOS) were measured while a participant simulated the monotonous driving task in a driving simulator; subjective fatigue was evaluated before and after the driving session.

Lastly, the present study validated the effectiveness of passive TR fatigue reduction of the motion seat system through on-road driving in a monotonous highway. An on-road driving route of the Daegu-Pohang highway, which was reconstructed in the driving scenario of the lab-based driving simulation, was selected due to monotonous driving environment.

Standard deviation of longitudinal velocity (SD of velocity), steering wheel rate (SR), HRV, and PERCLOS were measured, and fatigue behaviors of the driver were recorded using three cameras while a participant performed the monotonous driving task; subjective fatigue was evaluated before and after the driving session.

1.3. Significance of the Study

The present study on the motion seat system has three areas of significance, theoretically and practically. First, the proposed HL and EL prediction models can be effectively applied to the design of OPL by estimating the information of the HL and EL distributions. The HL and EL estimation models developed in the previous studies are insufficient to consider various seat control parameters such as fore-aft seat position, seat height, seatback recline angle, and cushion tilt angle. Although previous studies include seat height (SAE J4004; SAE J941; Reed et al., 2002; Park et al., 2016) and cushion tilt angle (Reed et al., 2002), some seat control parameters such as fore-aft seat position and seatback recline angle are not included in HL and EL estimation. HL and EL estimation models which include a comprehensive set of seat control parameters would be effectively used to design the neutral positions and adjustment ranges of OPL components.

Second, the passive TR fatigue assessment method developed in the present study can be applied to the identification of the effect of various driving fatigue factors on passive TR fatigue in the lab and/or on-road driving environment. Objective measures including driving performance measures (e.g., lateral positioning variability and brake reaction time) and physiological response measures (e.g., heart variability measures and eyelid closure rate) were employed in the present study as those applicable to on-road driving evaluation and sensitive to driver fatigue. Of the driving performance and physiological response measures, those less applicable to on-road driving evaluation due to on-road driving safety, sensitivity to a noisy environment, and driver discomfort were excluded from the lab-based simulation study stage. A multidimensional driver fatigue evaluation questionnaire consisting of eight questions was developed in the present study based on a review of existing questionnaires as those related to passive TR fatigue.

Third, the motion seat system developed in the present study can be used to help the driver reduce the degradation of alertness in a partially autonomous vehicle or a long-haul transportation vehicle. Vehicle automation taking over the role of the steering wheel control and/or acceleration and deceleration control to the vehicle is effective to decrease active TR fatigue by reducing the task demands on the driver. However, compared to manual control, partial automation or conditional automation requiring sustained monitoring by the driver can increase cognitive fatigue, brake response time, and steering wheel reaction time due to passive TR fatigue from increased monotony. Next, previous studies have reported that occupational drivers of commercial vehicles such as heavy trucks and buses are more likely to be exposed to higher driver fatigue than non-commercial vehicle drivers due to prolonged driving periods and boredom in work conditions. Therefore, the motion seat system can be applied as an effective countermeasure to mitigate passive TR fatigue while driving a partially autonomous vehicle and long-haul transportation vehicle.

1.4. Organization of the Dissertation

The remainder of this dissertation is organized into eight chapters and four appendices. Chapter 1 describes the background, objectives, and significances of the study. Chapter 2 reviews literature that is relevant to the present study, including the mechanism of driver fatigue, various methods for the driver fatigue assessment, and strategies of driver fatigue reduction. Chapter 3 describes the development of seat configuration- and driving posture-based models to predict drivers' hip and eye location. Chapter 4 describes the development of the seat motion profiles to provide coordinated motions of backrest recline, cushion tilt, and lumbar support inflation/deflation. Chapter 5 describes passive TR fatigue reduction effects of the motion seat system in terms of driving performance, physiological response, and subjective fatigue through simulation driving in a lab environment. Chapter 6 describes the on-road driving evaluation of the motion seat system to ensure the passive TR fatigue reduction effects in a real driving environment. Chapter 7 discusses the effectiveness and limitations of the present study and suggests agendas for future studies, and lastly chapter 8 describes the conclusion of this study.

Chapter 2 LITERATURE REVIEW

This chapter aims to provide the necessary background for identifying driver fatigue. Section 2.1 reviews existing theories on driver fatigue and provides an understanding of the importance, causes and consequences of human factors during driving tasks. Section 2.2 is a literature survey of a wide range of methods which can be used to assess driver fatigue using driving performance, physiological responses, performance tests, and subjective fatigue questionnaire. Lastly, section 2.3 explains various driver fatigue countermeasures that are developed/evaluated by previous research.

2.1. Definition of Driver Fatigue

Generally driver fatigue means a state of deteriorated work efficiency or a state of mental hesitation to performing a driving task. While the concept of driver fatigue is easily understood, there was no common agreement on the definition of driver fatigue. For example, Brown (1994) defined fatigue as a disinclination to continue performing the task, and that it involved an impairment of human efficiency when work continued after the person had become aware of their fatigued state. Verwey & Zaidel (1999) explains that driver's fatigue and drowsiness are conditions that impair drivers' information processing, thus increasing the likelihood of various perceptual and attention errors. Thiffault & Bergeron (2003) reported that fatigue is a general term which relates to both physiological and psychological process. Therefore, this section explains driver fatigue in terms of physical, sleep-related

(SR), task-related (TR) fatigue by considering various factors contributing to driver fatigue such as muscle pain, sleep deprivation, and driving environment.

2.1.1. Physical Fatigue

Physical fatigue is usually reflected by reduced muscular power and slowed body movement. In a stressed muscle, lactic acid and carbon dioxide accumulate while muscular fatigue occurs, and people usually find the muscular tissue becomes acidic, due to consumption of energy reserves (such as glucose and phosphorous) to supply energy needed for human activities of the driving task. Grandjean (1979) discussed that muscular fatigue contributes to impaired co-ordination and increased chances of errors and accidents. Physical fatigue is a complex phenomenon influenced by numerous psychophysiological factors and has been linked with: (1) a decline in alertness, mental concentration and motivation, (2) reduced work output, (3) weaker and slower muscular contractions, (4) muscular tremor and localized pain, (5) loading of respiratory, circulatory and neuromuscular functions, (6) a decrease in the frequency of the electromyogram (EMG) signal, (8) a decrease in duration of sustained isometric exertions and endurance time (9) increased lactate accumulation, and (10) increased core temperature (Basmajian & De Luca, 1985; Åstrand & Rodahl, 1986). Sufficient physical rest and energy intake are necessary for muscular fatigue recovery, during which the muscular tissue regains a normal internal environment. People can usually notice muscular/physical fatigue by themselves, through physical fatigue symptoms such as slowed movement, reduced muscular capacity, muscle soreness.

2.1.2. Sleep-Related (SR) Fatigue

SR fatigue can be caused by circadian rhythms, sleep deprivation, and sleep restriction. Sleep patterns follow the body's natural circadian rhythm or internal clock, which drives humans to sleep during the night and be awake during the day. The circadian rhythm also produces an alertness dip in the early afternoon during which people are sleepier (Monk, 1991). For instance, Pack et al. (1995) reported that an increased amount of sleep-related crashes occur between 2 and 6:00 am and also between 2 and 4:00 pm. Circadian effects have also been demonstrated during a driving simulator task because Lenne et al. (1997) demonstrated that speed deviation varied significantly as a result of time of day, with the greatest variability occurring at 6:00 am, 2:00 pm and 2:00 am. SR fatigue is also influenced by homeostatic factors, such as the duration of wakefulness and sleep deprivation. Performance becomes worse the longer a person remains awake. Sleep restriction, or not obtaining adequate sleep will also result in increased sleepiness and a decline in performance.

2.1.3. Task-Related (TR) Fatigue

TR fatigue is caused by the driving task and driving environment. Desmond & Hancock (2001) classified driving fatigue into active TR fatigue in a high workload condition and passive TR fatigue in a low workload condition. For example, active TR fatigue can occur in a high workload situation such as driving in heavy traffic or severe weather conditions, while passive TR fatigue can occur in a low workload situation such as driving on a monotonous highway or in a partially autonomous vehicle (Desmond & Hancock, 2001; Gimeno et al., 2006). Oron-Gilad et al. (2008) proposed a driver's workload model of driver state and situational demand to explain that the driver workload can vary depending on a driver's state for a particular level of situational demand. For example, Figure 2.1 shows that a partially automated driving condition requiring a relatively low situational demand compared with a manual driving condition may cause passive TR fatigue to an experienced driver due to the underload condition, but active TR fatigue to a novice driver due to the overload condition.

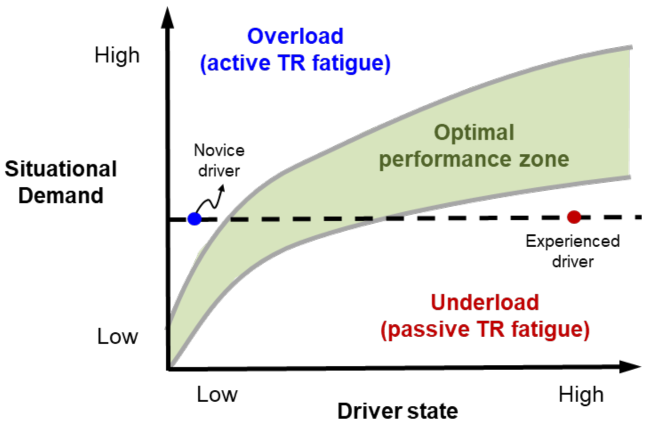


Figure 2.1. Driver's workload model: Active task-related (TR) fatigue and passive TR fatigue by driver state and situational demand

TR driver fatigue can be explained by resource theories and adaptive models of stress or performance. Resource theory proposed that an individual can be characterized by a finite resource capacity for attention processing and the depletion of that capability as a function of the performance of a task. As illustrated in Figure 2.2, overall mental load (ML) can be specified as the proportion of the mental capacity used at the moment (O'Donnell & Eggemeier, 1986; De Waard, 1996), that is, the ratio between the amount of recruited resources (R) as a response to a demand and the capacity (K) available at the moment. Increased ML is experienced during monotony or fatigue due to decreased capacity (De Waard, 1996). The capacity can then be increased and ML reduced by increasing arousal.

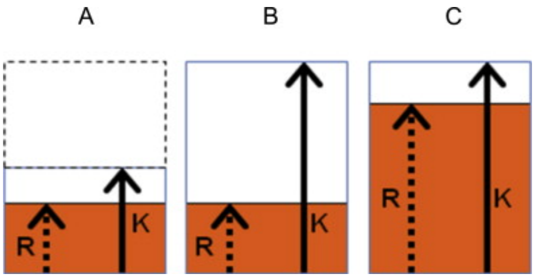


Figure 2.2. The mental load (ML) model of the resource used (R) and the available capacity (K). At low demands, the capacity can be increased by increasing arousal reducing ML (A to B). At high levels of demand capacity reaches its limit and more resources have to be mobilized with effort (C)

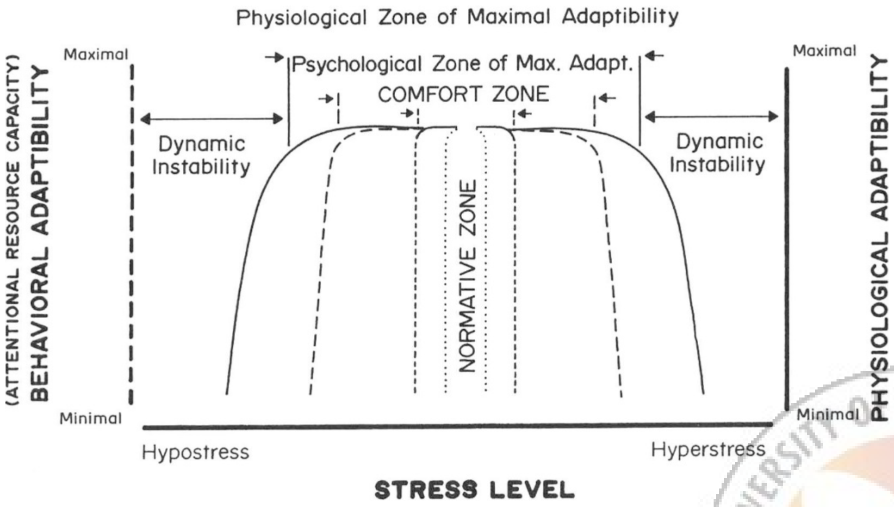


Figure 2.3. The extended-U model linking stress and human performance (Oron-Gilad & Hancock, 2005)

Also the recruited resources can be increased by mental mobilization or effort (Kahneman, 1973; Mulder, 1980) which then directly increases ML (Vicente et al., 1987). As shown in Figure 2.3, dynamic models of stress and sustained performance were based on the notion of adaptation to task demands (Oron-Gilad & Hancock, 2005). The dynamic models indicated that the drivers can maintain a specific skill level under a certain change in the load environment, but these models had a lower adaptability for underload/overload conditions.

The effect of active and passive fatigue on driving performances and subjective fatigue symptoms were differentiated through the simulation driving study. Active fatigue was induced through high workload wind gusts, which required the driver to actively steer and alternate acceleration changes, while passive fatigue was induced through required automation use and chronic under-stimulation (Saxby et al., 2007). Their results indicated that drivers are primarily subject to symptoms of increased distress during active fatigue induction, but experience of the passive fatigue induction increased task disengagement and distractibility. Essentially, the findings of Saxby et al. (2007) confirm some of the advantages of a multidimensional approach to defining and assessing subjective fatigue states as well as providing support for Desmond & Hancock's (2001) theory of active and passive fatigue, which suggests that driver responses can differ according to the nature of the fatigue induction. Next, Saxby et al. (2008) found that passive fatigue was associated with impaired alertness, but active fatigue was not. Drivers exposed to the monotony of full vehicle subsequently exhibited slowed braking and steering response times to a unexpectedly pulling out in front of them.

2.2. Assessment of Driver Fatigue

Various commonly used fatigue indicators were reviewed in the present study in terms of driving performance, psychological response, performance test, and subjective assessment. Studies on driver fatigue evaluation were searched by keywords including fatigue, monotony, sleepiness, drowsiness, vigilance, and alertness, and then 20 studies were screened for in-depth analysis.

2.2.1. Driving Performance

Driving performance reflects the driver ability to control the vehicle, and is essential to road safety. Driving performance can be categorized into three groups (see Table 2.1): (1) steering wheel control, (2) lateral position control, (3) speed control. First, representative steering wheel control measures were steering wheel angle input (SA), steering wheel rate (SR), and vehicle yaw rate (YR). Steering wheel angle input recorded instantaneous angular position of the steering wheel. Steering wheel rate was the time derivative of the steering wheel angle. Vehicle yaw rate recorded the rate of change in heading angles of the vehicle. Steering wheel control measures examined in the monotonous driving scenario show that more frequent large steering turns indicated more significant decrements in driving performance and increased fatigue levels in the more monotonous road scenario.

Second, lateral position control measures such as lateral position and lateral velocity account for the ability of the driver to maintain a safe distance to the road users on the roadway lanes. A lane-keeping task has been used to estimate driving performance and identify driver state by existing studies (Pilutti & Ulsoy, 1999; Thiffault & Bergeron, 2003). Lateral position was defined as the distance between the center line of the vehicle and the center of the current lane. Lateral velocity was the time derivative of lateral position. In general, the smaller of the mean value and standard deviation of the lane position, the better driving performance. When drivers are highly alert and able to concentrate, they can detect a very small deviation of the vehicle from the center of the lane, and can quickly respond to this deviation by adjusting the steering wheel to avoid propagation in this deviation. Trying to keep the vehicle at the center of the lane, the mean of the lane position is usually close to zero. Therefore, the mean and standard deviation of the lane position are both small when the driver is not fatigued.

Lastly, the third group was related to speed control, including longitudinal speed and acceleration. This can be checked through the following metrics from the vehicle comportment on the road; the average speed and the standard deviation of speed. It is also possible to assess it by the driver behaviour through the actions on pedals (Oron-Gilad et al., 2008). The limitation of such an indicator is that it does not take into account the environment (road geometry) which has an impact on speed behaviour. Thus, such systems are limited to simple driving contexts and should be relevant in the case of a monotonous road design where the road is mainly straight. In the case of more complex road geometry, this indicator can only be used on road sections which are straight.

Table 2.1. Summary of fatigue measures of driving performance

Measures		Description	Changes in fatigue	References
Steering wheel control	Angle input	Angular position of the steering wheel	⇑	Larue et al. (2011); Thiffault & Bergeron (2003); Van Loon et al. (2015);
	Rate	Rate of the change in steering wheel angles	⇑	
	Yaw rate	Rate of the change in heading angles of the vehicle	⇑	
Lateral position control	Position	Distance between the vehicle and lane centre	⇑	Merat & Jamson (2013); Oron-Gilad et al. (2008); Saxby et al. (2013); Ting et al. (2008); Vester & Roth (2013);
	Velocity	Time derivative of the lateral position	⇑	
	Acceleration	2nd derivative of the lateral position	⇑	
Speed control	Velocity	Time derivative of the longitudinal position	⇑	Oron-Gilad et al. (2008); Larue et al. (2011); Ting et al. (2008)
	Acceleration	2nd derivative of the longitudinal position	⇑	

2.2.2. Physiological Responses

Many physiological methods such as brain activity, cardiac activity, and eye activity are available to measure the levels of driver fatigue (see Table 2.2). First, the most reliable and reproducible way to observe psychological effects of monotonous driving is to use an electroencephalography (EEG, Lal & Craig, 2005; Pollock et al., 1991; Tomarken et al., 1992). EEG provides measurements of brain activity by measuring and graphing voltage fluctuations on the surface of the head. EEG signals are analyzed in the frequency domain, and four different bands contain the information: α (0.5 ~ 4 Hz), β (4 ~ 8 Hz), θ (8 ~ 13 Hz), and δ (13 ~ 30 Hz). It has been observed that EEG θ and α frequencies rhythms increase during monotonous tasks (Lal & Craig, 2005; Steele et al., 2004). Larue et al. (2011) and Atchley et al. (2011) considered that the most reliable method to measure this variation is to use the following algorithm: $(\theta + \alpha)/\beta$. When increasing, this ratio between slow and fast wave activities indicate a decrement of alertness (Lal et al., 2003; Bastien et al., 2000). However, An EEG device cannot be used in a vehicle for at least three reasons: (i) the inconvenience for the driver, (ii) the prohibitive cost, and (iii) the noise introduced due to electromagnetic field interferences. Nevertheless, such a device can be used in a laboratory-based experiment so that correlation with driving performance (observed variables from the driver the car and the environment) can be isolated and investigated.

Second, Heart rate, measured by electrocardiography (ECG), can be monitored to assess the individual physiological level of workload. The heart rate reflects the interplay between the sympathetic nervous system (SNS) with the parasympathetic nervous system (PNS), which are both parts of the autonomic nervous system (ANS) (Sammito et al., 2016). The sympathetic branch is responsible for activated states and the PNS is responsible for relaxed states (Pattyn et al., 2008). The ANS releases a chemical with its parasympathetic branch which leads to an increase in the variability of heart rate (Sammito et al., 2016). There are several measures that describe the variability in the inter-beat intervals of the HR signal. So-called time domain measures are the standard deviation of normal-to-normal intervals (SDNN) and the root mean square of successive differences (RMSSD) of intervals. Most studies show that the metric heart rate, if it changes at all, increases and the metric heart rate variability decreases during effortful mental processing (Oron-Gilad et al., 2008). It has also been shown that heart rate decreases significantly during a monotonous driving task (Jap et al., 2009). Other HRV measures can be retrieved from a spectral analysis of the inter-beat intervals. The LF (low frequency component) reflects the oscillations that lie in the frequency band of 0.04 ~ 0.15 Hz, and the HF (high frequency component) in the band of 0.15 ~ 0.4 Hz, respectively. The HF is regulated by parasympathetic activity, whereas the LF is influenced by both the SNS and the PNS (Sammito et al., 2016). Driving studies showed an increase in LF (Eglund, 1982; Michail et al., 2008) and in the ratio LF/HF (Tran et al., 2009; Wang et al., 2017) during fatigue, while others have shown a decrease in LF/HF (Michail et al., 2008; Patel et al., 2011).

Lastly, the pattern of eye activities has been studied to develop fatigue indicators by some researchers. Eye movements are usually fast at normal conditions for people with no fatigue, but become slow and small when people become fatigued (Lal & Craig, 2001). For example, Bekiaris et al. (2001) and Lal & Craig (2001) reported that fast eye movements were observed when the driver was alert, whereas limited eye movements such as increased blink duration and frequency were investigated during fatigue. Körber et al. (2015) found a decrease in pupil diameter caused by monotony-induced fatigue. In general, the pupil diameter is regulated by the ANS, and reflects changes in emotional arousal (Partala & Surakka, 2003). Next, percentage of eye closure rate (PERCLOS), the proportion of the time that the eyelids are closed by a designated percentage such as 70%, 75%, or 80% for a work period (Dinges et al., 1998; Li & Chung, 2013; Merat & Jamson, 2013), increases by fatigue. There was a significant increase in PERCLOS, both with increasing driving time (Grace, 2001; Hayami et al. 2002; Verwey & Zaidel 1999) as well with decreasing levels of attention (Bergasa et al. 2006; García et al. 2012).

2.2.3. Performance Tests

A performance test is used to study driver fatigue decrement through its impact on performance performing a task. The performance test often consists of a task which required several stages of information processing, and then level of fatigue has an impact on the results of these tasks. During a monotonous task, an increase in reaction times (RT) highlights a decrease in performance and hence of fatigue (Michael & Meuter, 2006). The arithmetic test is another example of a performance test, which involves basic numerical calculation. Arithmetic tasks were performed by subjects in an experiment, which was conducted to investigate the effects of traffic conditions on driver fatigue (Liu & Wu, 2009). The arithmetic task included additions and subtractions, and the subjects provided the answer orally. Increased fatigue also appears in the rate of correct detections of targets (missed targets are referred to as errors of omission) and the rate of non-targets reported (errors of commission) (Davies & Parasuraman, 1982). Such reaction times and accuracy are assessed through psychomotor tests, where a reduction of performance is interpreted as a sign of fatigue.

Table 2.2. Summary of fatigue measures of physiological response

Measures		Description	Changes in fatigue	References
Electroencephalography (EEG)	α wave power	α frequency band (0.5 ~ 4 Hz) power	⇑	Lal & Craig (2005); Steele et al. (2004)
	β wave power	β frequency band (4 ~ 8 Hz) power	↘	Lal & Craig (2005);
	θ wave power	θ frequency band (8 ~ 13 Hz) power	⇑	Campagne et al. (2004); Lal & Craig (2005); Steele et al. (2004);
	δ wave power	δ frequency band (13 ~ 30 Hz) power	⇑	Lal & Craig (2002);
	α/β wave power	Ratio of α frequency band power to β frequency band power	⇑	Oron-Gilad et al. (2008);
	$(\theta + \alpha)/\beta$ wave power	Ratio of θ and α frequency band power to β frequency band power	⇑	Atchley et al. (2011); Lal et al. (2003); Larue et al. (2011)
Electrocardiography (ECG)	Heart rate	Speed of the heartbeat measured by the number of contractions	↘	Lal & Craig (2000);
	SDNN	Standard deviation of normal to normal intervals	⇑	Kaida et al. (2007); Larue et al. (2015)
	RMSSD	Root mean square of successive differences of intervals	⇑	Kaida et al. (2007); Zhang et al. (2018)
	Low frequency power (LF)	Low frequency band (0.04 ~ 0.15 Hz) power	↘	Michail et al. (2008)
	High frequency power (HF)	High frequency band (0.15 ~ 0.4 Hz) power	⇑	Michail et al. (2008); Verwey & Zaidal (1999)

Measures		Description	Changes in fatigue	References
	Ratio of LF to HF (LF/HF)	Ratio of low frequency band power to high frequency band power	↘	Li & Chung (2013); Michail et al. (2008); Patel et al. (2011); Zhang et al. (2018)
Eye activity	Blink frequency	Number of eyelid closures with a duration of 50 to 500 ms	⇑	Körber et al. (2015); Larue et al. (2015)
	Blink duration	The elapsed time of eyelid closures with a duration of 50 to 500 ms	⇑	Körber et al. (2015)
	Eye closure time	The elapsed time of eyelid closures excess of 500 ms	⇑	Verwey & Zaidal (1999)
	Percentage of eyelid closure rate (PERCLOS)	The proportion of the time that the eyelids are closed by a designated percentage such as 70%, 75%, or 80% for a work period	⇑	Li & Chung (2013); Merat & Jamson (2013); Van Loon et al. (2015)

2.2.4. Subjective Assessments

Subjective assessment such as single- and multi-dimensional questionnaire is a traditional key measure in fatigue-related studies due to simple, direct, non-intrusive, and reasonably reliable method. First, single-dimensional questionnaire such as the Karolinska-Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990) and Stanford Sleepiness Scale (SSS; Hoddes et al. 1973) asked drivers to rate their sleepiness on a scale with 7 to 9 verbal anchors (1 = Extremely alert, 5 = Neither alert nor sleepy, 9 = Extremely sleepy for the KSS; 1 = Feeling active, 4 = Somewhat foggy, 7 = No longer fighting sleep for the SSS). The validity of KSS values could be confirmed by comparison with other indicators of fatigue. For example, Reyner & Horne (1998) found a positive correlation between the KSS value and the number of lane crossings. Horne & Baulk (2004) were able to confirm positive correlations of KSS values with the values from EEG measurements and Forsman et al. (2013) with the reaction time. Second, of the multi-dimensional questionnaires, Swedish Occupational Fatigue Inventory (SOFI; Åshberg, 1998) and Dundee Stress State Questionnaire (DSSQ; Matthews & Desmond, 1998) assess transient states associated with stress, arousal, and fatigue, and reflect the multidimensionality of these states, how changes in task engagement (and presumably boredom) vary with the cognitive demands of the task (Matthews & Desmond, 1998; Saxby, 2007). The SOFI inventory has been developed for measuring fatigue in five dimensions: (1) lack of energy, (2) physical exertion, (3) physical discomfort, (4) lack of motivation, and (5) sleepiness. The questionnaire includes 20 questions (4 for each dimension) with a Likert scale of 0 ~ 6 point (0 = not at all, 6 = extremely). The score on each dimension is the average of the responses to the four questions. The DSSQ assesses 11 scales for mood, motivation, and cognition in performance settings, grouped into three higher-order factors associated with task engagement (energy, task motivation, concentration), distress (tension, unpleasant mood, low confidence), and worry (self-focus, low self-esteem, task-related thoughts, task-unrelated thoughts). These three factors were estimated from the 11 primary scales using regression weights obtained from a large normative sample (Matthews et al., 2002).

2.3. Countermeasures of Driver Fatigue

Countermeasures of secondary tasks and sensory stimulation have been used to reduce the passive TR fatigue of the driver. First, various secondary task could be an effective countermeasure to prevent passive TR fatigue by increasing mental alertness during monotonous driving. For example, Verwey & Zaidel (1999) found that a speech-controlled game box system which provides a secondary task such as Tetris during driving decreased subjective drowsiness by 14.6% and the number of sleep-related errors including accidents and line crossing by 44.4% compared to the normal driving condition. Oron-Gilad et al. (2008) found that cognitive tasks, especially tasks involving long-term memory, helped maintain driver alertness during a monotonous long-haul driving. Gershon et al. (2009) reported that an interactive cognitive task (ICT) called “Trivia” in which drivers were asked questions via speakers in the fields of movies, sports, current events, general knowledge and cuisine while driving manually in a simulator increased physiological arousal and alertness. Similarly, Schömig et al. (2015) and Jarosch et al. (2017) demonstrated lower levels of subjective fatigue and lower PERCLOS while involving in a quiz task displayed on a tablet during an automated drive in simulators. However, secondary task bears the danger of completely turning the driver away from the driving task and thus poses a new safety risk. Reid (1995) reported that the driver might miss events hazardous to driving safety if the secondary task requires excessive attention from the driver. Therefore, Oron-Gilad et al. (2008) stated that the development of secondary tasks that increase the overall demand on the driver without distracting the driver from the primary driving task is needed.

Second, previous research demonstrated that sensory stimulation including haptic and thermal stimuli could be a possible countermeasure of passive TR fatigue. For example, Wang et al. (2017) reported that continuously exerts torque on a steering wheel increased physiological arousal and driving performance of the fatigued drivers. Zhang et al. (2018) reported that 4 ~ 7 Hz of vibration transmitted to the whole body from the seat while driving on a monotonous highway enhanced the alertness of the driver by increasing LF/HF. Next, Schmidt et al. (2019) reported that 15°C thermal stimuli directed to the face of a driver from the air vents of the center fascia increased the pupil diameter and significantly decreased the sleepiness level by .5 ~ .6 points using the 9-point KSS. Van Veen et al (2016) showed that repeated short-term cooling of the driver’s hands caused physiological arousal measured by an increase of heart rate.

Chapter 3 DEVELOPMENT OF HIP AND EYE LOCATION PREDICTION MODELS

This chapter is intended to develop statistical models which estimate a driver's hip location (HL) and eye location (EL) using anthropometric variables, driving postures, and seat configuration variables. Measurements of seat configurations, HLs, ELs, and sitting postures of participants in a driving simulation seating buck were collected using a motion capture system. Statistical HL and EL models were developed based on driving posture and seat configuration using multiple regression analysis. The proposed HL and EL models were compared with existing models in terms of adjusted R^2 and root mean square error (*RMSE*).

3.1. Participants

A total of 23 participants (10 females and 13 males) in their 20s to 50s ($M \pm SD = 29.3 \pm 7.3$; range = 24 ~ 51) having valid driving license participated in the experiment. Three stature groups (small: < 33^{rd} %ile, medium: 33^{rd} to 66^{th} %ile, and large: > 66^{th} %ile) were defined for each gender by referring to the 2010 Size Korea anthropometric survey (SizeKorea, 2010): for females, small: < 1,588 mm, medium: 1,588 to 1,611 mm, and large: > 1,611 mm; for males, small: < 1,686 mm, medium: 1,686 to 1,742 mm, and large: > 1,742 mm. Then, participants were recruited evenly for each group: for females, small: 3, medium: 4, and large: 3; for males, small: 4, medium: 5, and large: 4. The mean heights of female ($M \pm SD$

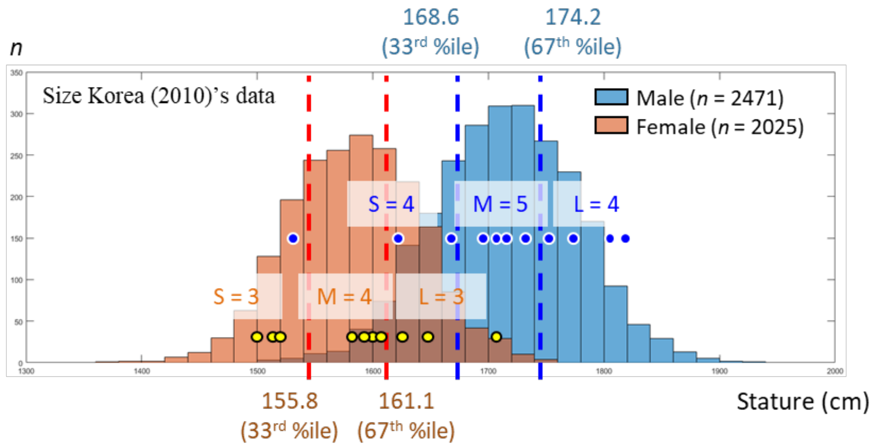


Figure 3.1. Stature distribution of Koreans in their 20s and 50s (Size Korea, 2010) and number of participants recruited by stature group (marked as circle)

= 1,584 ± 5.6; $t[2016] = 2.26$, $p = .54$) and male ($M \pm SD$ = 1,714 ± 6.1; $t[2459] = 2.18$, $p = .91$) participant groups were found similar with those of corresponding Korean population groups (see Figure 3.1). Excluded were from the experiment those having a history of musculoskeletal disorders, pains, and injuries. The experiment was approved by the Institutional Review Board of Pohang University of Science and Technology (PIRB-2016-E047).

3.2. Apparatus

A seating buck mounted with a power adjustable seat EQ900 (Hyundai-Kia Motors, Republic of Korea) and a G27 racing wheel and pedals (Logitech, Swiss) and a motion analysis system consisting of 8 Osprey cameras (Motion Analysis Co., Santa Rosa: CA, USA) were used in the driving simulation experiment. A PC-based seat control system developed in the present study to control the seat fore-aft position (adjustment range = -183.6 ~ 76.4 mm from seating reference point; SgRP), seat height (adjustment range = -43 ~ 32 mm from SgRP), seatback recline angle (SAE A40; neutral angle = 23°, and adjustment range = -23° ~ 44°), and cushion angle (SAE A27; neutral angle = 15° and adjustment range = -17° ~ 23°) was interconnected with the electronic control unit (ECU) of the seat. Driving postures and the configuration of the seat components were captured by the Osprey infrared cameras (frame rates = 60 Hz). As illustrated in Figure 3.2, the H-point of the seat was located by the seat design information, provided the seat manufacturer, explaining the relationship of the H-point location with the seatback hinge point and SgRP locations. The origin, positive x-axis, and positive z-axis of the seating buck were defined as the acceleration heel point (AHP), rearward direction, and upward direction, respectively, by following SAE J1100 (SAE, 2009).

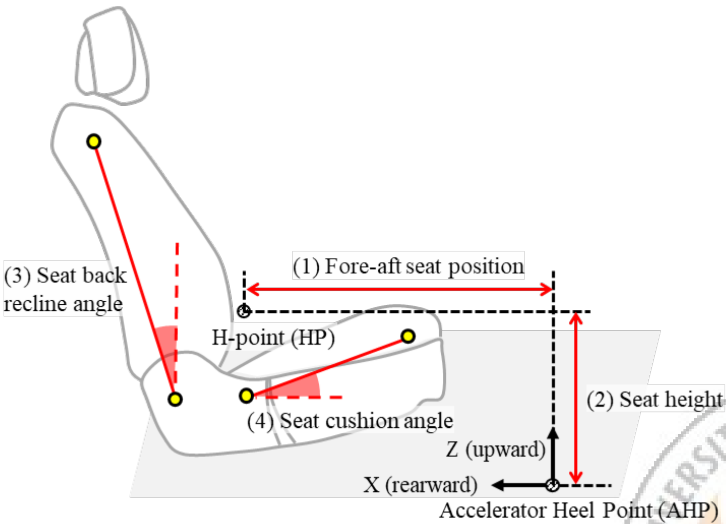


Figure 3.2. Definition of 3-dimensional coordinate system of the power adjustable seat

3.3. Experimental Procedure

The driving simulation experiment to collect driving postures of participants in various seat configurations in the seating buck was conducted in the preparation and main experiment stages. In the preparation stage, the purpose and procedure of the experiment were explained and informed consent was obtained. Then, the demographics of the participant including age, stature, and weight were recorded. A total of 19 retro-reflective markers (ϕ = 12.5 mm) were attached to the body (front head, right/left tragion, right/left acromion, right/left anterior superior iliac spine, right/left posterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, and second metatarsal head) as shown in Figure 3.3 by following the modified Helen-Hayes marker set to measure the joint angles of the body on the sagittal plane. In addition, four retro-reflective markers were attached to the seatback hinge point, cushion hinge point, top edge of seatback, and front edge of cushion to calculate fore-aft seat position, (2) seat height, (3) seatback recline angle, and (4) cushion angle. A sufficient period of time was provided for the participant to become familiarized with the seat adjustment mechanism of EQ900. In the main experiment stage, the seat was initially located to the neutral position (SAE L53 = 876 mm, SAE H30 = 221 mm, SAE A40 = 23°, and SAE A27 = 15°), and then the participant was asked to be seated and adjust the seat components to his/her preferred seating configuration. As completing the adjustment of the seating configuration, the participant was asked to hold the steering wheel at the 3 and 9 o'clock positions by the left and right hands, respectively, and place the left and right feet on the floor of the seating buck and the accelerator pedal, respectively (see Figure 3.4). A computer screen running a video clip is located to the eye level in front of the seating buck to help the participant maintain the seating posture watching the front. Seating postures of the participant and seat configurations were captured by the motion analysis system while simultaneously changing the fore-aft seat position by ± 60 mm, seat height by ± 25 mm, seatback recline angle by ± 5°, and seat cushion angle by ± 2.5° from the preferred seat configuration.

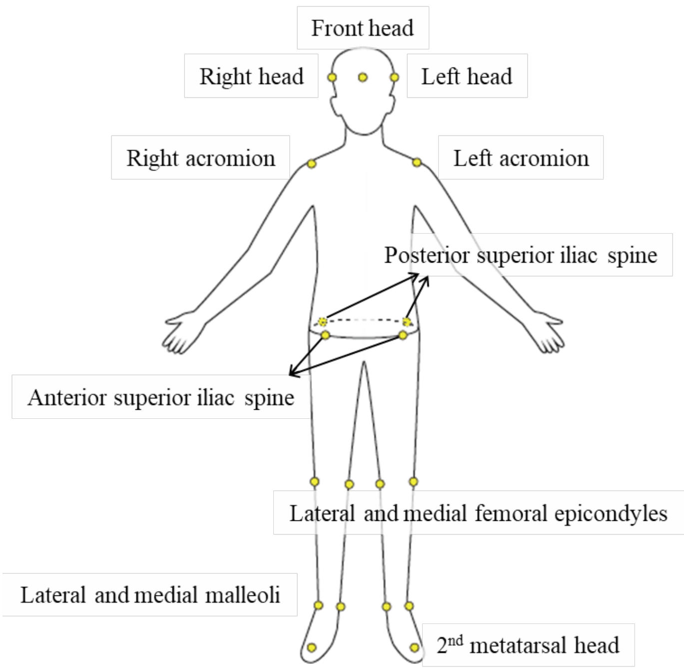


Figure 3.3. Attachment positions of 19 reflective markers to the body landmarks for acquiring hip locations, eye locations, driving posture

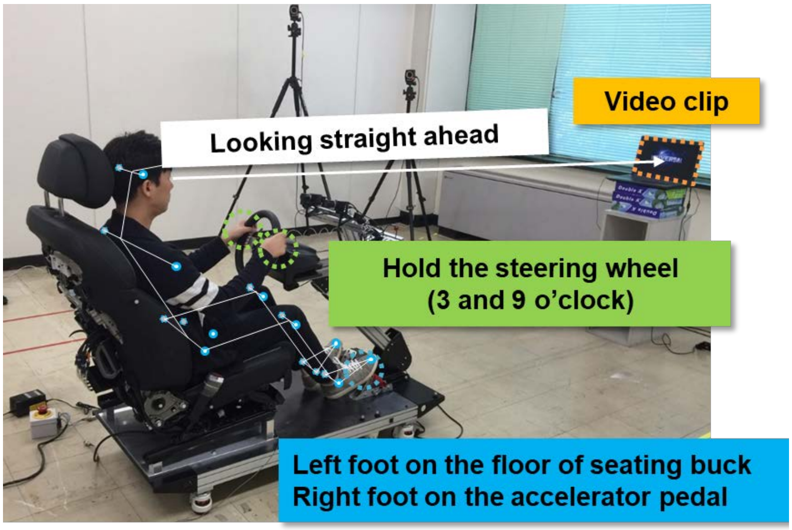


Figure 3.4. Instructions for maintaining a driving posture of the participants

3.4. Calculation of Driving Postures and Seat Configurations

The driving postures and seat configurations in the sagittal plan were calculated by the Euler angle rotation order. The kinematics and seat configuration data of the participant were smoothed by the zero-lag fourth-order Butterworth low-pass filter with a cut-off frequency of 15 Hz (Bisseling & Hof, 2006). Body joint centers were defined to establish a rigid body link consisting of six body segments (head, neck, trunk, thigh, shank, and foot). The hip joint center was determined by the location information of the markers attached to the right/left anterior superior iliac spine (ASIS) (Bell et al., 1989; Bell et al., 1990). As shown in Figure 3.6, a V-Mid-ASIS marker was virtually generated at the midpoint between the right and left ASIS markers and then the hip joint center was located to 64% lateral, 44% posterior, and 68% inferior (Bell et al., 1989; Bell et al., 1990) from the V-Mid-ASIS marker. The knee joint center was located at the midpoint of the lateral and medial femoral epicondyles markers and the angle joint center at the midpoint of the lateral and medial malleoli markers. The neck joint center was located the right and left acromion markers and the head center at the midpoint of the right and left head markers. By referring to the average tragion to ectocanthion distance (99.83 mm for males, 88.03 mm for females) presented in the 2010 Size Korea anthropometric survey (SizeKorea, 2010), the eye point on the sagittal plane is located horizontally from the right/left tragion markers.

The x-, y-, and z-axes of the global coordinate system were generated by the vectors to markers located at the rearward, inside, and upward directions, respectively, from AHP (see Figure 3.2). The fore-aft seat position and seat height were calculated as the horizontal distance on the x-axis and the vertical distance on the y-axis, respectively, between AHP and H-point. The seatback recline angle was calculated as the included angle of the vector connecting the marker located on the end of the seatback and the seatback hinge point from z-axis; the cushion tilt angle as the included angle of the vector connecting the marker located on the end of the cushion and the cushion hinge point from the x-axis. The measurement errors of seat configuration due to positions of markers were calibrated by comparing measurements of the seat configuration with the corresponding design specifications provided by the manufacturer by adjusting the seat to its minimum and maximum adjustment ranges.

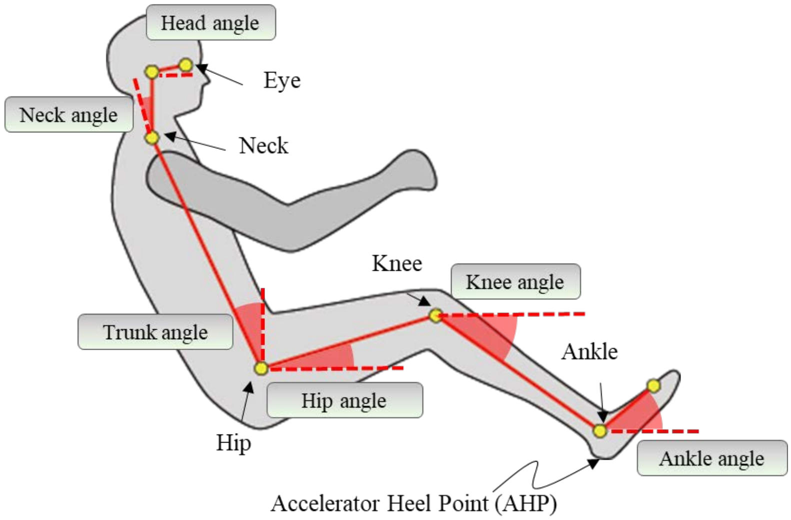


Figure 3.5. Illustration of body joint centers and kinematic linkage in a sagittal plane

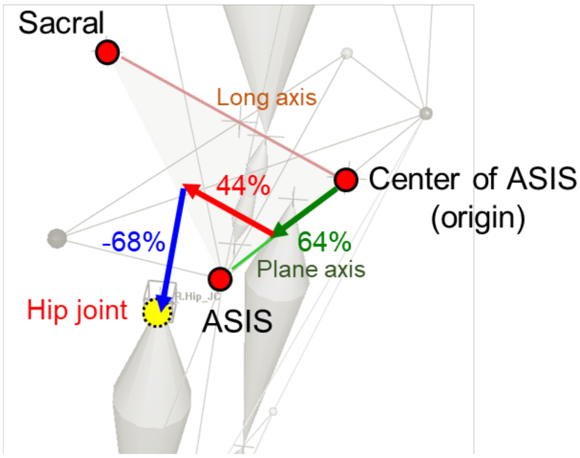
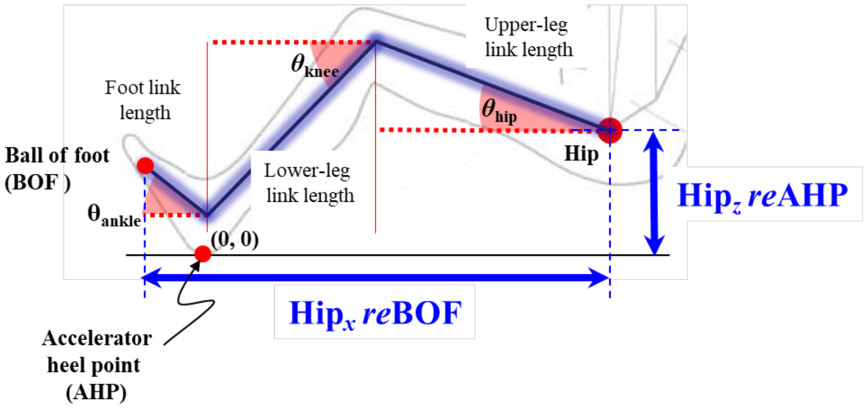


Figure 3.6. Definition of hip joint center

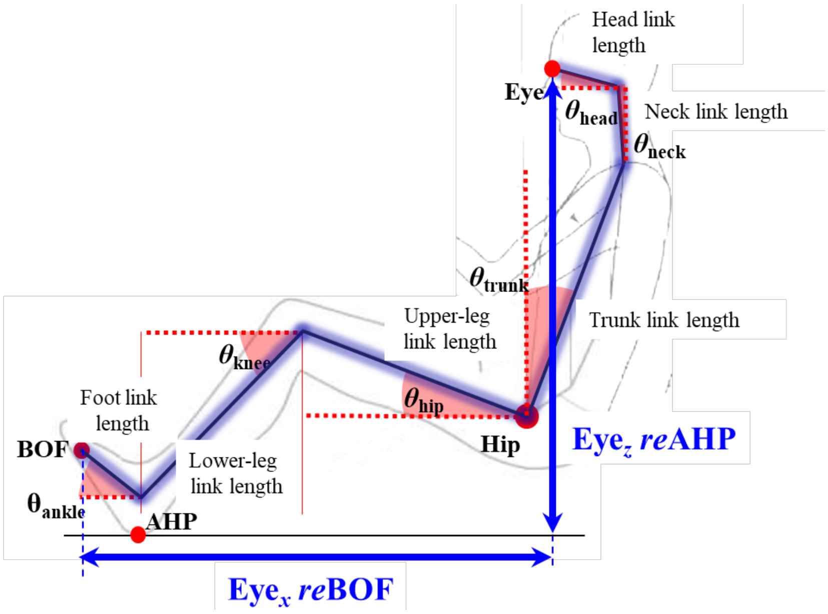
3.5. Development of Statistical Geometric Models

Estimation formulas of a driver's HL and EL were developed as two types of posture-based model and seat configuration-based model using the driver's posture and seat configuration variables as regressors. The horizontal and vertical components of the HL and EL estimation formulas were developed based on the ball-of-foot (BOF) of the accelerator pedal and the AHP, respectively. The posture-based models of HL and EL were developed using geometrical relationships of HL and EL with link lengths and joint angles. For example, as displayed in Figure 3.7, the models of horizontal HL (Hip_x *re*BOF) and vertical HL (Hip_z *re*AHP) were constructed using the lengths of femoral, shank, and foot links and the angles of hip, knee, and ankle. On the other hand, as illustrated in Figure 3.8, the seat configuration-based models of HL and EL were developed using stature of driver (S), fore-aft seat position (L53), seat height (H30), seatback recline angle (A40), and cushion tilt angle (L27). The horizontal components of HL and EL consist of S, L53, $\cos(\text{L27})$, and $\sin(\text{A40})$, while the vertical components include S, H30, $\sin(\text{L27})$, and $\cos(\text{A40})$.

The statistical driver HL and EL estimation formulas based on the driver's posture and seat configuration were developed by stepwise regression ($p_{\text{in}} < .01$ and $p_{\text{out}} < .05$) using Minitab release 14 (Minitab Inc., State College: PA, USA). To develop parsimonious models for HL and EL estimation for their practical use in OPL design of a vehicle, excluded were factors in which the regression performance did not improve at least .02% in adjusted R^2 even if found significant in stepwise regression. The multicollinearity between regressors was examined by checking values of variance inflation factor (VIF) are less than 1.5 for all the regressors (note that VIF > 5 or 10 indicates a multicollinearity problem; O'Brein, 2007). The performance of each HL and EL estimation formula was evaluated in terms of adjusted R^2 and root mean square error (*RMSE*). Lastly, 20% of the total captured data (n = 6,576) were randomly selected as a validation data set (n = 1,315) for cross validation of the HL and EL models in the present study and their comparison with existing HL and EL models (see Figure 3.9).



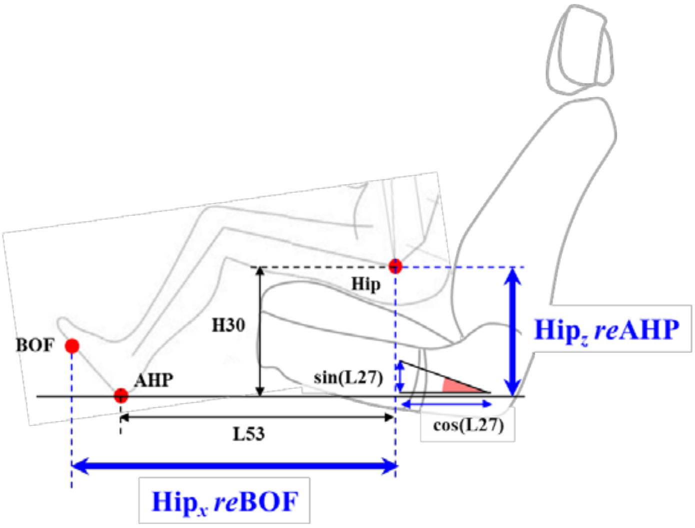
(a) Hip_x *re*BOF and Hip_z *re*AHP



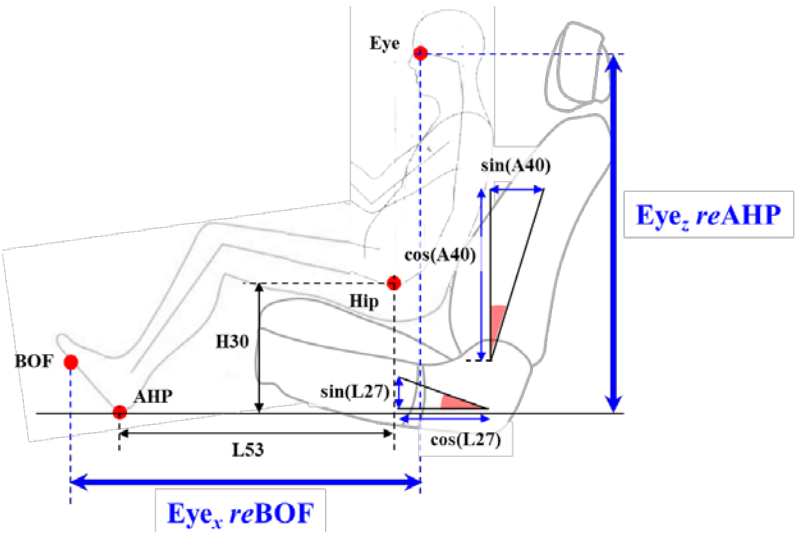
(b) Eye_x *re*BOF and Eye_z *re*AHP

Figure 3.7. Posture-related variables for predicting hip and eye locations of the driver

Note. BOF = ball of foot, AHP = accelerator heel point, FL = foot link length (mm), LL = lower leg link length (mm), UL = upper leg link length (mm), TL = trunk link length (mm), NL = neck link length (mm), HL = head link length (mm), θ_{ankle} = ankle angle (rad), θ_{knee} = knee angle (rad), θ_{hip} = hip angle (rad), θ_{trunk} = trunk angle (rad), θ_{neck} = neck angle (rad), θ_{head} = head angle (rad)



(a) Hip$_x$ *re*BOF and Hip$_z$ *re*AHP



(b) Eye$_x$ *re*BOF and Eye$_z$ *re*AHP

Figure 3.8. Seat configuration-related variables for predicting hip and eye locations of the driver

Note. S = stature, L53 = fore-aft seat position (mm), H30 = seat height (mm), A40 = seatback recline angle (rad), L27 = cushion tilt angle (rad)

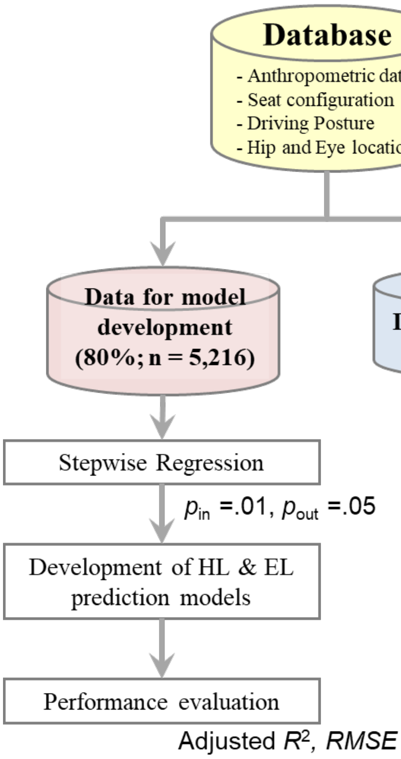


Figure 3.9. Procedure for developing driver's hip and eye locations prediction model

3.6. Statistical Hip and Eye Locations Prediction Models

Statistical posture- and seat configuration-based models were developed for HL and EL by incorporating both the geometric relationships of HL and EL with driving posture and seat control variables. As shown in Table 3.1, posture-based models for the horizontal HL (Hip_x *re*BOF) relative to the ball-of-foot (BOF) and the vertical HL (Hip_z *re*AHP) relative to the accelerator heel point (AHP) were constructed using the lengths of upper leg link, lower leg link, and foot link and the angles of hip, knee, and ankle. Similarly, the horizontal EL relative to the BOF (Eye_x *re*BOF) and the vertical EL relative to the AHP (Hip_z *re*AHP) were constructed using the lengths of trunk link, neck link, and head link and the angles of trunk, neck, and head in addition to those of the leg and foot. Next, as shown in Table 3.2, seat configuration-based models for the Hip_x *re*BOF and the Eye_x *re*BOF were constructed using the stature of the driver and horizontal components of the seat control variables such as fore-aft seat position (L53) and sine component of the seatback recline angle (A40). Similarly, the Hip_z *re*AHP and the Eye_z *re*AHP were constructed using the stature of the driver and vertical components of the seat control variables such as seat height (H30) and sine component of the cushion tilt angle (L27).

Table 3.1. Posture-based driver's hip and eye location prediction models

Hip and eye locations	**Prediction models**	**Adj. R^2**	***RMSE***
Hip_x *re*BOF	$133 + (0.316 \times FL \times \cos\theta_{ankle}) + (1.01 \times LL \times \cos\theta_{knee}) + (0.996 \times UL \times \cos\theta_{hip})$	0.90	26.3
Hip_z *re*AHP	$221 + (0.0438 \times FL \times \sin\theta_{ankle}) - (0.504 \times LL \times \sin\theta_{knee}) - (0.622 \times UL \times \sin\theta_{hip})$	0.68	15.6
Eye_x *re*BOF	$110 + (0.256 \times FL \times \cos\theta_{ankle}) + (0.981 \times LL \times \cos\theta_{knee}) + (0.950 \times UL \times \cos\theta_{hip}) + (0.918 \times TL \times \sin\theta_{trunk}) + (1.06 \times NL \times \sin\theta_{neck}) - (0.307 \times HL \times \cos\theta_{head})$	0.91	23.0
Eye_z *re*AHP	$245 + (0.0843 \times FL \times \sin\theta_{ankle}) - (0.481 \times LL \times \sin\theta_{knee}) - (0.343 \times UL \times \sin\theta_{hip}) + (0.880 \times TL \times \cos\theta_{trunk}) + (0.924 \times NL \times \cos\theta_{neck}) + (0.861 \times HL \times \sin\theta_{head})$	0.89	14.2

Table 3.2. Seat-configuration-based driver's hip and eye location prediction models

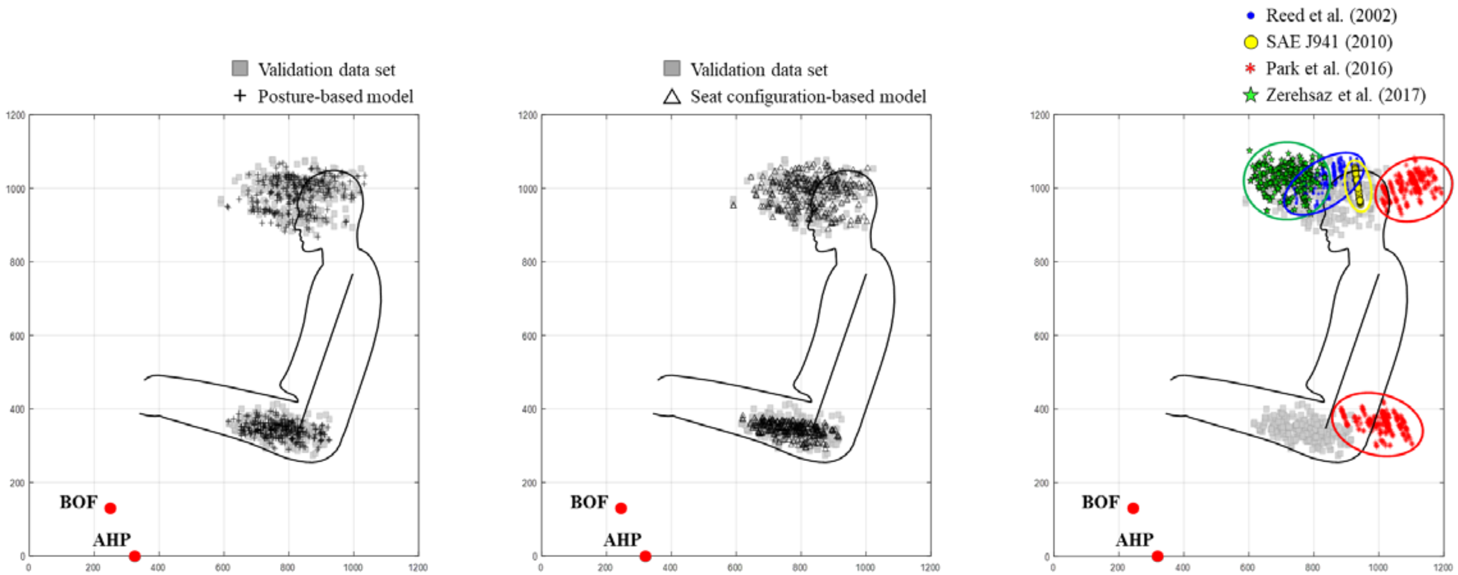
Hip and eye locations	**Prediction models**	**Adj. R^2**	***RMSE***
Hip_x *re*BOF	$-104 + (105 \times S) + (1.01 \times L53)$	0.91	17.7
Hip_z *re*AHP	$-50.9 + (8.23 \times S) + (0.907 \times H30) + \{115 \times \sin(L27)\}$	0.55	19.5
Eye_x *re*BOF	$221 - (87.4 \times S) + (1.04 \times L53) - \{693 \times \sin(A40)\}$	0.96	21.5
Eye_z *re*AHP	$-646 + (440 \times S) + (0.826 \times H30) + \{588 \times \sin(L27)\}$	0.82	16.8

As presented in Table 3.1 and 3.2, the developed posture- and seat configuration-based models showed high prediction performance in terms of adj. R^2 and *RMSE*. All the prediction models except for the vertical HL showed high prediction performance in terms of adj. R^2 for the posture-based models ($M \pm SD$ = .90 ± .01; *range* = .89 ~ .91) and seat configuration-based models ($M \pm SD$ = .90 ± .07; *range* = .82 ~ .96). In terms of *RMSE*, the prediction performance of all the prediction models showed small estimation errors for the posture-based models ($M \pm SD$ = 21.2 ± 6.3 mm; *range* = 14.2 ~ 26.3 mm) and seat configuration-based models ($M \pm SD$ = 18.7 ± 2.5 mm; *range* = 16.8 ~ 21.5 mm) and was found quite stable regardless of the regression variables used. No significant performance difference was found between the posture- and seat configuration models in terms of adj. R^2 ($t(3) = .87$, $p = .45$) and *RMSE* ($t(3) = .32$, $p = .77$).

The *RMSE* of the posture- and seat configuration-based models on the validation data set (for model development, $M \pm SD$ = 19.3 ± 4.1 mm; for model validation, $M \pm SD$ = 19.7 ± 4.6 mm) was similar to the development data set. As illustrated in Figure 3.10, HLs and ELs estimated using posture and seat configuration-based models are distributed similarly to the validation data set and showed high prediction performance in terms of *RMSE* (for posture-based models, $M \pm SD$ = 19.8 ± 5.8 mm; for seat configuration-based models, $M \pm SD$ = 18.9 ± 2.1 mm). The *RMSE* of the posture- and seat configuration-based models showed 1.7 ~ 15.7 times better prediction performance compared to the existing models when estimating HLs and ELs using the validation data set (Table 3.3).

Table 3.3. Comparison of prediction performance of the posture-based models, seat configuration-based models, and existing models on the validation data set

	Root mean squared error (*RMSE*) of existing models (mm)					
	Posture-based models	Seat configuration-based models	Reed et al. (2002)	SAE J941 (2010)	Park et al. (2016)	Zerehsaz et al. (2017)
Hip_x *re*BOF	24.3	21.6	66.2	-	243.0	-
Hip_z *re*AHP	14.2	16.8	-	-	29.9	-
Eye_x *re*BOF	27.8	17.7	86.9	135.8	277.4	124.5
Eye_z *re*AHP	16.0	19.5	48.1	55.4	32.2	44.1



(a) Posture-based models (b) Seat configuration-based models (c) Existing models

Figure 3.10. Comparison of predicted hip and eye location distributions using the (a) posture-based models, (b) seat configuration-based models, and (c) existing models on the validation set.

Chapter 4 DEVELOPMENT OF MOTION SEAT SYSTEM

This chapter describes a motion seat system developed in the present study to prevent the passive task-related (TR) fatigue of the driver. Section 4.1 describes the components of the motion seat system to control the seat positions such as hardware configuration, functions of the individual elements, and transmission of signals. Section 4.2 describes two types of bow and wave motion profiles developed with coordinated motions of backrest recline, cushion tilt, and lumbar support inflation/deflation. Lastly, section 4.3 describes the algorithm for compensating eye position changes of the driver by seat motion using the eye location prediction models developed in chapter 3.

4.1. Configuration of Motion Seat System

As shown in Figure 4.1, the motion seat system was constructed using the power-adjustable driver seat, electronic control unit (ECU) of the driver seat, controller area network (CAN) interface device, and PC-based seat control system. The ECU of the driver seat (EQ900 seat, Hyundai-Kia Motors, Korea) was connected with a CAN interface device (USB-8473, National Instruments, USA) and a PC-based seat control system to control the configuration of the seat according to a motion profile selected. The PC-based seat control system was developed to transmit electric pulses corresponding to the amount of adjustment range for each seat control variable selected by the user in the form of CAN signal according to the manufacturer's ECU design guidelines. For example, the seat height control variable, which is designed to move 0.063 mm per pulse by the ECU design guideline, adjusted by transmitting CAN signal of 100 pulses to the ECU when the user commands 6.3 mm of seat height adjustment through the PC-based seat control system. Note that the adjustment ranges of the power-adjustable seat for the fore-aft seat position (SAE L53), seat height (SAE H30), backrest recline angle (SAE A40), and cushion angle (SAE A27) are the same as those introduced in Chapter 3.2.

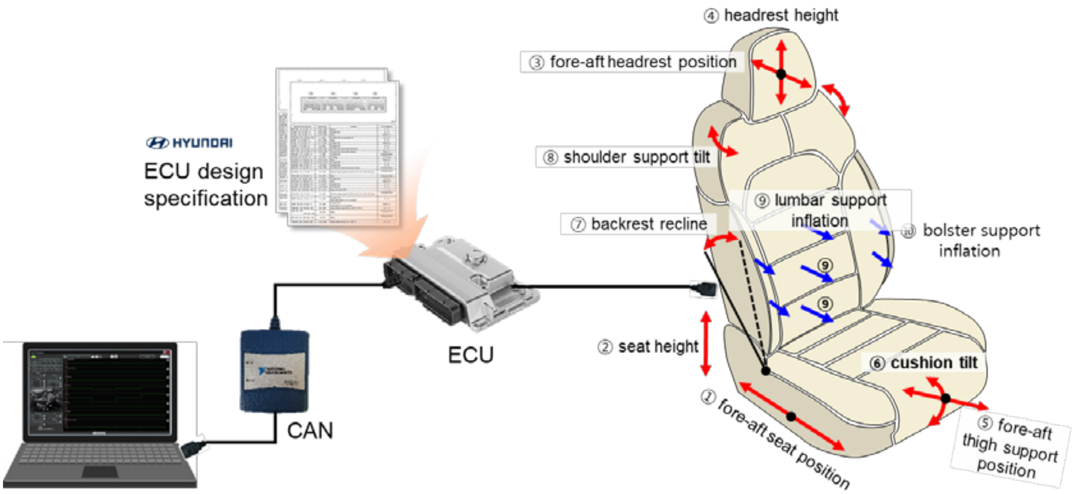
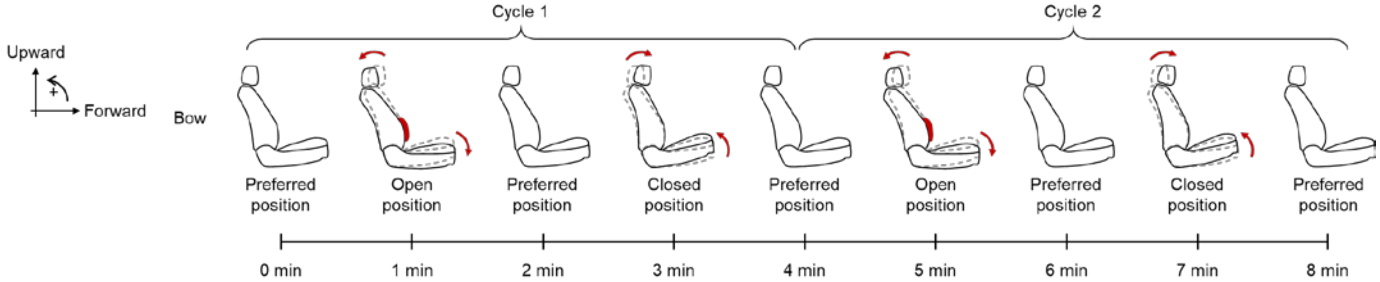


Figure 4.1. Architecture of motion seat system consisting of a power-adjustable seat, an electronic control unit (ECU), a controller area network (CAN) interface device, and a PC-based seat control system.

4.2. Development of Seat Motion Profiles

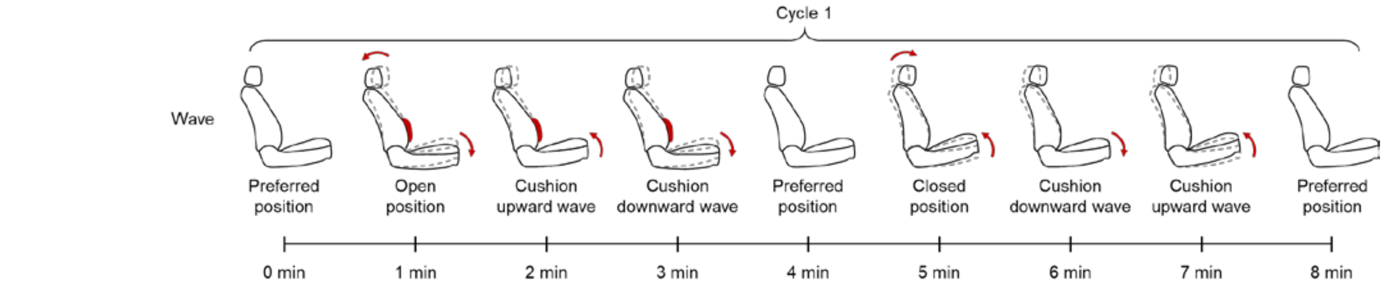
Backrest recline, cushion tilt, and lumbar support inflation/deflation were identified as important seat control variables that reduce the physical and/or mental fatigue of the driver. In terms of physical fatigue, the cushion tilt and lumbar support inflation/deflation motions could mitigate biomechanical, physiological, and subjective fatigue during prolonged sitting. Aota et al. (2007) reported that the continuous passive motion (CPM) device, which periodically changes the lumbar lordosis angle of the driver, decreases the buttock numbness by 27.1%, stiffness by 31.7%, and lumbar discomfort by 25.9% as compared to the no lumbar support condition. Similarly, Van Deursen et al. (2000) found that the CPM of the cushion tilt condition showed significantly lower leg swelling by 28% ~ 45% than the static seat condition. Durkin et al. (2006) demonstrated that the lumbar massage device using the roller, mechanical structure, or inflatable bladder could increase blood flow and oxygenation, which implies that the massage device could prevent the muscle fatigue of erector spinae during prolonged driving. Van Geffen et al. (2010) identified that cushion tilt motion was highly correlated ($r^2 > 0.8$) with lumbosacral force and torque estimated by the seating pressure distribution of the backrest interface, which supports the applicability of cushion tilt motion to the reduction of lumbar discomfort in a prolonged static sitting. In terms of mental fatigue, the backrest recline motion could be adopted to prevent driver fatigue along with the cushion tilt and lumbar support inflation/deflation motions. Comfort Motion Technologies (CMT) developed a power seat control system that provides subtle variations in a sitting position using the coordinated movement of backrest recline, cushion tilt, and lumbar support inflation/deflation (Dugan et al. 2009). Seat configuration changes by the CMT reported positive effects on biomechanical and physiological responses such as increased pressure distribution and blood flow and reduced reaction time compared to traditional static seat during the simulated driving task. Van Veen et al. (2015) and Varela et al. (2017) reported that cushion tilt and backrest recline motions made the drivers significantly more active, energetic, stimulated, and pleasantly surprised. Lastly, Vink & Hallbeck (2012) discussed that repetitive posture changes not only reduce discomfort during prolonged sitting but also increase the perceived comfort of the driver due to pleasant stimulation of tactile sensation associated with comfort.

A motion seat system which provides coordinated motions of backrest recline, cushion tilt, and lumbar support inflation/deflation was developed to induce the stretching and flexion of the whole body with two types (bow and wave) of motion profile with a particular time interval (e.g., 1 min). As shown in Figure 4.2.a, a bow motion profile was designed in which the seat moves cyclically from a preferred seat position to open and closed positions. The open position is configured by a recline (say, 5°) of the backrest, a downward tilt (say, 5°) of the cushion, and an inflation (say, 500 cc) of the lumbar support to stretch the body and the closed position by the opposite motions. Next, as shown in Figure 4.2.b, a wave motion profile was designed to induce an ascent and descent of the calf by repeated upward and downward cushion tilts (say, 5°) in addition to the stretching and flexion of the body by the bow motion profile.



Bow motion profile	Backrest	+5°	-5°	-5°	+5°	+5°	-5°	-5°	+5°
	Cushion	-5°	+5°	+5°	-5°	-5°	+5°	+5°	-5°
	Lumbar support	+500 cc	-500 cc			+500 cc	-500 cc		

(a) Bow motion profile



Wave motion profile	Backrest	+5°			-5°	-5°			+5°
	Cushion	-5°	+5°	-5°	+5°	+5°	-5°	+5°	-5°
	Lumbar support	+500 cc			-500 cc				

(b) Wave motion profile

Figure 4.2. Seat motion profiles: bow and wave motion profiles (illustrated).

4.3. Application of Eye Location Correction Algorithm

The eye location (EL) correction algorithm, which compensates the eye location change due to backrest recline and cushion tilt motions, was applied to the motion seat system using developed EL prediction models. The EL correction algorithm is operated to compensate for the driver's EL changes in the horizontal and vertical directions using the seat control variables of the fore-aft position and height. For example, as illustrated in Figure 4.3, the driver's EL is translated in the posterior and inferior directions (Figure 4.3.b) from the initial eye location of the preferred seat position (Figure 4.3.a) by the backrest recline and downward cushion tilt motions. Therefore, the EL is corrected by translating the seat in the forward and upward directions to fix the driver's EL in the initial position regardless of the seat motion (Figure 4.3.c). The adjustment range of the fore-aft seat position and seat height to correct the EL change by seat motion were inversely calculated in the form of Equations 4.3 & 4.4 using seat configuration-based models (Equations 4.1 & 4.2). Note that the initial eye location of the driver is calculated by using the driver's stature and information of seat configuration obtained from the PC-based seat control system.

$$\text{Eye}_x\ re\text{BOF} = 221 - (87.4 \times \text{S}) + (1.04 \times \text{L53}) - \{693 \times \sin(A40)\} \quad \text{(Eq. 4.1)}$$

$$\text{Eye}_z\ re\text{AHP} = -646 + (440 \times \text{S}) + (0.826 \times \text{H30}) + \{588 \times \sin(L27)\} \quad \text{(Eq. 4.2)}$$

$$\text{L53} = \{\text{Eye}_x\ re\text{BOF}_{\text{initial}} - 221 + (87.4 \times \text{S}) + [693 \times \sin(A40)]\}/1.04 \quad \text{(Eq. 4.3)}$$

$$\text{H30} = \{\text{Eye}_z\ re\text{AHP}_{\text{initial}} + 646 - (440 \times \text{S}) - [588 \times \sin(L27)]\}/0.826 \quad \text{(Eq. 4.4)}$$

where: S = stature,

L53 = fore-aft seat position (mm),

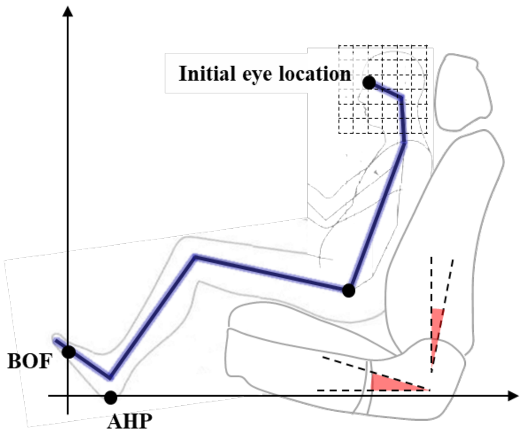
H30 = seat height (mm),

A40 = seatback recline angle (rad),

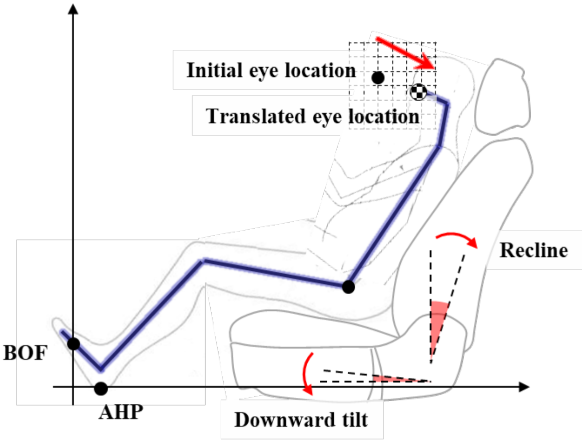
L27 = cushion tilt angle (rad),

Eye_x *re*$BOF_{initial}$ = horizontal EL relative to BOF of initial driving posture (mm),

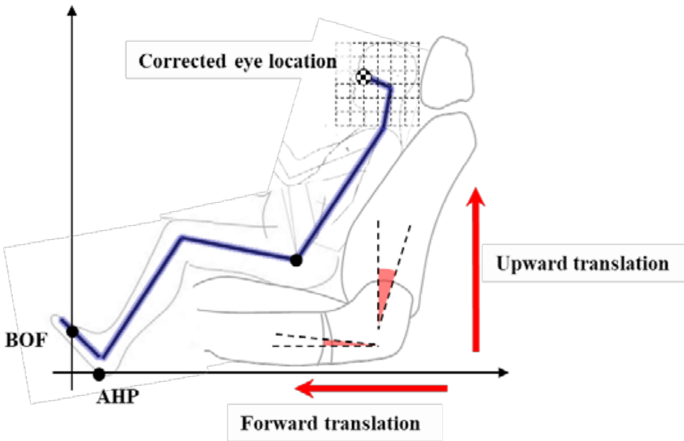
Eye_z *re*$AHP_{initial}$ = vertical EL relative to AHP of initial driving posture (mm)



(a) Initial seat position



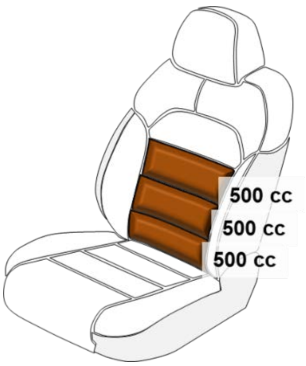
(b) Translated eye location by the seat motion



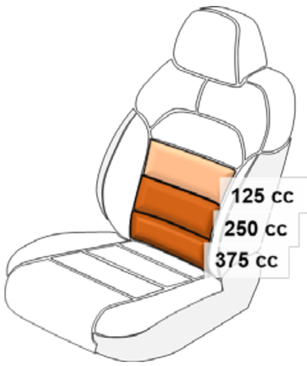
(c) Corrected eye location by the eye location correction algorithm

Figure 4.3. The eye location correction algorithm of the motion seat system

Seating comfort and driving safety for the developed motion profiles were reviewed through a preliminary experiment conducted with seat evaluation experts (n = 10). Seat evaluation experts (stature = 1.60 m ~ 1.83 m) participated with an interview for the developed motion profiles after performing a driving task with sufficient time in a vehicle with the motion seat system mounted on a 4.5 km long high-speed circuit (Hyundai-Kia Motors, Republic of Korea). The preliminary experiment found that motion profiles developed in the present study show excessive pressure on the lumbar and thoracic spine areas and low support on the lumbar spine area during the open position. Therefore, as illustrated in Figure 4.4, the maximum volume of the lumbar support inflation was reduced from 500 cc to 375 cc to eliminate the excessive pressure on the lumbar and thoracic area, and the inflation volume was linearly decreased from the lumbar area to the thoracic area to improve lumbar support. Lastly, a driver's 360-degree visibility was evaluated in an outdoor in a vehicle by checking if the rubber traffic cones placed on the front, side, and rear of the vehicle were visible (Bhise, 2011) and a driver's reach by checking if the hands and feet could comfortably reach on the steering wheel and pedal.



(a) Original



(b) Improved

Figure 4.4. Changes of inflation/deflation patterns to prevent excessive pressure on the lumbar and thoracic area and increase lumbar support

Chapter 5 SIMULATION DRIVING EVALUATION OF A MOTION SEAT SYSTEM

This chapter examines the passive TR fatigue reduction effects of the motion seat system in terms of driving performance, physiological response, and subjective fatigue through simulation driving in a lab environment. A driving scenario on a 130-km long monotonous highway was planned to induce passive TR fatigue on a driver. Standard deviation of lane position (SDLP), brake reaction time (BRT), heart rate variability (HRV), and percentage of eyelid closure rate (PERCLOS) were measured while a participant simulated the monotonous driving task in a driving simulator; subjective fatigue was evaluated before and after the driving session.

5.1. Participants

Seventeen Korean participants in their 20s to 50s (mean ± *SD* = 33.4 ± 11.4) with more than two years of driving experience were recruited in the present study. Healthy participants without cardiovascular and musculoskeletal disorders were recruited. The participants were asked to sustain from drinking alcohol and caffeine for 24 hours before the experiment and sleep more than 8 hours on the day before the driving experiment. The present study was approved by the Institutional Review Board (IRB) of the Pohang University of Science and Technology (PIRB-2016-E047).

5.2. Apparatus

As shown in Figure 5.1, a driving simulator was constructed using components of G90 (Hyundai-Kia Motors, Republic of Korea). Torque motors of the G27 gaming wheel (Logitech, Swiss) were installed inside the steering wheel, acceleration pedal, and brake pedal of the driving simulator and then tuned to provide the driver with an operational resistance similar to the actual vehicle. A driving scenario was displayed to participants through a screen (resolution: 1024 × 768) placed in front of the driving simulator. The electronic control unit (ECU) of the driver seat was connected with a controller area network (CAN) interface device (USB-8473, National Instruments, USA) and a PC to control the configuration of the seat according to a motion profile selected.

Figure 5.1. Fixed-base driving simulator for evaluation of driver passive task-related fatigue

The driving environment of the Daegu-Pohang highway was reconstructed using the driving simulation software UC-win/Road ver. 10 (Forum8, Japan). The route and altitude data of the Daegu-Pohang highway were obtained from Google maps (Google, USA) and topographic maps (National Geographic Information Institute, Republic of Korea). The Daegu-Pohang highway consists of a two-lane mostly straight road with occasional gentle curves, low traffic density, and monotonous scenery. The widths of lane, shoulder, and central reservation are 3.6 m, 3.0 m, and 3.0 m, respectively, according to the corresponding road design guidelines (Ministry of Land, Infrastructure, and Transport, Republic of Korea). Road facilities such as fences and tunnels were placed by referring to the corresponding road views available on Kakaomap (Kakao, Republic of Korea).

A wireless ECG measurement system (DTS BioMonitor XPTM, NORAXON Inc., USA, sampling rates = 1,500 Hz) and an eye tracker (faceLAB 5, Seeing Machines Inc., USA, sampling rates = 60 Hz) were used to obtain HRV and PERCLOS data of the driver during the driving experiment. HRV was quantified as SDNN in terms of time-domain and LF/HF in terms of frequency domain for the ECG measurements. SDNN was calculated using a standard deviation of R-R interval measurements that were extracted using the R-peak detection algorithm of Tompkins et al. (1993). LF/HF was calculated as a ratio of low-frequency band (0.04-0.15 Hz) power to high-frequency band (0.15-0.4 Hz) power by applying the fast Fourier transform (FFT) algorithm to R-R interval measurements. The eye tracker mounted on the dashboard of the simulator did not interfere with the driver's view (see Figure 5.1) and was calibrated for eye activity measurement of less than 2° of visual angle error during driving. PERCLOS was calculated as the percentage of time in which the driver's eyelids are closed for more than 75% over a 3-minute moving window (Dinges et al. 1998; Li & Chung, 2013; Merat & Jamson, 2013).

5.3. Experimental Procedure

The driving fatigue reduction effect of a motion seat system was evaluated in four phases for a total of two hours: (1) preparation of the experiment, (2) subjective fatigue evaluation before driving, (3) main experiment, and (4) subjective fatigue evaluation after driving (see Figure 5.2). In the preparation phase, informed consent was obtained after explaining the purpose and procedure of the experiment to the participant. The participant was allowed to adjust the fore-aft position, height, backrest recline angle, and cushion tilt angle of the seat to their preferred configuration by operating the buttons on the side of the seat. ECG electrodes were attached to the left clavicle, right clavicle, and stomach of the participant. Lastly, a 10-minute driving practice session was given to familiarize the participant with the driving task and then the subjective fatigue of the participant before driving was evaluated using the driver fatigue evaluation questionnaire (Table 5.1). In the main experiment phase, a monotonous driving task was performed while maintaining speed and lane position on the highway driving environment under static and motion (bow and wave) seat conditions. The participant was instructed to perform a monotonous driving task for 90 min. on the second lane at a vehicle speed of about 90 to 100 km/h. Vehicle positions from the center of the lane, ECG signals, and eyelid closure rates were measured while driving. The driving task was performed in the static seat condition during the first half of the driving session to induce the passive TR fatigue of the participant and then in the static (static-static, SS) or motion seat (static-motion, SM) condition during the second half of the driving session to identify the effect of the motion seat on passive TR fatigue (Figure 5.3). Break reaction tasks (BRTs) were administered at designated locations on the route ten times in each of the first half and the second half of the driving session. Lastly, the subjective fatigue of the participant was evaluated after completing the driving task. The driving experiment was performed for three conditions (SS, SM with the bow profile, and SM with the wave profile) counterbalanced over three days (one day for each condition).

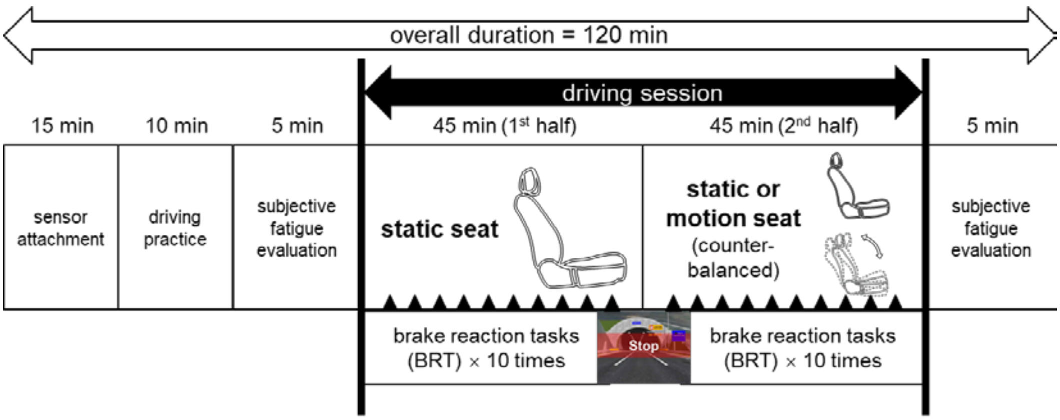


Figure 5.2. Experimental protocol for evaluation of driver's passive task-related fatigue in static- and motion-seat systems

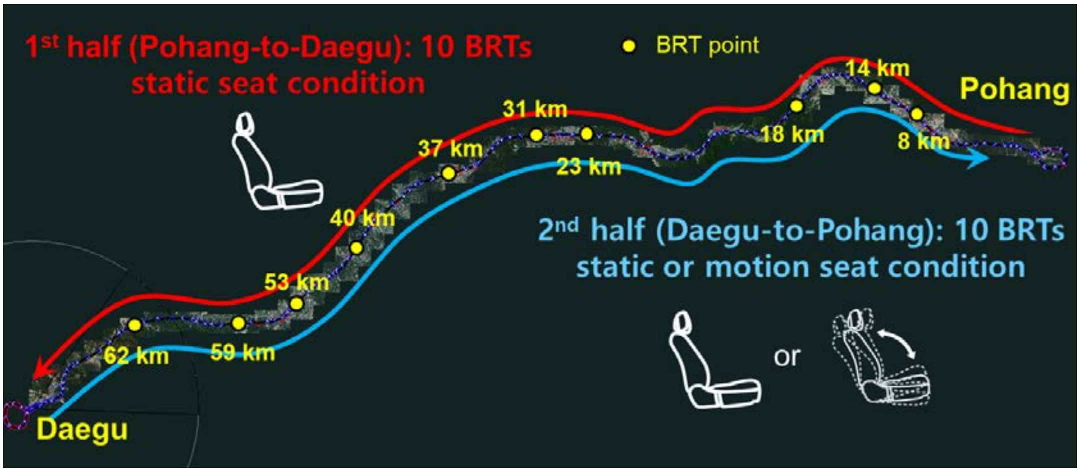


Figure 5.3. Driving route between Pohang and Daegu (brake reaction tasks were tested at the locations marked with dots along the route)

Table 5.1. Driver’s fatigue assessment questionnaire

Item			Description	Visual analog scale (VAS)
Overall fatigue			The degree of overall physical and mental fatigue	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)
Physical fatigue			The degree of overall physical fatigue	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)
Mental fatigue			The degree of overall mental fatigue	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)
Mental fatigue	Active task-related fatigue		The degree of mental fatigue due to driving tasks (e.g., lane change, brake pedaling)	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)
	Passive task-related fatigue		The degree of mental fatigue due to sustained attention	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)
	Passive TR fatigue	Degradation in driving safety	The degree of fatigue that interferes with driving safety	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)
		Drowsiness	The degree of fatigue that leads to drowsiness	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)
		Degradation in concentration	The degree of fatigue that lowers driving concentration	not at all (0) – slightly (25) – moderately (50) – highly (75) – extremely (100)

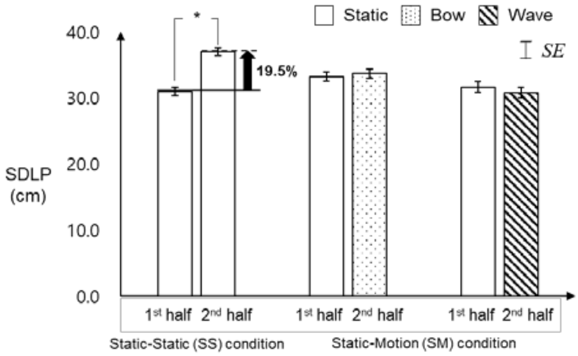
5.4. Statistical Analysis

The measurements of driving performance and physiological responses between the first half and the second half of the 90-min. driving session were compared for the SS and SM conditions. Visual analog scale (VAS) was converted to fatigue state change data by subtracting the rating before driving from the rating after driving. Unlike objective measures, the subjective fatigue levels of the participants before driving could be evaluated differently between the experiments conducted over three days, even though factors that might affect the fatigue status levels of the participants were controlled. Therefore, state changes were standardized by the standard deviations of state scores obtained before driving, which was employed by Matthews et al. (2002) for the DSSQ analysis. Repeated measures ANOVA was performed at $\alpha = .05$ to assess the effectiveness of one within-subject factor of seat condition. Fisher's least significant difference (LSD) test was performed at $\alpha = .05$ as post hoc analysis for multiple comparisons of means. SPSS v. 18.0 (International Business Machines INC., USA) was used for the statistical analysis.

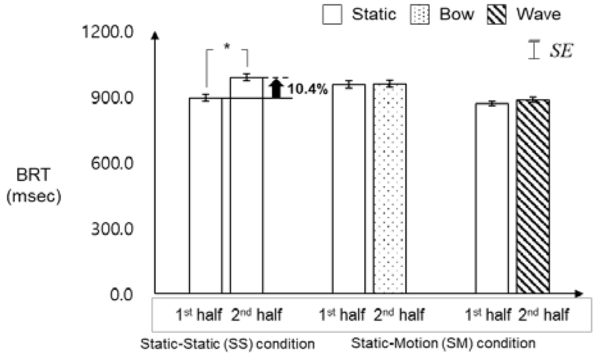
5.5. Results

5.5.1. Driving Performance

No significant differences over the driving session were shown in SDLP and BRT for the SM conditions, whereas significant increases were identified for the SS condition. Figure 5.4.a shows that the SDLP in the SS condition significantly increased by 19.5% in the second half of the driving session compared to that in the first half (F [1,16] = 24.80, p < .01). Similarly, Figure 5.4.b displays that the BRT in the SS condition significantly increased by 10.4% in the second half of the driving session as compared to that in the first half (F [1,16] = 8.75, p < .01).



(a) standard deviation of lave position (SDLP)

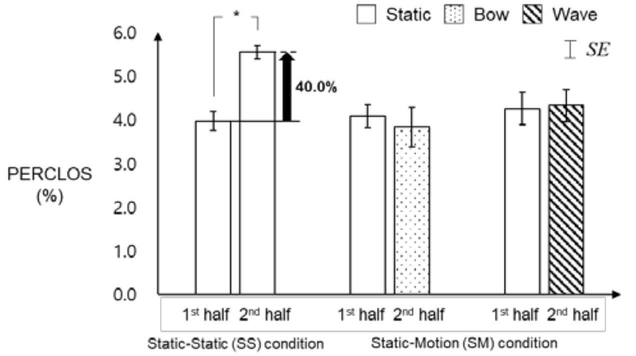


(b) brake reaction time (BRT)

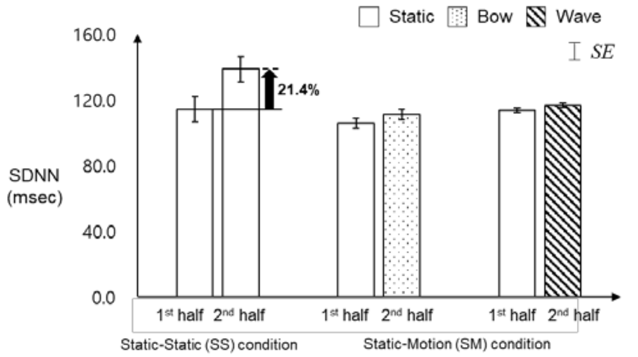
Figure 5.4. Changes of driving performance between the first half of the driving session and the second half for static (S) and motion (M) seat conditions

5.5.2. Physiological Responses

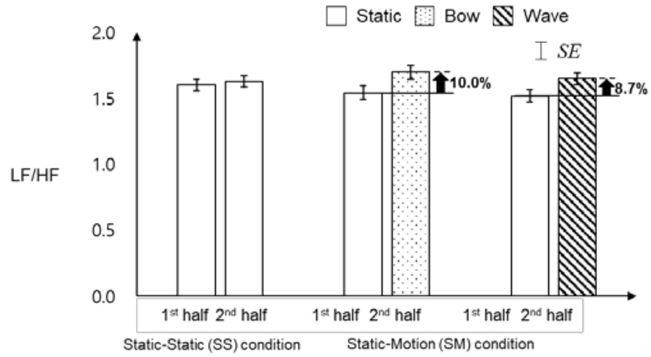
No significant changes over the driving session are identified in all the physiological measures for the SM conditions, whereas there was a significant physiological change over the driving session only in PERCLOS for the SS condition (Figure 5.5). Figure 5.5.a shows that PERCLOS in the SS condition significantly increased by 40.0% in the second half of the driving session as compared to that in the first half (F [1,16] = 25.09, p < .01). Next, Figure 5.5.b shows that the SDNN in the SS condition moderately, but not significantly, increased by 21.4% in the second half of the driving session as compared to that in the first half (F [1,16] = 2.69, p = .12). Lastly, Figure 5.5.c exhibits that the LF/HF values in the SM conditions slightly, but not significantly, increased by 8.7% ~ 10.0% in the second half as compared to those in the first half.



(a) percentage of eyelid closure rates (PERCLOS)



(b) standard deviation of NN interval (SDNN)

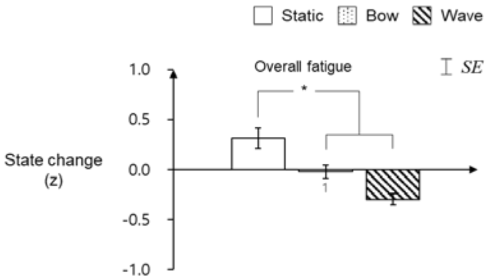


(c) ratio of low frequency power to high frequency power (LF/HF)

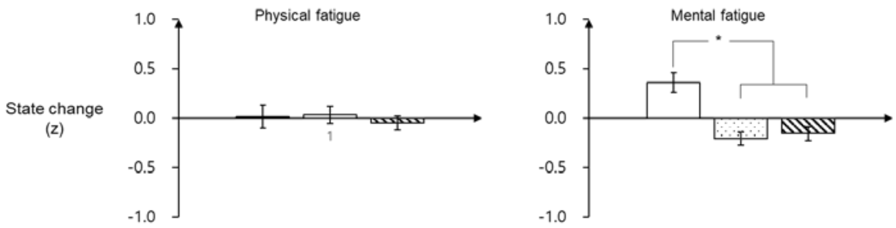
Figure 5.5. Changes of physiological responses between the first half of the driving session and the second half for static (S) and motion (M) seat conditions

5.5.3. Subjective Fatigue

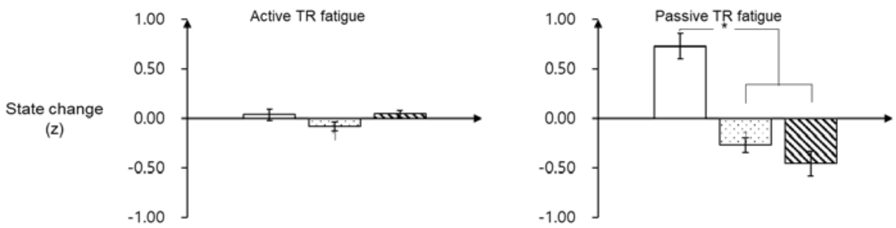
As shown in Figure 5.6, all the fatigue measures except physical and active TR fatigue measures were found significantly lower in the SM conditions than those in the SS condition. Figure 5.6.a shows that the state changes of overall fatigue in the SM conditions were significantly lower by 0.34 ~ 0.61 than that in the SS condition (F [2,32] = 10.16, $p < .01$). Figure 5.6.b exhibits that the state changes of mental fatigue in the SM conditions were significantly lower by 0.51 ~ 0.57 than that of the SS condition (F [2,32] = 10.15, $p < .01$), while no significant difference was observed in physical fatigue for all the SS and SM conditions (F [2,32] = 0.14, $p = .87$). Next, Figure 5.6.c displays that significantly lower state changes of 1.00 ~ 1.18 were found in passive TR fatigue in the SM conditions (F [2,32] = 20.99, $p < .01$), while there were no significant differences in active TR fatigue for all the SS and SM conditions (F [2,32] = 1.32, $p = .28$). Lastly, Figure 5.6.d shows that there were significantly lower state changes for driving safety (F [2,32] = 9.87, $p < .01$), drowsiness (F [2,32] = 5.41, $p < .01$), and degradation in concentration (F [2,32] = 3.45, $p = .04$) in the SM conditions compared to that in the SS condition.



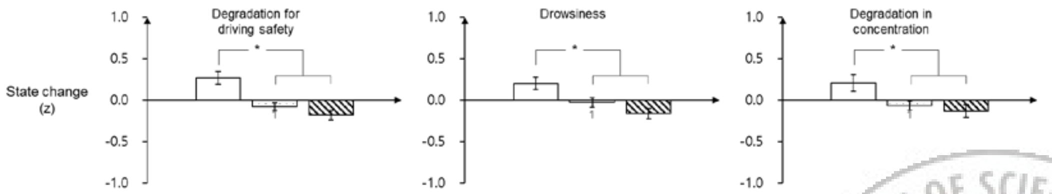
(a) overall fatigue



(b) physical fatigue vs. mental fatigue



(c) active task-related (TR) fatigue vs. passive TR fatigue



(d) passive TR fatigue measures

Figure 5.6. Fatigue state changes between the before- and after-driving session for static- and motion-seat conditions

Chapter 6 ON-ROAD DRIVING EVALUATION OF A MOTION SEAT SYSTEM

This chapter examine the effects of a motion seat system on passive TR fatigue in terms of driving performance, physiological response, fatigue behavior, and subjective fatigue in an on-road driving environment. A 90-min monotonous driving task was administered on a highway with low traffic to induce passive TR fatigue from drivers. The longitudinal velocity and steering wheel rate of the vehicle and the HRV, PERCLOS, facial expressions, and gestures of the driver were recorded during the driving; subjective fatigue was evaluated before and after the driving using a multidimensional driver fatigue evaluation questionnaire.

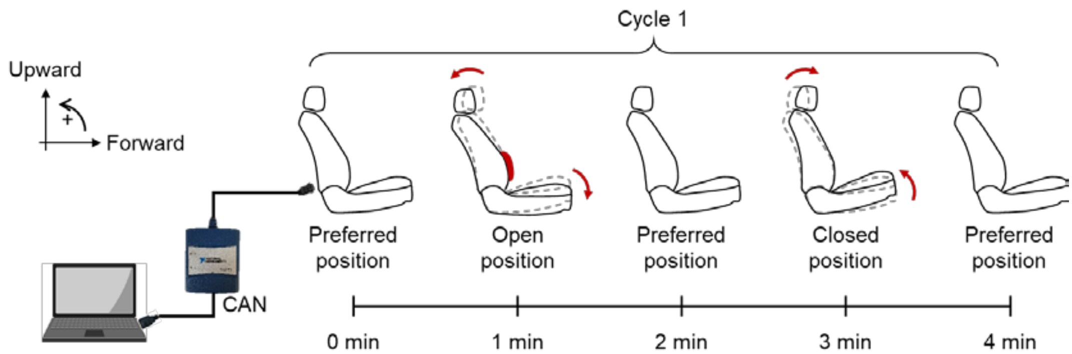
6.1. Participants

Twenty Korean participants (male: 15, female: 5) in their 20s to 50s (mean ± *SD* = 38.5 ± 12.2; *range* = 24 ~ 63 years) with more than two years of driving experience (mean ± *SD* = 14.0 ± 12.2 years; *range* = 3 ~ 35 years) participated in the on-road driving evaluation. Healthy participants without cardiovascular and musculoskeletal disorders were recruited to minimize changes caused by factors other than fatigue. The participants were asked to keep from drinking alcohol and caffeine for 24 h before the experiment (Merat & Jamson, 2013; Patel et al., 2011) and sleep more than 8 h on the day before the driving experiment. The present study was approved by the Institutional Review Board (IRB) of the Pohang University of Science and Technology (PIRB-2018-E080).

6.2. Apparatus

As shown in Figure 6.1, a vehicle of G90 (Hyundai-Kia Motors, Republic of Korea) with a motion seat system was retrofitted to the on-road driving evaluation in the present study. The motion seat system was configured by connecting the electronic control unit (ECU) of the driver seat and a PC using the USB-8473 controller area network (CAN) interface device (National Instruments, USA) to control the configuration of the seat. The motion seat system was able to control the coordinated motions of the backrest recline, cushion tilt, and lumbar support inflation/deflation at a one-minute time interval following a designated motion profile to induce the stretching and flexion of the whole body. As shown in Figure 6.2, the motion profile was designed for the seat to move cyclically from the preferred seat position of the driver to open and closed positions. The open position, which induces the extension of the body, was configured by a recline (say, 5°) of the backrest, a downward tilt (say, 5°) of the cushion, and an inflation level (say, 500 cc) of the lumbar support to stretch the body. The closed position, which induces the flexion of the body, was configured by the opposite motion. Measurements of driving performance such as longitudinal velocity and steering wheel rate were transmitted from the ECU of the vehicle to the PC at 250 Hz using the VN1630A CAN interface device (Vector, Germany) and Vehicle Network Toolbox™ (MathWorks Inc., Natick: MA, USA). Finally, the driving assistance systems of the vehicle, such as adaptive cruise control and lane-keeping assistance systems, were deactivated to observe the decrease in the driving performance of the driver over the driving session.

Figure 6.1. Driver cockpit for the on-road evaluation of passive task-related fatigue of the driver



Bow motion profile	Backrest	+5°	-5°	-5°	+5°
	Cushion	-5°	+5°	+5°	-5°
	Lumbar support	+500 cc	-500 cc		

Figure 6.2. Designated seat motion profile of backrest recline, cushion tilt, and lumbar support inflation/deflation

The wireless ECG measurement system DTS BioMonitor XPTM (NORAXON Inc., USA, sampling rate; 1,500 Hz) and the eye tracker faceLAB 5 (Seeing Machines Inc., USA; sampling rate = 60 Hz) were used to obtain HRV and PERCLOS data of the driver during the driving experiment (see Figure 6.1). HRV was quantified by low- to high-frequency power (LF/HF) in the frequency domain using RR interval measurements of ECG signals extracted using the QRS detection algorithm of Pan & Tompkins (1985). Artifacts of RR interval measurements such as ectopic beats and arrhythmic events were removed by detecting the abnormal R-peak which appeared within the next 350 msec after the adjacent R-peak (Pan & Tompkins, 1985). RR interval measurements were interpolated via cubic spline and re-sampled at 5.69 Hz (1024 samples per 3-min time window) to create a uniformly spaced time series for spectral HRV analysis (Clifford, 2002) because the RR interval measurements were not evenly sampled and hence fast Fourier transform (FFT) algorithm could not be used directly. LF/HF was calculated as the ratio of low-frequency band (0.04 ~ 0.15 Hz) power to high-frequency band (0.15 ~ 0.4 Hz) power by applying the FFT algorithm to RR interval measurements by Equation (1). The eye tracker mounted on the dashboard without interfering with the driver's visibility was calibrated for eye activity measurement with an error of less than 2°. PERCLOS was calculated as the percentage of time in which the driver’s eyelids are closed for more than 75% over a 3-min moving window (Dinges et al. 1998; Li & Chung, 2013; Merat & Jamson, 2013).

$$\text{LF/HF} = \int_{0.04Hz}^{0.15Hz} f(\lambda)d\lambda \Big/ \int_{0.15Hz}^{0.40Hz} f(\lambda)d\lambda, \quad (1)$$

Three action cameras of HDR-AS200V (SONY Inc., Japan; sampling rate = 60 Hz) were used to record the fatigue behaviors of the driver and driving environments. The action cameras were installed to the A-pillars of the driver and passenger sides and the windshield next to the room mirror to observe the driver's facial expressions, gestures, and driving environments (see Figure 6.1). The two action cameras at the A-pillars recorded facial expressions such as eye blinking, yawning, and head motions such as head shaking and face scratching; the action camera at the windshield recorded the driving environments in front of the vehicle to exclude measurements during situations interrupting monotonous driving (e.g., construction areas, traffic congestion areas, and lane change areas) from the analysis. The fatigue status of the driver was assessed by three ergonomists into one of three fatigue status categories (awake, drowsy, and very drowsy) by observing video clips segmented at a three-minute interval according to the driver fatigue level criteria (see Table 6.1) (Li et al., 2017). Lastly, CAN signals, ECG signals, eye-tracking data, and action camera video-recordings with different sampling rates were synchronized.

A multidimensional driver fatigue evaluation questionnaire (see Table 5.1) developed in the present study was used to evaluate the driver's passive TR fatigue. Multidimensional questionnaires such as Swedish Occupational Fatigue Inventory-20 (SOFI; Åshberg, 1997) and Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999) were used to measure various fatigue behaviors caused by monotonous driving (Körber et al., 2015; Oron-Gilad et al., 2008; Saxby et al., 2013). In this study, subjective fatigue was further divided into overall fatigue, physical fatigue (e.g., muscle pain and eye strain), and mental fatigue (e.g., boredom and decreased alertness); mental fatigue into active TR fatigue caused by active driving tasks (e.g., pedal and steering wheel operations) and passive TR fatigue caused by sustained attention tasks. Lastly, passive TR fatigue was further divided into decreases in motivation, energy arousal, and concentration of task engagement, which were selected from DSSQ as those related to passive TR fatigue (Matthews et al., 2002; Matthews et al., 2011; Matthews et al., 2013). A visual analog scale (VAS) consisting of five anchors (0 = not at all, 25 = slight, 50 = moderate, 75 = high, and 100 = extreme) was employed to the driver fatigue evaluation questionnaire. A driver fatigue change was calculated to a state change (z) by subtracting a VAS rating before driving from a VAS rating after driving. Since the levels of subjective fatigue can be assessed differently within the participant or between the participants even if the fatigue levels were identical, a state change was normalized by the standard deviation of the state scores obtained before driving, which was employed by Matthews et al. (2002) for the DSSQ analysis.

6.3. Experimental Procedure

The experiment of on-road motion seat system evaluation was conducted in four phases: (1) preparation, (2) subjective fatigue evaluation before driving, (3) main experiment, and (4) subjective fatigue evaluation after driving (Figure 6.3). First, in the preparation phase, informed consent was obtained after explaining the purpose and procedure of the experiment to the participant. The participant was allowed to adjust to his/her preference the fore-aft and height of the seat, recline angle of the seatback, and tilt of the cushion for comfortable posture and the side and review mirrors for proper visibility. The eye cameras were

Table 6.1. Criteria for driver fatigue status evaluation (adapted from Li et al., 2017).

Fatigue status	Level	Features			
		Head	Eye	Gestures	Attention
Awake	1	- Keep upright	- The eyes open widely - Blinking the eyes quickly - Moving the eyeballs actively - Closing the eyes briefly	- Single yawning - Single stretching	- Attentive to the outside
Drowsy	2	- Tilting/Shaking	- The eyelids half-closed - Moving the eyeballs slowly - Droopy eyelids - Blinking the eyes often	- Multiple yawning - Scratching the face - Swallowing - Sighing - Deep breathing - Rubbing the eyes - Multiple stretching - Moving around in the seat	- Decreased attention to the outside
Very drowsy	3	- Nodding	- Having trouble with keeping the eyes open - Blinking the eyes frequently - Closing the eyes for more than two sec. - Heavy eyelids	- Dozing/napping occasionally	- Almost losing the driving capability

calibrated based on the eye position of the participant; ECG electrodes were attached to the left clavicle, right clavicle, and stomach of the participant. A 15-min driving practice session was provided for the participant to become familiarized with the driving task. Second, subjective fatigue before driving was evaluated using the driver fatigue evaluation questionnaire. Third, in the main experiment phase, a monotonous driving task of maintaining 90 to 100 km/h while staying in the second lane on the highway was conducted in the static and motion seat conditions. The 134-km-long highway of Daegu to Pohang mostly consists of straight two-lane roads with occasional moderate curves. Note that a preliminary experiment in the present study confirmed that the driving environment of the Daegu-Pohang highway was proper for monotonous driving because of its low traffic density and similar scenery. The driving experiment was administered from noon to six o'clock in the afternoon when the weather is fair without rain to ensure proper driving conditions and safety. The driving task was performed in the static seat condition during the first half of the driving session to induce passive TR fatigue from the participant and then was continued in the static (static–static, SS) or motion seat (static–motion, SM) condition during the second half of the driving session (Figure 6.3). Vehicle speed, steering wheel rate, ECG parameters, and eyelid closure rate of the participant were measured while driving. A researcher accompanied the participant in the front passenger seat to observe the fatigue status of the participant and driving environment changes; the experiment was discontinued if the driver's fatigue was significantly high so that driving safety could be compromised. Lastly, subjective fatigue after driving was evaluated. The SS and SM conditions (one day for each condition) were counterbalanced.

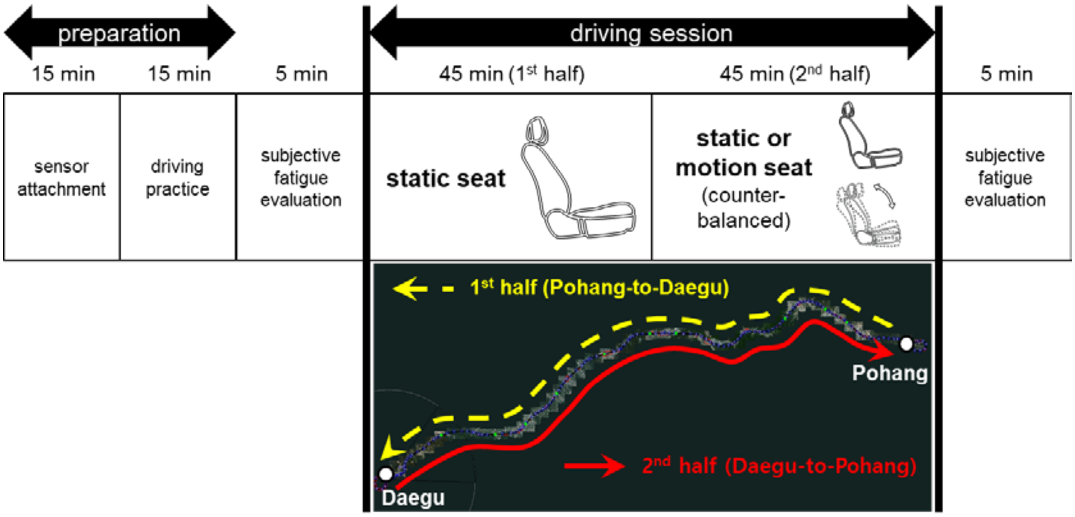


Figure 6.3. Experimental procedure for on-road evaluation of driver's passive task-related fatigue in static and motion seat system

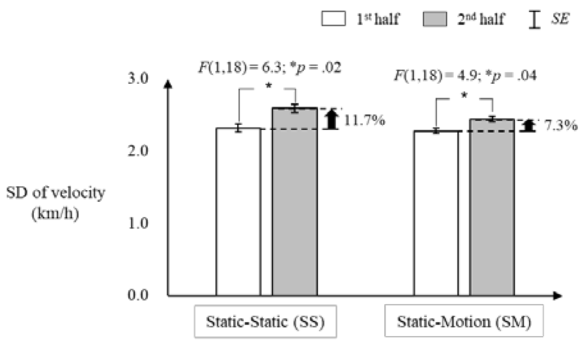
6.4. Statistical Analysis

The measures of driving performance, physiological responses, and driving behaviors between the first-half and second-half sessions of the 90-min driving were compared for the SS and SM conditions. Passive TR fatigue data of 19 participants except for one driver who showed the severe drowsiness level during the driving task was analyzed. The detour section (61 km to 70 km from Pohang) with high variability of roadside scenery and traffic flow was excluded due to relatively low monotony compared to the first- and second half of the driving session. Repeated measures ANOVA were performed at the significance level α = .05 to assess the effectiveness of one within-subject factor of the seat condition. The normality assumption of the test variables were confirmed by Shapiro-Wilk test (Shapiro & Wilk, 1965). SPSS v. 18.0 (International Business Machines INC., USA) was used for the statistical analysis.

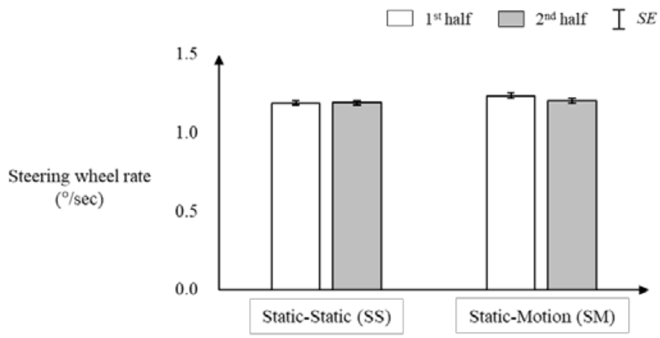
6.5. Results

6.5.1. Driving Performance

The SD of velocity significantly increased over the driving sessions for both the SS and SM conditions, while no significant difference was observed in steering wheel rate regardless of seat condition. Figure 6.4.a shows that the SD of velocity in the SS condition significantly increased by 11.7% in the second-half ($M \pm SE$ = 2.59 ± .05 km/h) driving session compared to that in the first-half ($M \pm SE$ = 2.32 ± .05 km/h) (F [1,18] = 6.3, p = .02), while the SM condition increased by 7.3% ($M \pm SE$ = 2.28 ± .04 km/h in first-half and 2.44 ± .04 km/h in second-half) (F [1,18] = 4.9, p = .04). Figure 6.4.b shows that no significant difference in steering wheel rate was found between the first-half and second-half sessions for all the SS and SM conditions ($p > 0.05$).



(a) standard deviation of velocity



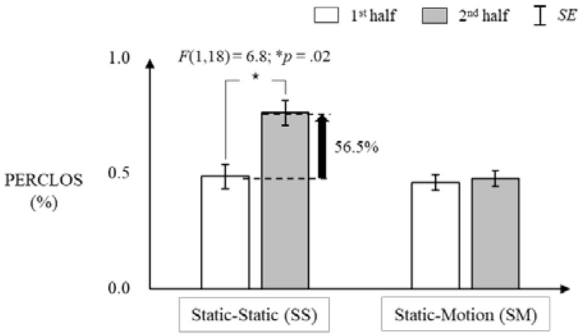
(b) steering wheel rate

Figure 6.4. Changes in driving performance between the first-half and second-half driving sessions for the static (S) and motion (M) seat conditions

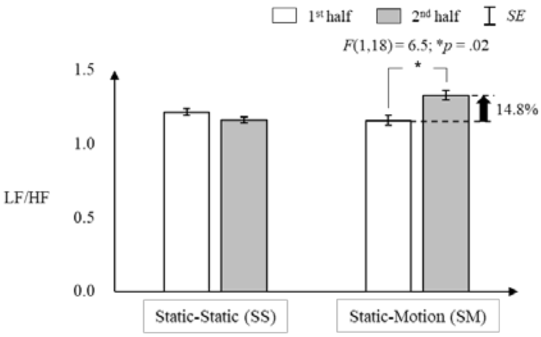
6.5.2. Physiological Responses

PERCLOS significantly increased in the SS condition but was maintained in the SM condition, while LF/HF was maintained in the SS condition but significantly increased in the SM condition over the driving sessions (Figure 6.5). Figure 6.5.a shows that PERCLOS in the SS condition significantly increased by 56.5% in the second-half ($M \pm SE$ = .76%

± .05%) driving session compared to that in the first-half (*M* ± *SE* = .49% ± .05%) (*F* [1,18] = 6.8, *p* = .02). Next, Figure 6.5.b shows that LF/HF in the SM condition significantly increased by 14.8% in the second-half (*M* ± *SE* = 1.33 ± .03) driving session compared to that in the first half (*M* ± *SE* = 1.16 ± .03) (*F* [1,18] = 6.5, *p* = .02).



(a) percentage of eyelid closure rates (PERCLOS)



(b) ratio of low frequency power to high frequency power (LF/HF)

Figure 6.5. Changes in physiological responses between the first-half and second-half driving sessions for the static (S) and motion (M) seat conditions

6.5.3. Number of Fatigue Behaviors

The number of fatigue behaviors increased less in the SM condition than in the SS condition over the driving sessions. All the observed fatigue statuses (see Table 6.1) did not exceed level 2 (drowsy) because the experiment was planned to terminate by the researcher before the fatigue level of the participant was aggravated more than level 2. As shown in Figure 6.6, the number of fatigue behaviors in the first-half driving session was similar among the SS (1.16 ± 1.21 times) and SM conditions (1.42 ± .54 times) ($p > 0.05$), but increased 11.4 times for the SS condition (F [1,18] = 24.5, $p < .01$) and 3.1 times for the SM condition (F [1,18] = 7.8, $p = .01$) in the second-half driving session compared to those in the first-half.

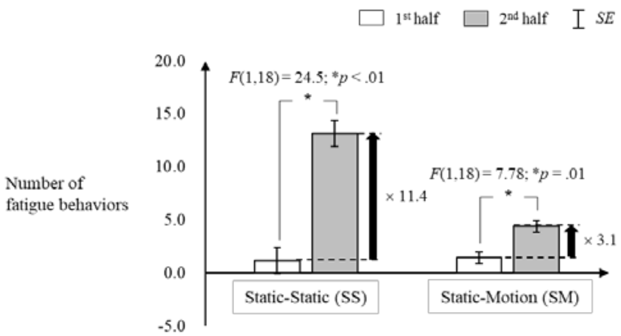
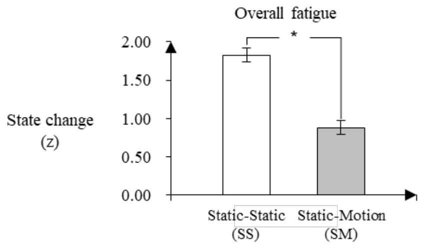


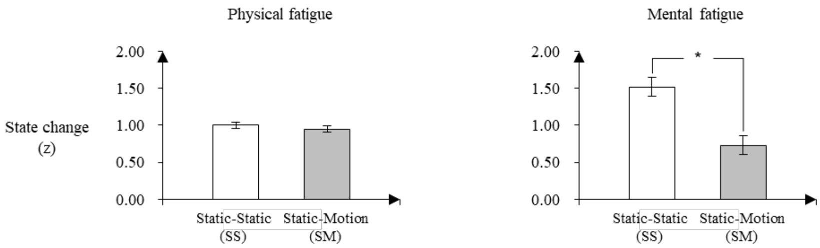
Figure 6.6. Number of fatigue behaviors

6.5.4. Subjective Fatigue

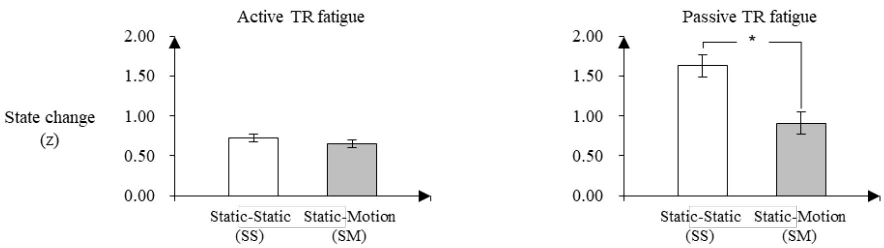
As shown in Figure 7.7, the state changes of all the subjective fatigue measures except physical fatigue, active TR fatigue, and degradation of driving safety were significantly lower in the SM condition than those in the SS condition. Figure 7.7.a shows that the state change of overall fatigue in the SM condition ($M \pm SE$ = .88 ± .09) was significantly lower by .95 than that in the SS condition ($M \pm SE$ = 1.83 ± .09) (F [1,18] = 31.4, p < .01). Figure 7.7.b exhibits that the state change of mental fatigue in the SM condition ($M \pm SE$ = .73 ± .13) was significantly lower by .79 than that of the SS condition ($M \pm SE$ = 1.52 ± .13) (F [1,18] = 11.0, p < .01), while no significant difference in the state change of physical fatigue between the SS and SM conditions was found (F [1,18] = 0.5, p = .50). Next, Figure 7.7.c displays that the state change of passive TR fatigue in the SM condition ($M \pm SE$ = .91 ± .14) was significantly lower by .72 (F [1,18] = 7.4, p = .01), while no significant difference in the state change of active TR fatigue was observed between the SS and SM conditions (F [1, 18] = 0.6, p = .46). Lastly, Figure 7.7.d shows that the state changes of drowsiness ($M \pm SE$ = 1.40 ± .13 in SS condition and .73 ± .13 in SM condition) (F [1,18] = 7.8, p = .01) and degradation in concentration ($M \pm SE$ = 1.73 ± .15 in SS condition and .87 ± .15 in SM condition) (F [1,18] = 9.8, p < .01) in the SM condition were significantly lower compared to those in the SS condition, while no significant difference in the state change of degradation of driving safety was found between the SS and SM conditions (F [1,18] = 0.1, p = .72).



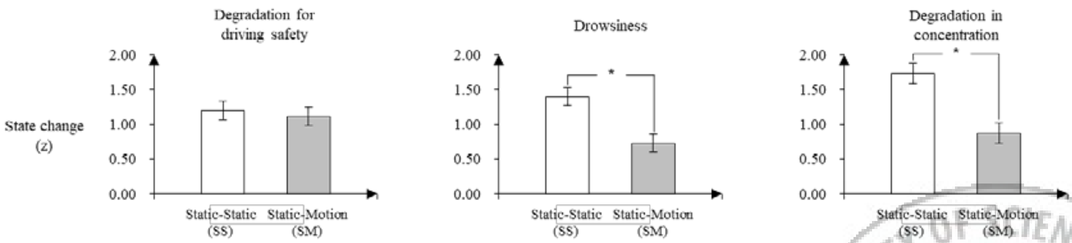
(a) overall fatigue



(b) physical fatigue vs. mental fatigue



(c) active task-related (TR) fatigue vs. passive TR fatigue



(d) passive TR fatigue measures

Figure 6.7. Fatigue state changes between the before- and after-driving session for the static- and motion-seat conditions.

Chapter 7 DISCUSSION

7.1. Prediction Models of Hip and Eye Location

Posture- and seat configuration-based models for estimating the driver's HLs and ELs were developed using a comprehensive geometric relationship with the driver's anthropometric dimensions, driving posture, and seat control variables, while existing models used limited anthropometric dimensions and OPL variables. The posture-based models are preferred to the existing models because the geometric relationships between HL, EL, anthropometric dimensions, and joint angles are comprehensively incorporated into the models, thus developed models could have better applicability to the various populations and driving postures. The driver's HLs and ELs estimation models developed in the previous study used limited anthropometric dimensions such as stature (Park et al., 2016; Reed et al., 2002; SAE J4004, 2005), sitting height (Park et al., 2016; Reed et al., 2002), and BMI (Park et al., 2016) as estimation variables. Next, the HL and EL estimation models developed in the previous studies are insufficient to consider various seat control parameters. Although previous studies include seat height (SAE J4004, 2005; SAE J941, 2010; Reed et al., 2002; Park et al., 2016; Zerehsaz et al., 2017; Park et al., 2019) and cushion tilt angle (Reed et al., 2002; Park et al., 2019) in addition to the OPL variables, some seat control parameters such as fore-aft seat position and seatback recline angle are not included in HL and EL estimation. On the contrary, the seat configuration-based models developed in the present study were constructed using the fore-aft seat position, seat height, backrest angle, and cushion angle variables provided by the highly adjustable seat of contemporary vehicles.

The developed posture- and seat configuration-based models show predominant prediction accuracy in terms of adj. R^2 ($M \pm SD$ = .83 ± .14) and *RMSE* ($M \pm SD$ = 19.3 ± 4.1 mm). Adj. R^2s of the posture- and seat configuration-based models are 1.0 ~ 1.3 times higher than the Reed et al.'s models in average and *RMSE* of the prediction models are 1.4 ~ 2.2 times smaller than the Reed et al.'s models. Moreover, the *RMSE* of the prediction models is found quite stable regardless of the regression variables used and have better prediction stability than existing models (*RMSE* range is 36.3 mm ~ 124.9 mm for the Reed et al.'s models and 14.2 mm ~ 26.3 mm for the posture- and seat configuration-based models). Additionally, the *RMSE* of the posture- and seat configuration-based models showed 1.7 ~ 15.7 times better prediction performance compared to the existing models when estimating HLs and ELs using the validation data set. As a result of the performance evaluation of the models, the posture- and seat configuration-based models have better prediction accuracy than the existing models because of a small estimation error and better prediction stability.

Posture- and seat configuration-based models can be used for the OPL design to provide optimal accommodation, visibility, and clearance for the driver considering the human body size, driving posture, and seat control variables. The HL and EL distributions of driver are used to determine the neutral positions and adjustment ranges of OPL components including seat, steering wheel, pedals, gear lever, and instrument panels (Bhise, 2011; Parkinson et al., 2007; Philippart et al., 1984). More specifically, information of the HL and EL distributions of driver is important to avoid an improper OPL design which can lead to uncomfortable driving postures, improper interior and exterior visibilities, insufficient clearances to the head and knee, and reduced driving safety for a designated population of drivers in various sizes. Although the SAE models are of use in OPL design, they do not include anthropometric variables so that their HL and EL estimation performance would decrease for driver populations other than US drivers. Lastly, the driver's HL and EL prediction models can be applied for the intelligent car design (e.g., auto seat adjustment and side mirror control) and ergonomic simulation based on the digital human model considering various body sizes, sitting postures, and seat configurations.

The developed prediction models have two limitations, one is that the posture-based models require predetermined posture information (joint angles) to predict that driver's HL and EL. Although many studies have been conducted to develop models to predict joint angles or analyze a range of each joint angle in driving, Reed et al. (2002) reported that driving posture variables such as head, neck, thorax angles are not accurately predictable due to a large variation between drivers. The other limitation is that the models were developed only in sedan OPL conditions. Even though the participants were asked to adjust the initial seat configurations to their preferred positions in sedan OPL conditions, their adjustment might be limited to cover a wide range of vehicle configurations such as SUV, coupe, and truck. Thus, the models have less generalizability to predict HL and EL in a certain OPL condition such as in between the coupe and the sedan conditions.

7.2. Effectiveness of Motion Seat System

The present study supports the use of a motion seat system can be an effective countermeasure to reduce passive TR fatigue by 4.4% ~ 56.5% during monotonous driving in both simulation and on-road driving environments. First, from the aspect of driving performance, the SM condition shows lower SDLP by 19.5%, BRT by 10.4%, and SD of velocity by 4.4% compared to the SS conditions over the 90-min driving session, which indicates that the motion seat system was effective in preventing the deterioration of driving performance. Oron-Gilad et al. (2008) reported that SDLP significantly decreased by 6.5 cm when multiple-choice questions were provided as a secondary task during monotonous driving; Saxby et al. (2013) found that BRT increased by 0.16 sec in a full automation condition (1.38 ± 0.35 sec) which requires a relatively lower situational demand compared to that in a manual driving condition (1.22 ± 0.28 sec); Ting et al. (2008) reported that the SD of velocity progressively increased by time-on-task during the 90-min monotonous driving task and had a high correlation (r = .858) with reaction time, which is closely related to driving safety (Körber et al. 2015; Lal & Craig, 2001; Philip et al. 2005; Saxby et al. 2013). Second, from the aspect of physiological responses, our study revealed that no significant changes over the driving session were identified in PERCLOS for the SM conditions, whereas there was a significant increase in the SS conditions by 40.0% for the simulation driving environment and by 56.5% for the on-road driving environment. In addition, while performing a monotonous driving task in the on-road driving environment, PERCLOS kept leveled and LF/HF significantly increased in the second-half driving session compared to those in the first-half for the SM condition, while the opposite was observed for the SS condition, which indicates that the motion seat system was effective in reducing drowsiness and increasing alertness. Van Loon et al. (2015) reported that PERCLOS significantly increased during a 60-min monotonous driving and had a significant positive correlation with SDLP (r = .31). Schömig et al. (2015) and Jarosch et al. (2017) reported that solving quiz questions on a tablet increased the cognitive workload of the driver in an automated driving condition by resulting in a significant decrease in PERCLOS (the higher the PERCLOS, the higher the drowsiness). Next, Zhang et al. (2018) reported that 4 ~ 7 Hz of vibration transmitted to the whole body from the seat while driving on a monotonous highway enhanced the alertness of the driver by increasing LF/HF (Michail et al., 2008; Patel et al., 2011). Third, from the aspect of fatigue behavior, the number of fatigued driving behaviors increased much less in the SM condition than in the SS condition over the first-half and second-half driving sessions. Lastly, from the aspect of subjective fatigue, the state changes of all the subjective fatigue measures except physical fatigue, active TR fatigue, and degradation of driving safety were significantly lower in the SM condition than those in the SS condition. The increases in the subjective fatigue measures observed in the present study were consistent with the findings of the existing studies, indicating that subjective fatigue was significantly increased also in low-workload situations such as driving in a monotonous environment (Oron-Gilad & Ronen, 2007, Verwey & Zaidel, 1999) or a partially autonomous vehicle (Körber et al. 2015) compared to the normal driving condition. The results of subjective fatigue evaluation in the present study indicate that the motion seat system was effective in reducing overall fatigue, mental fatigue, passive TR fatigue, drowsiness, and degradation in concentration, but not physical fatigue, and did not compromise driving safety.

The passive TR fatigue reduction of the motion seat system can be explained by the following four-step psychophysiological mechanism: (1) driving posture change by seat motion, (2) activation of proprioceptors by driving posture change, (3) activation of the parietal lobe by activation of proprioceptors, and (4) increase of situational demand by activation of the parietal lobe. First, the motion seat system which coordinates the backrest recline, cushion tilt, and lumbar support inflation/deflation according to a time-stamped protocol changes the posture of the driver's whole body. Second, the driving posture change would activate the proprioceptors in the muscles and joints (Tuthill & Azim, 2018). Third, the activated signals of the proprioceptors would stimulate the parietal lobe which recognizes the position and posture change of the body (Culham & Kanwisher, 2001; Fix, 2002). Lastly, the increased activities of the parietal lobe would reduce the level of boredom, reducing the level of passive TR fatigue eventually.

The motion seat system in the present study which does not provide secondary tasks to the driver can be preferred to interactive technologies because it is less distracting during driving. Interactive technologies such as a speech-controlled game box system (Verwey & Zaidel, 1999), common knowledge questions (Gershon et al., 2009; Oron-Gilad et al., 2008; Song et al., 2017), and conversation (Atchley & Chan, 2011; Matthews et al., 2019), which assign a secondary task to the driver during driving have demonstrated their effectiveness in maintaining the driver's alertness. However, Reid (1997) reported that the driver might miss events hazardous to driving safety if the secondary task requires excessive attention from the driver. Therefore, Oron-Gilad et al. (2008) stated that the development of secondary tasks that increase the overall demand on the driver without distracting the driver from the primary driving task is needed. The motion seat system would be preferred to the interactive technologies because the former has a lower possibility of distraction during driving than the latter requiring the active involvement of the driver.

The findings of the passive TR fatigue reduction of the motion seat system can be used to help the driver reduce the degradation of alertness in a partially autonomous vehicle or a long-haul transportation vehicle. Vehicle automation taking over the role of the steering wheel control and/or acceleration and deceleration control to the vehicle is effective to decrease active TR fatigue by reducing the task demands on the driver (Neubauer et al., 2011; Saxby et al., 2013). However, compared to manual control, partial automation (SAE level 2, SAE international 2016) or conditional automation (SAE level 3, SAE international 2016) requiring sustained monitoring by the driver can increase cognitive fatigue, brake response time, and steering wheel reaction time due to passive TR fatigue from increased monotony (Eriksson & Stanton, 2017; Körber et al., 2015; Neubauer et al., 2011; Neubauer et al., 2012; Saxby et al., 2007; Saxby et al., 2008; Young & Stanton, 2007). Next, previous studies have reported that occupational drivers of commercial vehicles such as heavy trucks and buses are more likely to be exposed to higher driver fatigue than non-commercial vehicle drivers due to prolonged driving periods and boredom in work conditions (Kee et al., 2010; Mandal et al., 2016; Sahayadhas et al., 2012). Therefore, the motion seat system can be applied as an effective countermeasure to mitigate passive TR fatigue while driving a partially autonomous vehicle and long-haul transportation vehicle.

Further research is needed to examine the effects of the motion seat system on passive TR fatigue by individual factors including age, driving experience, and fatigue propensity. First, Filtness et al. (2012) and Otmani et al. (2005) identified that older drivers showed greater stability in driving and were less vulnerable to the prolonged monotonous driving compared to younger drivers. Next, Oron-Gilad et al. (2008) discussed that a low situational demand condition such as driving on a monotonous highway or in a partially autonomous vehicle could cause passive TR fatigue to experienced drivers due to underload but active TR fatigue to novice drivers due to overload. Lastly, Thiffault & Bergeron (2003) found that extrovert drivers were more sensitive to monotony and thus more prone to fatigue-related driving errors in a low attention-demanding road environment. Note that tools such as a driver stress inventory (Matthews et al., 2002) or a driving coping questionnaire (Matthews et al., 1996) can be used to evaluate individual propensities affecting driving safety.

7.3. Assessment Method of Passive Task-Related Fatigue

An experimental protocol for evaluating the passive TR fatigue of drivers, which could be applicable in both simulation and on-road driving environments, was developed by considering monotonous driving scenarios and sensitive measures of passive TR fatigue. A driving scenario with low variability in roadside scenery and traffic flow is widely used to manipulate passive TR fatigue from the driver (Thiffault & Bergeron, 2003; Gastaldi et al., 2014; Ting et al., 2008; Larue et al., 2011; Oron-Gilad et al., 2008). Therefore, the monotonous simulation driving scenario of this study was reconstructed by referring to the driving environment of the Daegu-Pohang highway composed of a two-lane mostly straight roads with occasional gentle curves, low traffic density, and monotonous scenery. However, it is challenging to cause passive TR fatigue in an on-road experiment because on-road driving often requires a high level of vigilance from the driver or various environmental factors such as a sudden change in traffic or weather can affect the level of vigilance by acting as external stimuli (Nilsson et al., 1997; Oron-Gilad & Ronen et al., 2007; Oron-Gilad et al., 2008). For example, Philip et al. (2005) reported that inappropriate line crossing was increased by prolonged driving in the simulation driving condition, but no significant changes in driving performance could be observed in the first 2 h of on-road driving because the driver might allocate more attention to possible hazardous events. Therefore, this study was verified whether the driving environment and the variability of traffic flow of the Daegu-Pohang highway are appropriate to induce the monotony of drivers through preliminary experiments before on-road driving evaluation. Besides, this study confirmed that 90 minutes of the driving period was long enough to generate passive TR fatigue from the driver because existing studies have reported that fatigue symptoms of the driver occur after 20 to 40 minutes of monotonous driving (Thiffault & Bergeron, 2003; Gastaldi et al., 2014).

Driving performance measures and physiological response measures were employed in the present study as those applicable to simulation and on-road driving evaluation and sensitive to driver fatigue. Of the driving performance and physiological response measures, those less applicable to on-road driving evaluation due to on-road driving safety, sensitivity to a noisy environment, and driver discomfort were excluded from the results of this lab-based simulation study to be validated in an on-road driving environment. For example, SW reversal rate was excluded due to high possibility of a traffic accident, EEG due to high sensitivity to noise environment in on-road driving condition (Larue et al., 2011), and skin conductance (SC) due to the discomfort of the attachment of SC electrodes to the fingers while operating the SW. Lastly, driving performance and physiological response measures showing a consistent trend by fatigue with high sensitivity were selected for the present study. Of the driving performance measures, SDLP and reaction time to brake, which indicate a psychomotor ability (Saxby et al., 2013), increase by fatigue. Of the physiological response measures, standard deviation of NN interval (SDNN) and root mean square of the successive differences (RMSSD) representing a variability of heart rate increase, but the ratio of low frequency power to high frequency power (LF/HF) of ECG signal indicating the degree of balance between sympathetic and parasympathetic nerve systems decreases by fatigue. Lastly, PERCLOS, the proportion of the time that the eyelids are closed by a designated percentage such as 70%, 75%, or 80% for a work period (Dinges et al., 1998), increases by fatigue.

A multidimensional driver fatigue evaluation questionnaire consisting of eight questions was developed in the present study based on a review of existing questionnaires for driver's passive TR fatigue. Multidimensional questionnaires such as the Swedish Occupational Fatigue Inventory-20 (SOFI, Åshberg, 1998) and the Dundee Stress State Questionnaire (DSSQ, Matthews et al., 1999) have been used to evaluate various fatigue symptoms caused by monotonous driving (Köber et al., 2015; Oron-Gilad et al., 2008; Saxby et al., 2013). In this study, subjective driver fatigue was evaluated in terms of overall fatigue, physical fatigue (e.g., muscle pain and eye strain), and mental fatigue (e.g., boredom and loss of alertness). The mental fatigue was further divided into active TR fatigue by active driving tasks such as pedal and SW operations and passive TR fatigue by sustained attention. Lastly, passive TR fatigue was further evaluated in detail for motivation, energy arousal, and concentration of task engagement selected from the DSSQ as those related to passive TR fatigue (Matthews et al., 2002; Matthews et al., 2011; Matthews et al., 2013). A visual analog scale (VAS) with five anchors (0 = not at all, 25 = slightly, 50 = moderately, 75 = highly, and 100 = extremely) was employed in the driver fatigue evaluation questionnaire. The multidimensional driver fatigue evaluation questionnaire developed in this study was useful in distinguishing the driver fatigue generated during monotonous driving into passive and active TR fatigue aspects.

Chapter 8 CONCLUSION

The present study was to achieve four specific objectives as follows: (1) development of statistical estimation models for HLs and ELs of the driver, (2) development of a motion seat system to mitigate passive TR fatigue, (3) evaluation of the effects of the motion seat system on driver's passive TR fatigue reduction through simulation driving in a lab environment, and (4) validation of the passive TR fatigue reduction of the motion seat system in an on-road driving environment.

First, the posture- and seat configuration-based models to estimate the hip locations and eye locations of the driver was developed by incorporating the geometric relationships of the HLs, ELs, anthropometric dimensions, joint angles, and seat control parameters. The developed posture- and seat configuration-based models show high prediction performance in terms of adj. R^2 ($M \pm SD$ = .83 ± .14) and *RMSE* ($M \pm SD$ = 19.3 ± 4.1 mm). A split percentage (80% for model development and 20% for validation) validation results confirmed that developed prediction models have better prediction accuracy than existing models because *RMSE* of the developed models was 1.7 ~ 15.7 times lower as compared to the existing models.

Second, the motion seat system to reduce the passive TR fatigue by increasing the situational demand (or cognitive workload) of the driver during monotonous driving was developed. The motion seat system was able to control the coordinated motions of the backrest recline, cushion tilt, and lumbar support inflation/deflation at a particular time interval following a designated motion profile to induce the stretching and flexion of the whole body. The passive TR fatigue reduction of the motion seat system was intended by the following four-step psychophysiological mechanism: (1) driving posture change by seat motion, (2) activation of proprioceptors by driving posture change, (3) activation of the parietal lobe by activation of proprioceptors, and (4) increase of situational demand by activation of the parietal lobe.

Third, the effects of the motion seat system on the passive TR fatigue reduction was evaluated in terms of driving performance, physiological response, and subjective fatigue through simulation driving in a lab environment. The motion seat system with a bow or wave profile was found preferred to the conventional static seat system to mitigate passive TR fatigue in terms of SDLP, BRT, PERCLOS, and subjective fatigue. No significant differences in SDLP, BRT, PERCLOS, and subjective fatigue were observed over a 90-min driving session for the SM conditions, while significant increases by 6.0 cm (19.5%) in SDLP and 0.093 sec (10.4%) in BRT were observed for the SS condition. Next, all the fatigue measures except physical and active TR fatigue measures were found 0.34 ~ 0.61 significantly lower in the SM conditions than those in the SS condition.

Lastly, the relative validity of the motion seat system on the passive TR fatigue reduction was examined in an on-road driving environment. The passive TR fatigue reduction effect of the motion seat system compared to the static in an on-road environment was similar to the lab-based evaluation in terms of driving performance, physiological response, and subjective fatigue. From the aspect of driving performance, the increased percentage of the SD of velocity over the first-half and second-half driving sessions was 4.4% lower in the SM condition compared to that of the SS condition. The number of fatigue behaviors in the first-half driving session was similar among the SS (1.16 ± 1.21 times) and SM conditions (1.42 ± .54 times), but increased 11.4 times for the SS condition and 3.1 times for the SM condition in the second-half driving session than those in the first-half. The state change of the subjective fatigue measure was significantly lower in the SM condition compare to the SS condition, and these results were consistent with the simulation driving in a lab environment.

SUMMARY IN KOREAN

운전자 피로는 운전자의 각성(alertness)과 성능을 저하시켜 교통사고를 유발시킬 수 있다. 운전자 피로는 정신적 각성 (mental alertness)이 손상된 상태로써 시각적 공간 능력(visual-spatial ability), 기억력(memory), 정보 처리(information processing), 그리고 운전 작업에 요구되는 빠른 반응(rapid reaction)과 같은 인지(cognitive) 및 정신 운동(psychomotor) 기능에 부정적인 영향을 미친다. 운전자 피로는 인지적 overload 에 의한 active task-related (TR) fatigue 와 인지적 underload 에 의한 passive TR fatigue 로 구분될 수 있다. 예를 들어, active TR fatigue 는 교통 밀도가 높거나 시계가 좋지 않은 환경과 같은 높은 작업량이 요구되는 상황에서 운전하는 경우 발생될 수 있는 반면, passive TR fatigue 는 단조로운 고속도로 또는 부분 자율주행 차량에서 운전하는 경우와 같이 낮은 작업량이 요구되는 상황에서 발생될 수 있다. 선행 연구들은 20% ~ 35%의 교통사고가 운전자 피로에 의해 발생된다고 보고하였다.

본 연구의 목적은 운전자의 passive TR fatigue 를 저감하기 위한 동적 승객석 운동 시스템(motion seat system)을 개발하는 것이다. 본 연구의 세부적인 목적은 다음과 같다: (1) 운전자의 hip location (HL)과 eye location (EL)을 추정하기 위한 통계적 모델 개발 및 평가, (2) 단조로운 주행 중 운전자의 passive TR fatigue 를 저감하기 위한 motion seat system 과 motion profiles 개발, (3) 실험실 환경에서 시뮬레이션을 통한 motion seat system 의 passive TR fatigue 저감 효과 평가, 그리고 (4) 실제 도로 환경에서 motion seat system 의 passive TR fatigue 저감 효과 검증.

첫째, 운전자의 HL 과 EL 을 추정하기 위한 통계적 모델이 인체 치수, 관절 각도, 그리고 좌석 제어 변수를 사용하여 개발되었다. 23 명의 한국인 운전자(여성 10 명, 남성 13 명)에 대한 운전 자세가 선호 자세로부터 좌석의 앞뒤 위치, 높이, backrest recline, 그리고 cushion tilt 를 동시에 변화시키며 seating

buck 에서 측정되었다. HL, EL, 관절 각도, 그리고 좌석 구성 변수의 조절량이 motion capture system 을 사용하여 수집되었다. 운전 자세(posture-based models)와 좌석 구성(seat configuration-based models)에 기반한 HL 및 EL 추정 모델이 stepwise regression 을 통해 개발되었다. 제안된 추정 모델은 HL 과 EL 을 예측하는데 평균적인 adj. R^2 ($M \pm SD$ = .83 ± .14)와 *RMSE* ($M \pm SD$ = 19.3 ± 4.1 mm) 측면에서 높은 정확도를 보였다. 운전 자세와 좌석 구성에 기반한 모델은 추정 성능에 통계적으로 유의한 차이가 없었다.

둘째, motion seat system 이 전동 조종식 운전석, 운전석의 전자제어 유닛(electronic control unit, ECU), 계측 제어기 통신망(controller area network, CAN) 장치, PC 기반 시트 제어 시스템으로 구성되었다. motion seat system 은 특정 시간 간격(예: 1 분)으로 backrest recline, cushion tilt, 그리고 요추 팽창/수축의 조합된 동작을 제공하는 두 가지 종류(bow, wave)의 motion profile 이 전신의 펼침과 굽힘을 유도하도록 개발되었다. Backrest recline 과 cushion tilt 에 의한 눈 위치 변동을 보상하는 눈 위치 보정 알고리즘이 개발된 EL 추정 모델을 사용하여 motion seat system 에 적용되었다. 개발된 motion profile 에 대한 착좌 안락감과 주행 안전성이 차량 시트 평가 전문가(n = 10)를 대상으로 수행된 사전 실험을 통해 확인되었다.

셋째, 운전자의 passive TR fatigue 저감에 대한 motion seat system 의 효용성이 실험실 기반 주행 시뮬레이션을 통해 평가되었다. 운전 경력 2 년 이상의 한국인 운전자 17 명이 90 분의 단조로운 주행을 수행하는 동안 차선 위치의 표준편차(Standard Deviation of Lane Position, SDLP), 브레이크 반응 시간 (Brake Reaction Time, BRT), 눈 꺼풀 감김 비율(PERcentage of eyelid CLOSure rate, PERCLOS), 심전도 신호의 심장 박동 간격의 표준편차(Standard Deviation of NN interval, SDNN)와 저주파 대비 고주파 파워 비율(ratio of Low Frequency power to High Frequency power, LF/HF)이 측정되었다. 주행 세션은 전반기의 static seat 조건과 후반기의 static seat (static-static, SS) 또는 motion seat (static-motion, SM)

조건으로 구성되었다. SS 조건은 주행 전반 대비 후반에서 SDLP, BRT, 그리고 PERCLOS 가 10.4% ~ 40.0% 유의하게 증가된 반면, SM 조건은 주행 전반과 후반에 대해 통계적으로 유의한 차이가 없었다. 이와 더불어, SM 조건은 SS 조건보다 주행 전에 비해 주행 후에서 유의하게 낮은 주관적인 피로 상태의 변화가 전반적 피로, 정신적 피로, passive TR fatigue, 주행 안전성, 졸음, 그리고 집중도 저하 척도에서 나타났으며, 육체적 피로와 active TR fatigue 에는 유의한 차이가 없었다.

마지막으로, 운전자 passive TR fatigue 저감에 대한 motion seat system 의 효용성이 실제 도로 환경에 적용 가능한 자동차 및 생리학적 센서를 사용하여 검증되었다. 2 년 이상의 운전 경력을 보유한 20 명의 한국인 운전자가 2 가지 조건의 실차 주행 평가에 참여하였다: static–static (SS), static–motion (SM). SM 조건은 SS 조건에 비해 종방향 속도의 표준편차, PERCLOS, 그리고 LF/HF 측면에서 passive TR fatigue 가 4.4% ~ 56.5% 유의하게 낮았다. 실험참여자의 주관적인 피로 상태의 변화가 SM 조건에서 SS 조건보다 전반적 피로, 정신적 피로, passive TR fatigue, 주행 안전성, 졸음, 그리고 집중도 저하에서 낮다고 평가되었다.

본 연구에서 개발된 motion seat system 은 단조로운 주행 시 정신적 각성을 증가시켜 운전자의 passive TR fatigue 를 완화하는데 기여할 수 있다. Motion seat system 에 대한 passive TR fatigue 저감 효과는 부분 자율 주행 차량 또는 장거리 운송 차량에 적용되어 운전자 각성의 저하를 감소시키는데 도움이 될 수 있다. 다음으로, 운전자에게 부가 작업을 제공하지 않는 motion seat system 은 주행 시 운전자 주의 집중을 덜 방해하기 때문에 선행 연구의 interactive technologies 보다 선호될 수 있다.

REFERENCES

Åhsberg, E. (1998). *Perceived fatigue related to work.* Arbetslivsinstitutet, Stockholm.

Åkerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, *52*(1-2), 29-37.

Aota, Y., Iizuka, H., Ishige, Y., Mochida, T., Yoshihisa, T., Uesugi, M., & Saito, T. (2007). Effectiveness of a lumbar support continuous passive motion device in the prevention of low back pain during prolonged sitting. *Spine*, *32*(23), E674-E677.

Åstrand, P. O., & Rodahl, K. (1986). *Textbook of Work Physiology*. McGraw-Hill, New York.

Atchley, P., Dressel, J., Jones, T. C., Burson, R. A., & Marshall, D. (2011). Talking and driving: applications of crossmodal action reveal a special role for spatial language. *Psychological research*, *75*(6), 525-534.

Atchley, P., & Chan, M. (2011). Potential benefits and costs of concurrent task engagement to maintain vigilance: A driving simulator investigation. *Human factors*, *53*(1), 3-12.

Balkin, T. J., Horrey, W. J., Graeber, R. C., Czeisler, C. A., & Dinges, D. F. (2011). The challenges and opportunities of technological approaches to fatigue management. *Accident Analysis & Prevention*, *43*(2), 565-572.

Basmajian, J. V., & De Luca, C. J. (1985). *Muscles Alive*. Williams and Wilkins, Baltimore.

Bastien, C. H., Ladouceur, C., & Campbell, K. B. (2000). EEG characteristics prior to and following the evoked K-Complex. *Canadian Journal of Experimental Psychology*, *54* (4), 255–265.

Bekiaris, E., Amditis, A., & Wevers, K. (2001). Advanced driver monitoring-the awake project. In *8th World Congress on ITS, Sydney–Australia*.

Bell, A. L., Brand, R. A., & Pedersen, D. R. (1989). Prediction of hip joint centre location from external landmarks. *Human movement science, 8*(1), 3-16.

Bell, A. L., Pedersen, D. R., & Brand, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. *Journal of biomechanics*, *23*(6), 617-621.

Bergasa, L. M., Nuevo, J., Sotelo, M. A., Barea, R., & Lopez, M. E. (2006). Real-time system for monitoring driver vigilance. *IEEE Transactions on Intelligent Transportation Systems*, *7*(1), 63-77.

Bhise, V. (2011). *Ergonomics in the automotive design process*. CRC Press, Boca Raton.

Bisseling, R. W., & Hof, A. L. (2006). Handling of impact forces in inverse dynamics. *Journal of biomechanics*, *39*(13), 2438-2444.

Brown, I. D. (1994). Driver fatigue. *Human Factors*. *36*(2), 298-314.

Campagne, A., Pebayle, T., & Muzet, A. (2004). Correlation between driving errors and vigilance level: influence of the driver's age. *Physiology & behavior, 80*(4), 515-524.

Clifford, G. D. (2002). *Signal processing methods for heart rate variability*, Doctoral dissertation, Oxford University.

Culham, J. C., & Kanwisher, N. G. (2001). Neuroimaging of cognitive functions in human parietal cortex. *Current opinion in neurobiology*, *11*(2), 157-163.

Davies, D. R., & Parasuraman, R. (1982). *The psychology of vigilance*. London, England: Academic Press.

Desmond, P. A., & Hancock, P. A. (2001). *Active and passive fatigue states*, in: Desmond, P.A., and Hancock, P.A. (Eds.), Workload and Fatigue. Lawrence Erlbaum Associates, London, 455-465.

De Waard, D., & te Groningen, R. (1996). *The measurement of drivers' mental workload*. Netherlands: Groningen University, Traffic Research Center.

De Winter, J., Van Leeuwen, P.M., & Happee, R. (2012). Advantages and disadvantages of driving simulators: A discussion. In *Proceedings of the measuring behavior*, *8*, 47-50.

Dinges, D. F., Mallis, M. M., Maislin, G., & Powell, J. W. (1998). *Evaluation of techniques for ocular measurement as an index of fatigue and as the basis for* *alertness management* (No. DOT-HS-808-762). United States. National Highway Traffic Safety Administration.

Dugan, E. L., Nagelkirk, P. R., & Wang, G. (2009). Comfort Motion Technology Equipped Automobile Seats: Effects on Load Distribution, Comfort, Blood Flow, Alertness, and Reaction Time. Ball State University Biomechanics Laboratory.

Durkin, J. L., Harvey, A., Hughson, R. L., & Callaghan, J. P. (2006). The effects of lumbar massage on muscle fatigue, muscle oxygenation, low back discomfort, and driver performance during prolonged driving. *Ergonomics*, *49*(1), 28-44.

Egelund, N. (1982). Spectral analysis of heart rate variability as an indicator of driver fatigue. *Ergonomics*, *25*(7), 663-672.

Eriksson, A., & Stanton, N. A. (2017). Takeover time in highly automated vehicles: noncritical transitions to and from manual control. *Human factors*, *59*(4), 689-705.

Filtness, A. J., Reyner, L. A., & Horne, J. A. (2012). Driver sleepiness—Comparisons between young and older men during a monotonous afternoon simulated drive. *Biological psychology*, *89*(3), 580-583.

Fix, J. D. (2002). *Neuroanatomy*. Lippincott Williams & Wilkins, Philadelphia.

Forsman, P. M., Vila, B. J., Short, R. A., Mott, C. G., & Van Dongen, H. P. (2013). Efficient driver drowsiness detection at moderate levels of drowsiness. *Accident Analysis & Prevention*, *50*, 341-350.

Garcia, I., Bronte, S., Bergasa, L. M., Almazán, J., & Yebes, J. (2012). Vision-based drowsiness detector for real driving conditions. In *2012 IEEE Intelligent Vehicles Symposium*, 618-623.

Gaspar, J. G., Brown, T. L., Schwarz, C. W., Lee, J. D., Kang, J., & Higgins, J. S. (2017). Evaluating driver drowsiness countermeasures. *Traffic injury prevention*, *18*(sup1), S58-S63.

Gastaldi, M., Rossi, R., & Gecchele, G. (2014). Effects of driver task-related fatigue on driving performance. *Procedia-social and behavioral sciences*, *111*(0), 955-964.

Gershon, P., Ronen, A., Oron-Gilad, T., & Shinar, D. (2009). The effects of an interactive cognitive task (ICT) in suppressing fatigue symptoms in driving. *Transportation research part F: traffic psychology and behaviour*, *12*(1), 21-28.

Gimeno, P. T., Cerezuela, G. P., & Montanes, M. C. (2006). On the concept and measurement of driver drowsiness, fatigue and inattention: implications for countermeasures. *International journal of vehicle design*, *42*(1/2), 67-86.

Grace, R., & Steward, S. (2001). Drowsy Driver Monitor and Warning System. Proceedings of the international driving symposium on human factorsin driver assessment, training and vehicle design, Iowa City.

Grandjean, E. (1979). Fatigue in industry. *Occupational and Environmental Medicine*, *36*(3), 175-186.

Hartley L.R. (2004). *Fatigue and driving*. In: Rothengatter T., Huguenin R.D., Traffic and transport psychology: Theory and application. Elsevier, Oxford, 221-229.

Hayami, T., Matsunaga, K., Shidoji, K., & Matsuki, Y. (2002). Detecting drowsiness while driving by measuring eye movement-a pilot study. In *Proceedings. The IEEE 5th International Conference on Intelligent Transportation Systems* (pp. 156-161). IEEE.

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R., & Dement, W. C. (1973). Quantification of sleepiness: a new approach. *Psychophysiology*, *10*(4), 431-436.

Horne, J. A., & Baulk, S. D. (2004). Awareness of sleepiness when driving. *Psychophysiology*, *41*(1), 161-165.

Jap, B. T., Lal, S., Fischer, P., & Bekiaris, E. (2009). Using EEG spectral components to assess algorithms for detecting fatigue. *Expert Systems with Applications*, *36*(2), 2352-2359.

Jarosch, O., Kuhnt, M., Paradies, S., & Bengler, K. (2017). It’s out of our hands now! Effects of non-driving related tasks during highly automated driving on drivers’ fatigue. In *Proceedings of the International Driving Symposium on Human Factors in Driver Assessment*, 319-325.

Kahneman, D. (1973). *Attention and effort* (Vol. 1063). Englewood Cliffs, NJ: Prentice-Hall.

Kaplan, S., & Prato, C. G. (2012). Associating crash avoidance maneuvers with driver attributes and accident characteristics: a mixed logit model approach. *Traffic injury prevention*, *13*(3), 315-326.

Kee, S., Tamrin, S. B. M., & Goh, Y. (2010). Driving fatigue and performance among occupational drivers in simulated prolonged driving. *Global Journal of Health Science*, *2*(1), 167.

Körber, M., Cingel, A., Zimmermann, M., & Bengler, K. (2015). Vigilance decrement and passive fatigue caused by monotony in automated driving. *Procedia Manufacturing*, *3*, 2403-2409.

Lal, S. K., & Craig, A. (2001). A critical review of the psychophysiology of driver fatigue. *Biological psychology*, *55*(3), 173-194.

Lal, S. K., Craig, A., Boord, P., Kirkup, L., & Nguyen, H. (2003). Development of an algorithm for an EEG-based driver fatigue countermeasure. *Journal of safety Research*, *34*(3), 321-328.

Lal, S. K., & Craig, A. (2005). Reproducibility of the spectral components of the electroencephalogram during driver fatigue. *International Journal of Psychophysiology*, *55*(2), 137-143.

Larue, G. S., Rakotonirainy, A., & Pettitt, A. N. (2011). Driving performance impairments due to hypovigilance on monotonous roads. *Accident Analysis & Prevention*, *43*(6), 2037-2046.

Larue, G. S., Rakotonirainy, A., & Pettitt, A. N. (2015). Predicting reduced driver alertness on monotonous highways. *IEEE Pervasive Computing*, *14*(2), 78-85.

Lenné, M. G., Triggs, T. J., & Redman, J. R. (1997). Time of day variations in driving performance. *Accident Analysis & Prevention*, *29*(4), 431-437.

Li, G., & Chung, W. Y. (2013). Detection of driver drowsiness using wavelet analysis of heart rate variability and a support vector machine classifier. *Sensors*, *13*(12), 16494-16511.

Li, Z., Chen, L., Peng, J., & Wu, Y. (2017). Automatic detection of driver fatigue using driving operation information for transportation safety. *Sensors*, *17*(6), 1212.

Liu, Y. C., & Wu, T. J. (2009). Fatigued driver's driving behavior and cognitive task performance: Effects of road environments and road environment changes. *Safety Science*, *47*(8), 1083-1089.

MacLean, A. W., Davies, D. R., & Thiele, K. (2003). The hazards and prevention of driving while sleepy. *Sleep medicine reviews*, *7*(6), 507-521.

Mandal, B., Li, L., Wang, G. S., & Lin, J. (2016). Towards detection of bus driver fatigue based on robust visual analysis of eye state. *IEEE Transactions on Intelligent Transportation Systems*, *18*(3), 545-557.

Matthews, G., & Desmond, P. A. (1998). Personality and multiple dimensions of task-induced fatigue: A study of simulated driving. *Personality and Individual Differences*, *25*(3), 443-458.

Matthews, G., Joyner, L., Gilliland, K., Campbell, S., Falconer, S., & Huggins, J. (1999). Validation of a comprehensive stress state questionnaire: Towards a state big three. *Personality psychology in Europe*, *7*, 335-350.

Matthews, G., Campbell, S. E., Falconer, S., Joyner, L. A., Huggins, J., Gilliland, K., ... & Warm, J. S. (2002). Fundamental dimensions of subjective state in performance settings: Task engagement, distress, and worry. *Emotion*, *2*(4), 315.

Matthews, G., Saxby, D. J., Funke, G. J., Emo, A. K., & Desmond, P. A. (2011). *Driving in states of fatigue or stress*. CRC Press, Boca Raton.

Matthews, G., Szalma, J., Panganiban, A. R., Neubauer, C., & Warm, J. S. (2013). Profiling task stress with the dundee stress state questionnaire. *Psychology of stress: New research*, *1*, 49-90.

Matthews, G., Neubauer, C., Saxby, D. J., Wohleber, R. W., & Lin, J. (2019). Dangerous intersections? A review of studies of fatigue and distraction in the automated vehicle. *Accident Analysis & Prevention*, *126*, 85-94.

Merat, N., & Jamson, A. H. (2013). The effect of three low-cost engineering treatments on driver fatigue: A driving simulator study. *Accident Analysis & Prevention*, *50*, 8-15.

Michael, R., & Meuter, R. (2006). Sustained attention and hypovigilance: The effect of environmental monotony on continuous task performance and implications for road safety. In *Proceedings of the Australasian road safety research, policing and education conference* (Vol. 10). Monash University.

Michail, E., Kokonozi, A., Chouvarda, I., & Maglaveras, N. (2008, August). EEG and HRV markers of sleepiness and loss of control during car driving. In *2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 2566-2569). IEEE.

Monk, T. H. (1991). *Circadian aspects of subjective sleepiness: A behavioral messenger?* In T. H. Monk (Ed.), Sleep, sleepiness and performance (pp. 39–63). John Wiley and Sons, New York.

Mulder, G. (1980). The heart of mental effort. *Unpublished Dissertation, Univ of Groningen The Netherlands*.

Neubauer, C., Matthews, G., Saxby, D., & Langheim, L. (2011, September). Individual differences and automation choice in simulated driving. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 55, No. 1, pp. 1563-1567). Sage CA: Los Angeles, CA: SAGE Publications.

Neubauer, C., Matthews, G., Langheim, L., & Saxby, D. (2012). Fatigue and voluntary utilization of automation in simulated driving. *Human factors*, *54*(5), 734-746.

Nilsson, T., Nelson, T. M., & Carlson, D. (1997). Development of fatigue symptoms during simulated driving. *Accident Analysis & Prevention*, *29*(4), 479-488.

O'Brien, R.M. (2007). A caution regarding rules of thumb for variance inflation factors. *Quality & Quantity*. *41*(5), 673.

O'donnell, R.D., & Eggemeier, E.T. (1986). *Workload assessment methodology*. In: Boff, K.R., Kaufman, L., Thomas, J.P. (Eds.), Handbook of Human Performance. Wiley, New York.

Oron-Gilad, T., & Hancock, P. A. (2005). Road environment and driver fatigue. In *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 318-324.

Oron-Gilad, T., & Ronen, A. (2007). Road characteristics and driver fatigue: a simulator study. *Traffic Injury Prevention*, *8*(3), 281-289.

Oron-Gilad, T., Ronen, A., & Shinar, D. (2008). Alertness maintaining tasks (AMTs) while driving. *Accident Analysis & Prevention*, *40*(3), 851-860.

Otmani, S., Rogé, J., & Muzet, A. (2005). Sleepiness in professional drivers: Effect of age and time of day. *Accident Analysis & Prevention*, *37*(5), 930-937.

Pack, A. I., Pack, A. M., Rodgman, E., Cucchiara, A., Dinges, D. F., & Schwab, C. W. (1995). Characteristics of crashes attributed to the driver having fallen asleep. *Accident Analysis & Prevention*, *27*(6), 769-775.

Park, J., Ebert, S. M., Reed, M. P., & Hallman, J. J. (2016). Statistical models for predicting automobile driving postures for men and women including effects of age. *Human factors*, *58*(2), 261-278.

Park, J., Jung, K., Lee, B., Choi, Y., Yang, X., Lee, S., & You, H. (2019). Development of statistical geometric models for prediction of a driver's hip and eye locations. *International Journal of Industrial Ergonomics*, *72*, 320-329.

Parkinson, M., Reed, M., Kokkolars, M., & Papalambros, P. (2007). Optimizing truck cab layout for driver accommodation. *ASME Journal of Mechanical Design*. *129*(11), 1110-1117.

Philippart, N. L., Roe, R.W., Arnold, A.J., & Kuechenmeister, T.J. (1984). *Driver selected seat position model*. SAE Technical Paper 840508. Warrendale, PA: Society of Automotive Engineer Inc.

Pan, J., & Tompkins, W. J. (1985). A real-time QRS detection algorithm. *IEEE transactions on biomedical engineering*, (3), 230-236.

Partala, T., & Surakka, V. (2003). Pupil size variation as an indication of affective processing. *International journal of human-computer studies*, *59*(1-2), 185-198.

Patel, M., Lal, S. K., Kavanagh, D., & Rossiter, P. (2011). Applying neural network analysis on heart rate variability data to assess driver fatigue. *Expert systems with Applications*, *38*(6), 7235-7242.

Pattyn, N., Neyt, X., Henderickx, D., & Soetens, E. (2008). Psychophysiological investigation of vigilance decrement: boredom or cognitive fatigue?. *Physiology & behavior*, *93*(1-2), 369-378.

Philip, P., Sagaspe, P., Taillard, J., Valtat, C., Moore, N., Åkerstedt, T., ... & Bioulac, B. (2005). Fatigue, sleepiness, and performance in simulated versus real driving conditions. *Sleep*, *28*(12), 1511-1516.

Pilutti, T., & Ulsoy, A. G. (1999). Identification of driver state for lane-keeping tasks. *IEEE transactions on systems, man, and cybernetics-Part A: Systems and humans*, *29*(5), 486-502.

Pollock, V. E., Schneider, L. S., & Lyness, S. A. (1991). Reliability of topographic quantitative EEG amplitude in healthy late-middle-aged and elderly subjects. *Electroencephalography and clinical neurophysiology*, *79*(1), 20-26.

Reed, M.P., Manary, M.A., Flannagan, C.A.C., & Schneider, L.W. (2002). A statistical method for predicting automobile driving posture. *Human Factors*. *44*(4), 557–568.

Reid, J. M. (1995). 23 Dysfunctional driving behaviours: a cognitive approach to road safety research. *Fatigue and Driving: Driver Impairment, Driver Fatigue, And Driving Simulation*, 233-247.

Reyner, L. A., & Horne, J. A. (1998). Falling asleep whilst driving: are drivers aware of prior sleepiness?. *International journal of legal medicine, 111*(3), 120-123.

SAE international. (2016). Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. *SAE International, (J3016).*

SAE J4004. (2005). *Positioning the H-Point Design Tool - Seating Reference Point and Seat Track Length*. Warrendale, PA: Society of Automotive Engineers, Inc.

SAE J1100. (2009). *Motor vehicle dimensions*. Warrendale, PA: Society of Automotive Engineers, Inc.

SAE J941. (2010). *Motor vehicle drivers' eye locations*. Warrendale, PA: Society of Automotive Engineers, Inc.

Size Korea. (2010). *Report on the Fifth Survey of Korean Anthropometry*. Retrieved June 26, 2010 from http://sizekorea.kats.go.kr/

Sahayadhas, A., Sundaraj, K., & Murugappan, M. (2012). Detecting driver drowsiness based on sensors: a review. *Sensors*, *12*(12), 16937-16953.

Saxby, D. J., Matthews, G., Hitchcock, E. M., & Warm, J. S. (2007, October). Development of active and passive fatigue manipulations using a driving simulator. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 51, No. 18, pp. 1237-1241). Sage CA: Los Angeles, CA: SAGE Publications.

Saxby, D. J., Matthews, G., Hitchcock, E. M., Warm, J. S., Funke, G. J., & Gantzer, T. (2008, September). Effect of active and passive fatigue on performance using a driving simulator. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 52, No. 21, pp. 1751-1755). Sage CA: Los Angeles, CA: Sage Publications.

Saxby, D. J., Matthews, G., Warm, J. S., Hitchcock, E. M., & Neubauer, C. (2013). Active and passive fatigue in simulated driving: discriminating styles of workload regulation and their safety impacts. *Journal of experimental psychology: applied*, *19*(4), 287.

Schmidt, E., & Bullinger, A. C. (2019). Mitigating passive fatigue during monotonous drives with thermal stimuli: Insights into the effect of different stimulation durations. *Accident Analysis & Prevention*, *126*, 115-121.

Schömig, N., Hargutt, V., Neukum, A., Petermann-Stock, I., & Othersen, I. (2015). The interaction between highly automated driving and the development of drowsiness. *Procedia Manufacturing*, *3*, 6652-6659.

Shahid, A., Wilkinson, K., Marcu, S., & Shapiro, C. M. (2011). Karolinska sleepiness scale (KSS). In *STOP, THAT and One Hundred Other Sleep Scales* (pp. 209-210). Springer, New York, NY.

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, *52*(3/4), 591-611.

Shinar, D. (1993). Traffic safety and individual differences in drivers' attention and information processing capacity. *Alcohol, Drugs & Driving*, *9*(3-4), 219-237.

Song, W., Woon, F. L., Doong, A., Persad, C., Tijerina, L., Pandit, P., ... & Giordani, B. (2017). Fatigue in younger and older drivers: effectiveness of an alertness-maintaining task. *Human factors*, *59*(6), 995-1008.

Steele, T., Cutmore, T., James, D. A., & Rakotonirainy, A. (2004). An investigation into peripheral physiological markers that predict monotony. In *2004 Road Safety Research, Policing and Education Conference (Perth).*

Thiffault, P., & Bergeron, J. (2003). Monotony of road environment and driver fatigue: a simulator study. *Accident Analysis & Prevention*, *35*(3), 381-391.

Ting, P. H., Hwang, J. R., Doong, J. L., & Jeng, M. C. (2008). Driver fatigue and highway driving: A simulator study. *Physiology & behavior*, *94*(3), 448-453.

Tomarken, A. J., Davidson, R. J., Wheeler, R. E., & Kinney, L. (1992). Psychometric properties of resting anterior EEG asymmetry: Temporal stability and internal consistency. *Psychophysiology*, *29*(5), 576-592.

Tompkins, W. J. (1993). *Biomedical digital signal processing*. Prentice Hall, New Jersey.

Tran, Y., Wijesuriya, N., Tarvainen, M., Karjalainen, P., & Craig, A. (2009). The relationship between spectral changes in heart rate variability and fatigue. *Journal of Psychophysiology*, *23*(3), 143-151.

Tuthill, J. C., & Azim, E. (2018). Proprioception. *Current Biology*, *28*(5), R194-R203.

Tzamalouka, G., Papadakaki, M., & Chliaoutakis, J. E. (2005). Freight transport and non-driving work duties as predictors of falling asleep at the wheel in urban areas of Crete. *Journal of safety research*, *36*(1), 75-84.

Van Deursen, D. L., Van Deursen, L. L. J. M., Snijders, C. J., & Goossens, R. H. M. (2000). Effect of continuous rotary seat pan movements on physiological oedema of the lower extremities during prolonged sitting. *International Journal of Industrial Ergonomics*, *26*(5), 521-526.

Van Geffen, P., Reenalda, J., Veltink, P. H., & Koopman, B. F. (2010). Decoupled pelvis adjustment to induce lumbar motion: A technique that controls low back load in sitting. *International journal of industrial ergonomics*, *40*(1), 47-54.

Van Loon, R. J., Brouwer, R. F., & Martens, M. H. (2015). Drowsy drivers' under-performance in lateral control: How much is too much? Using an integrated measure of lateral control to quantify safe lateral driving. *Accident analysis & prevention*, *84*, 134-143.

Veen, S. V., Orlinskiy, V., Franz, M., & Vink, P. (2015). Investigating car passenger well-being related to a seat imposing continuous posture variation. *Journal of Ergonomics*, *4*, 140.

Van Veen, S. (2016). Driver vitalization: investigating sensory stimulation to achieve a positive driving experience. *Doctoral Dissertation*. TU Delft.

Varela, M., Gyi, D. E., Mansfield, N. J., Picton, R., & Hirao, A. (2017). Designing movement into automotive seating-does it improve comfort?. In *Proceedings of the First International Comfort Congress*, Salerno.

Verster, J. C., & Roth, T. (2013). Vigilance decrement during the on-the-road driving tests: The importance of time-on-task in psychopharmacological research. *Accident Analysis & Prevention*, *58*, 244-248.

Verwey, W. B., & Zaidel, D. M. (1999). Preventing drowsiness accidents by an alertness maintenance device. *Accident Analysis & Prevention*, *31*(3), 199-211.

Vicente, K. J., Thornton, D. C., & Moray, N. (1987). Spectral analysis of sinus arrhythmia: A measure of mental effort. *Human factors*, *29*(2), 171-182.

Vink, P., & Hallbeck, S. (2012). Comfort and discomfort studies demonstrate the need for a new model. *Applied Ergonomics*, *43*(2), 271-276.

Wang, Z., Zheng, R., Kaizuka, T., Shimono, K., & Nakano, K. (2017). The effect of a haptic guidance steering system on fatigue-related driver behavior. *IEEE Transactions on Human-Machine Systems*, *47*(5), 741-748.

Williamson, A. M., Feyer, A. M., & Friswell, R. (1996). The impact of work practices on fatigue in long distance truck drivers. *Accident Analysis & Prevention*, *28*(6), 709-719.

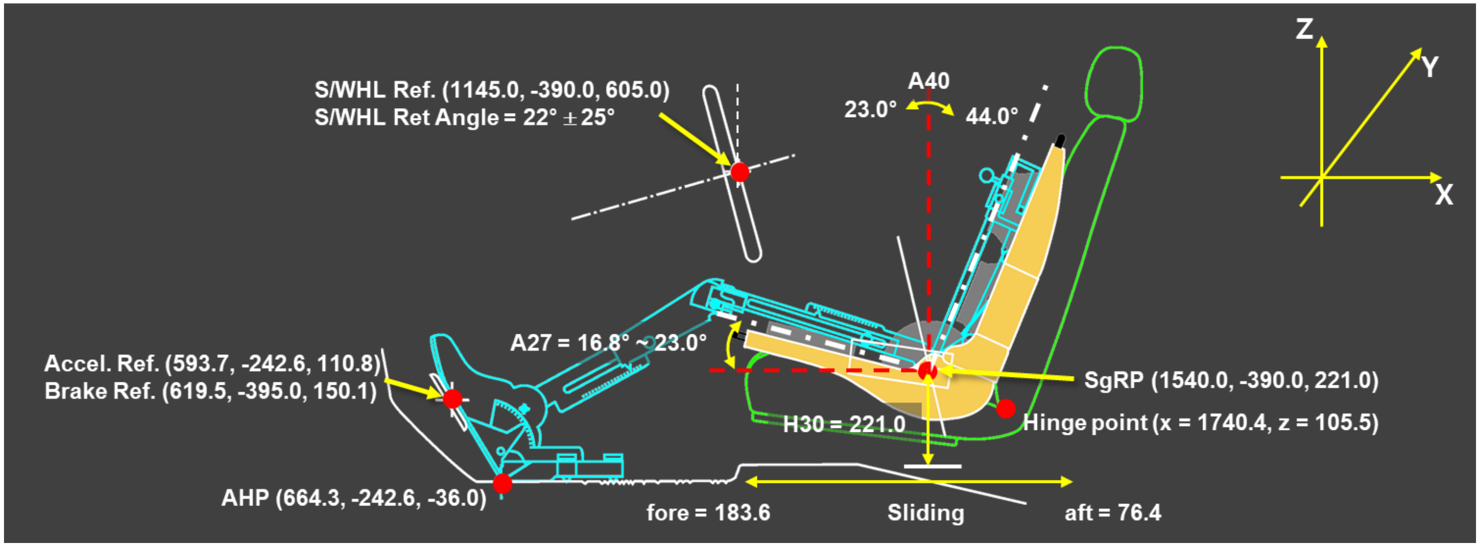
Young, M. S., & Stanton, N. A. (2007). Back to the future: Brake reaction times for manual and automated vehicles. *Ergonomics*, *50*(1), 46-58.

Zerehsaz, Y., Jin, J. J., Ebert, S. M., & Reed, M. P. (2017). Statistical prediction of eye locations for drivers of military ground vehicles. *International Journal of Industrial Ergonomics*, *59*, 20-28.

Zhang, N., Fard, M., Bhuiyan, M. H. U., Verhagen, D., Azari, M. F., & Robinson, S. R. (2018). The effects of physical vibration on heart rate variability as a measure of drowsiness. *Ergonomics*, *61*(9), 1259-1272.

APPENDICES

Appendix A. Design of the Adjustable Vehicle Seating Buck



Appendix B. Informed Consent Form (IRB)

Informed Consent Form

Approval Number: PIRB-2018-E080
Date: January 19, 2018

Consent of Participation in a Driving Study

Ergonomic Design Technology Laboratory
Department of Industrial & Management Engineering
Pohang University of Science & Technology

Title of Project: Evaluation of a Motion Seat System on Driver's Passive Task-Related (TR) Fatigue: An On-Road Driving Study

Principal Investigator Heecheon You, Ph.D.
Investigator Seunghoon Lee, M.S.

This is to certify that I, ______________________________________, have been given the following information with respect to my participation as a volunteer in a program of investigation under the supervision of Dr. Heecheon You.

1. Purpose of the study: The purpose of this study is to examine the effectiveness of a motion seat system, which is proposed to reduce driver fatigue by increasing cognitive alertness on the driver by changing the driving posture passively. Information collected through the experiment will be used to better understand the discipline concerned with drivers in the context of safety-related driving behaviors.

2. Procedures to be followed: The experiment of on-road motion seat system evaluation would be conducted in four phases: (1) preparation, (2) subjective fatigue evaluation before driving, (3) main experiment, and (4) subjective fatigue evaluation after driving. In the main experiment phase, a monotonous driving task of maintaining 90 to 100 km/h while staying in the second lane on the highway will be conducted. The researcher will provide detailed instructions.

3. Discomfort and risks: Discomfort or fatigue such as buttock numbness, low back pain, and joint stiffness may occur from conducting the prolonged sitting. Otherwise, minimal discomforts and risks are anticipated in participating in the experiment. However, if any significant discomfort occurs during the participation, I should stop and inform the investigator of the discomfort.

4. a. Benefits to me: There are no benefits to me from my participation in this experiment.
   b. Potential benefits to society: This study may contribute to preventing driver fatigue-related accidents in a monotonous driving environment by increasing the alertness of the driver using the motion seat system proposed in the present study.

5. Alternative procedures which could be utilized: I may decline to participate in this experiment when any alternative procedure is utilized.

6. Time duration of the procedures and study: To complete the experiment, approximately two hours of time will be needed each of two days.

7. Statement of confidentiality: My participation in this research is confidential. Only the investigators will have access to my identity and to information that can associated with my identity. All records associated with my participation in the study will be subject to the usual confidentiality standards applicable to relevant laws, and in the event of any publication resulting from the research no personally identifiable information will be disclosed. Also, I understand that an officer from the Institutional Review Board of the Pohang University of Science and Technology will have access to my records for regulatory review process.

8. Right to ask questions: I have been given an opportunity to ask any questions I may have, and all such questions or inquires have been answered to my satisfaction. Questions regarding the nature of the research should be directed to either Dr. Heecheon You (e-mail: hcyou@postech.ac.kr, phone: 054-279-2210) or Mr. Seunghoon Lee (e-mail: shooonlee@postech.ac.kr, phone: 054-279-8247).

9. Compensation: I will be compensated 15,000 won per hour of the time for my participation in the study. In addition, I understand that in the event of physical injury resulting from research, the costs of medical treatment would be covered by the car insurance purchased by the research sponsor Hyundai Motors Company. Lastly, I understand that neither financial compensation nor free medical treatment is provided by the University in the event that I suffer from a research-related injury.

10. Voluntary participation: I understand that my participation in this study is voluntary, and that I may withdraw from this study at any time by notifying the investigator. My withdrawal from this study or my refusal to participate will make me no disadvantages.

This is to certify that I consent to and give permission for my participation as a volunteer in this program of investigation. I understand that I will receive a signed copy of this consent form. I have read this form, and understand the consent of this consent form.

____

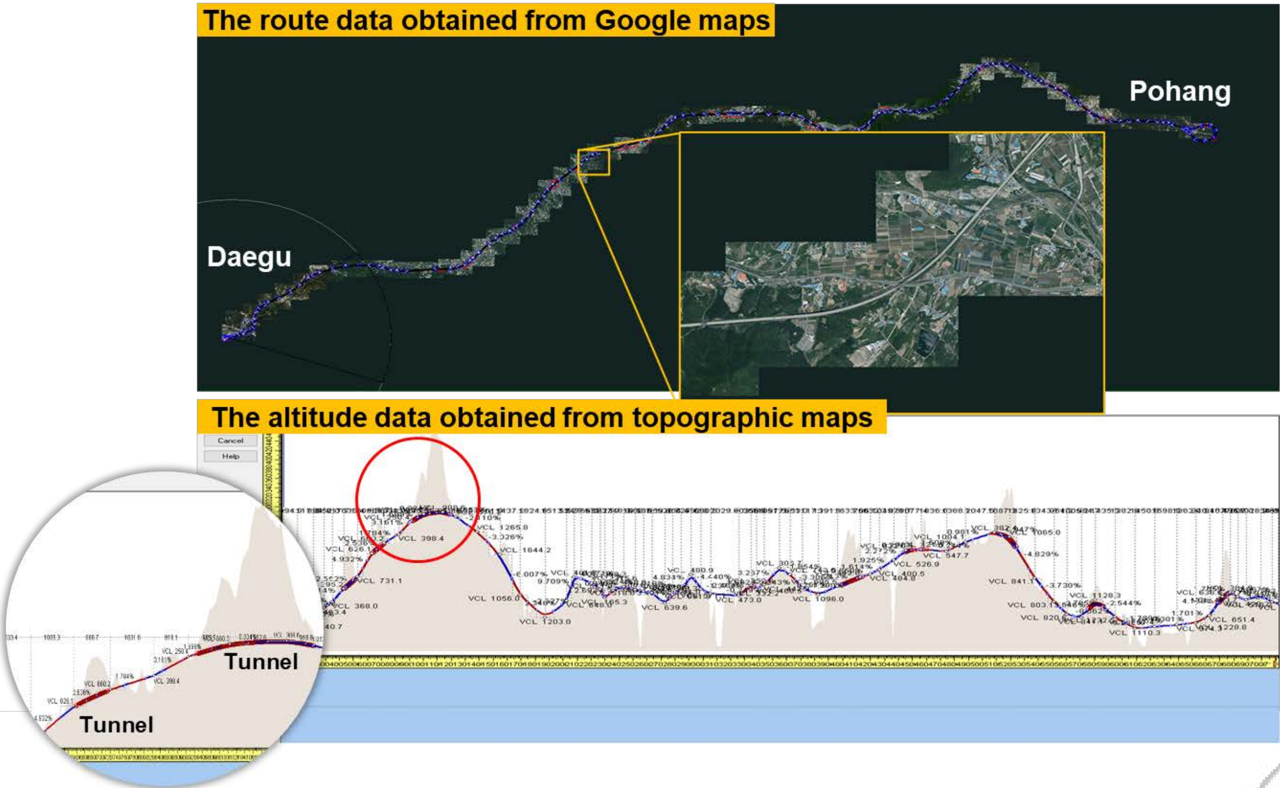
Volunteer Date

I, the undersigned, have planned and explained the study involved to the above volunteer.

____

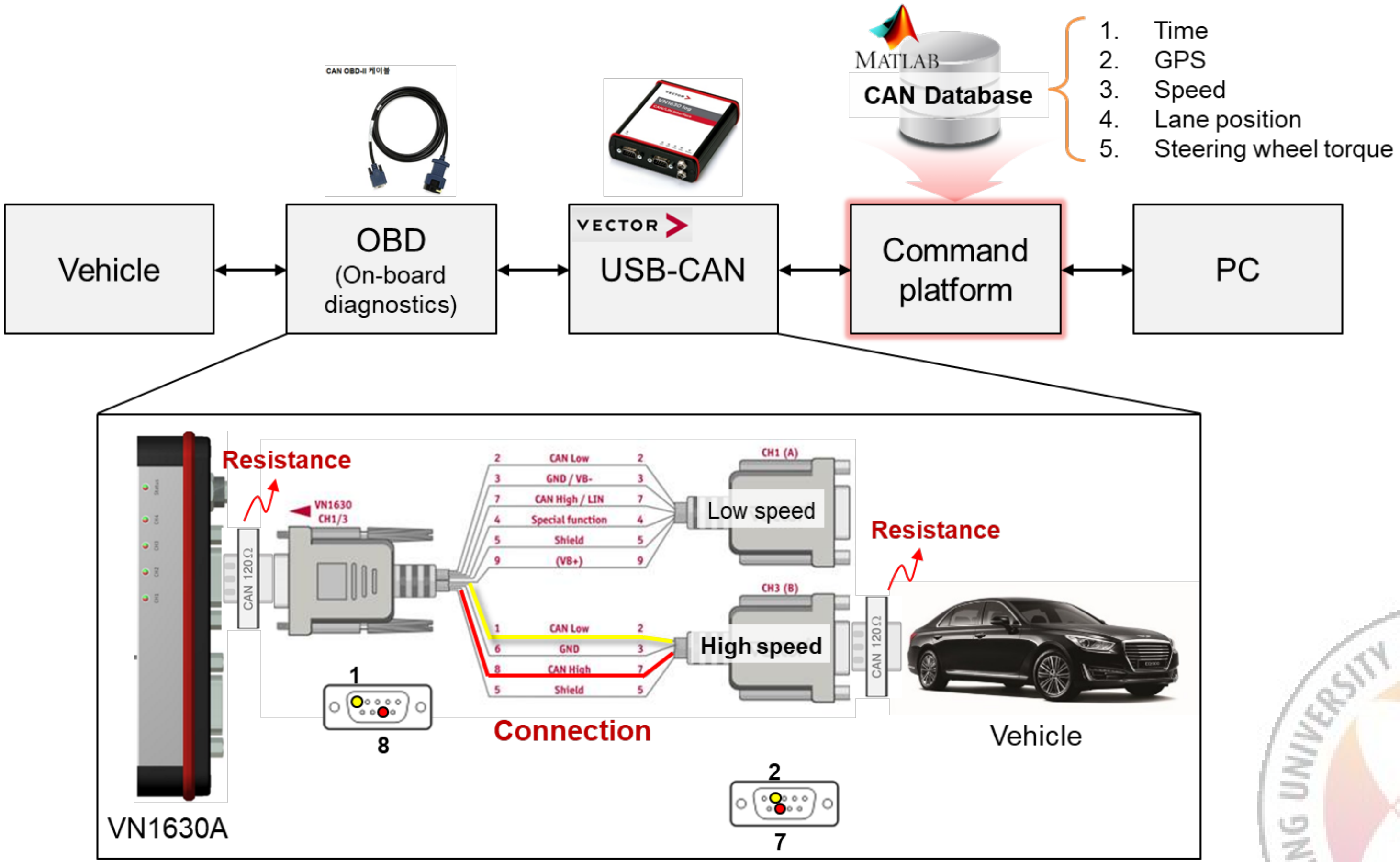
Investigator Date

Appendix C. Reconstruction of Driving Simulation Environment



Appendix D. Controller Area Network (CAN)

D.1. Hardware configuration for serial communications



D.2. CAN signal information

Communication verified   Communication **NOT** verified

Name	Output Period [ms]	Send Type	Signal Name	Definition	Min	Max	Unit	
CGW_PC4	10	P	N	Engine speed	0	16.4e3	rpm	Vehicle & engine speed
			VS	Vehicle speed	0	254	km/h	
EMS12	10	P	BRAKE_ACT	Indication of brake switch ON/OFF	0	3		Pedal ON/OFF
			PV_AV_CAN	Accelerator Pedal value	0	99.60	%	
ESP12	10	P	LAT_ACCEL	Lateral acceleration speed	-10.23	10.24	m/s^2	Vehicle stability
			LONG_ACCEL	Longitudinal acceleration speed	-10.23	10.24	m/s^2	
			YAW_RATE	Yaw rate	-40.95	40.96	°/s	
WHL_SPD11	20	P	WHL_SPD_FL	Wheel speed (high reolution), front, left-hand	0	511.97	km/h	Wheel speed
			WHL_SPD_FR	Wheel speed (high reolution), front, right-hand	0	511.97	km/h	
			WHL_SPD_RL	Wheel speed (high reolution), rear, left-hand	0	511.97	km/h	
			WHL_SPD_RR	Wheel speed (high reolution), rear, right-hand	0	511.97	km/h	
LKAS14	70	P	CF_LeftLine_Departure		0	1		Driving lane information
			CF_LeftLine_Position		-2	1.99		
			CF_LeftLine_HeadingAngle		-0.06	0.06		
			CF_RightLine_Departure		0	1		
			CF_RightLine_Position		-2	1.99	m	
			CF_RightLine_HeadingAngle		-0.06	0.06		
SAS11	10	P	SAS_Angle	Steering wheel angle	-3276.8	3276.7	Deg	Steering wheel rotation
			SAS_Speed	Steering wheel speed	0	1016		

CURRICULUM VITAE

Seunghoon Lee

Department of Industrial and Management Engineering

Pohang University of Science and Technology (POSTECH)

Education

Ph.D. Industrial and Management Engineering — Aug. 2020

Pohang University of Science and Technology, Pohang, South Korea

Dissertation: Development of Dynamic Seat Motion System for Reduction of Driver's Passive Task-Related Fatigue

Advisor: Dr. Heecheon You

M.S. Mechanical Engineering — Feb. 2013

Sogang University, Seoul, South Korea

Thesis: The Effect of Shoes on Knee Kinematics, Kinetics, and Energetics

Advisor: Dr. Choongsoo Shin

B.S. Mechanical Engineering — Feb. 2011

Sogang University, Seoul, South Korea

Research Interests

- Biological signal sensing system
- Automobile ergonomics and autonomous driving
- Human performance and workload assessment
- Anthropometric and biomechanical analysis for product design
- Product design and evaluation with digital human models

B. Journals

B.1 International Journal Articles

1. **Lee, S.**, Kim, M, Jung, H., Kwon, D., Choi, S., and You, H. (2020). Effects of a motion seat system on driver's passive task-related fatigue: an on-road driving study. *Sensors*, *20*(9), 2688-2702.

2. **Lee, S.**, Jung, H., Kim, M., Choi, S., and You, H. Effects of a motion seat system on driver's passive task-related fatigue reduction: A lab-based driving simulation study. *Applied Ergonomics* (under review).
3. Park, J., Jung, K., Choi, Y., Yang, X., **Lee, S.**, and You, H. (2019). Development of statistical geometric models for prediction of a driver's hip and eye locations. *International Journal of Industrial Ergonomics*, *72*, 320-329.
4. Yang, X., Yang, J., **Lee, S.**, Hwang, H., Ahn, S., Yu, H., and You, H. (2018). Estimation of standard liver volume using CT volume, body composition, and abdominal geometry measurements for Korean adults. *Yonsei Medical Journal*, *59*(4), 546-553.
5. **Lee, S.**, and Shin, C. (2013). The effect of frame rates on knee kinetics during landing and cutting. *International Journal of Precision Engineering and Manufacturing*, *14*(2), 333-336.

B.2 Korean Journal Articles

1. Jeon, E., Kim, H., You, H., **Lee, S.**, Kim, K., and Yoon, S. (2017) Evaluation of the wearing characteristics of hip protectors based on draping pattern design and body shape in Korean elderly people. *Journal of the Korean Fracture Society*, *30*(4), 180-185.
2. Jung, H., **Lee, S.**, Kim, M., Choi, H., and You, H. (2017) Ergonomic evaluation and improvement of bus seat armrest design. *Journal of the Ergonomics Society of Korea*, *36*(2), 69-86
3. Kim, S., Lee, J., **Lee, S.**, Yeon, Y., Tsolmonbaatar, B., and You, H. (2015) A survey of eco product development methods and strategies. *J. of Life Cycle Assessment*, *16*(1), 95-106.
4. **Lee, S.**, Choi, Y., Lee, W., Yu, M., Ko, M., Park, J., and You, H. (2015). Development of a physical therapy system for enhancement of balance ability. *Journal of Korean Society for Computer Game*, *28*(2), 205-214.
5. Choi, Y., Jung, H., Lee, W., Yang, X., **Lee, S.**, You, H., Yu, M., Ko, M., and Park, J. (2015). Development of a serious game for active Kegel exercise. *Journal of Korean Society for Computer Game*, *28*(2), 195-203.
6. Lee, W., Yang, X., **Lee, S.**, Choi, Y., Jung, H., Lee, H., You, H., Yu, M., Ko, M., and Park, J. (2015). Development of a serious game for rehabilitation of articulation and fluency disorders. *Journal of Korean Society for Computer Game*, *28*(2), 1-9.
7. Kwon, Y.N., Sung, M.J., Cho, H.A., Chang, E.C., Park, K.A., Park, J., Jeon, E.J., Kim, E., **Lee, S.**, You, H., Ha, T., and Shin, W.C. (2014). Effects of an indigo blanket on insomnia symptoms: Double blind, placebo-controlled, randomized pilot study. *Journal of Korean Sleep Research Society*, *11*(1), 33-37.
8. Park, H., **Lee, S.**, Lee, B., and You, H. (2013). Development of eco-design solutions for an electric hair dryer through performance, usability, and life-cycle assessments. *Korean Journal of Life Cycle Assessment*, *14*(1), 19-32.

C. Conference Proceedings

C.1 International Conference Proceedings

1. **Lee, S.**, Kim, M., Choi, S., and You. H. (2018). Evaluation of a motion seat system for reduction of a driver's passive task-related (TR) fatigue. *In Proceedings of the Human Factors and Ergonomics Society (HFES) 62nd Annual Meeting* (Philadelphia, PA: The Human Factors and Ergonomics Society)
2. **Lee, S.**, Park, J., Jung, K., Yang, X., and You. H. (2017). Development of statistical models for predicting a driver's hip and eye locations. *In Proceedings of the Human Factors and Ergonomics Society (HFES) 61st Annual Meeting* (Austin, TX: The Human Factors and Ergonomics Society)

3. Lee, N., **Lee, S.**, Lee, B., Jung, H., and You, H. (2016). Ergonomic evaluation on handle designs of vacuum cleaner. *In Proceedings of the Human Factors and Ergonomics Society (HFES) 60th Annual Meeting* (Washington, DC: The Human Factors and Ergonomics Society)
4. Jung, H., **Lee, S.**, Lee, N., Lee, W., and You, H. (2016). Bus seat design development based on 3D human body shape. *In Proceedings of the 18th International Conference on Human-Computer Interaction* (Toronto, Canada: HCI International 2016)
5. Hong, Y., Jeong, J., **Lee, S.**, Yoon, Y., and Shin, C. (2013). The effect of shoes on knee kinetics and anterior tibial translation during single-leg landing. *In Proceedings of the 31th International Conference on Biomechanics in Sports*.
6. **Lee, S.**, Kim, Y., and Shin, C. (2012). Effects of Sampling Rates on Knee Kinematics and Kinetics during Single-leg landing. *In Proceedings of the Orthopedic Research Society (ORS) 2012 Annual Meeting* (San Francisco, CA: Orthopedic Research Society)

C.2 Korean Conference Proceedings

1. **Lee, S**., Kim, M., Choi, S., and You, H. (2019). Evaluation of a Motion Seat System for Reduction of a Driver's Passive Task-Related Fatigue. *In Proceedings of the 2019 Spring Conference of the Korean Institute of Industrial Engineers.*
2. Ko, J., Jeon, E, **Lee, S**., and You, H. (2018). Cognitive Workload Evaluation of the User Interface of a Smart Home Appliance Product Based on Electrocardiography. *2018 Spring Conference of the Ergonomics Society of Korea and the 20th Korea-Japan Joint Symposium.*
3. **Lee, S.**, Kim, M., Ko, J., Oh, J., and You, H. (2018). An on-road driver fatigue analysis using a driver's physiological signal and driving performance data. *2018 Spring Conference of the Ergonomics Society of Korea and the 20th Korea-Japan Joint Symposium.*
4. Lee, H., **Lee, S.**, Jeong, Y., and You, H. (2017). Development of finite element model for impact force attenuation of hip protector. *In Proceedings of the 2017 Fall Conference of the Ergonomics Society of Korea*.
5. Oh, G., Jung, K., **Lee, S.**, and You, H. (2017). Development of personalized model for early detection of driver's negative emotion. *In Proceedings of the 2017 Fall Conference of the Ergonomics Society of Korea*.
6. Moon, S., Lee, N., **Lee, S.**, Jung, H., Lee, S., Moon, J., and You. (2017). Ergonomic Design and Evaluation of Vaginal Probe. *In Proceedings of the 2017 Spring Conference of the Ergonomics Society of Korea*.
7. Oh, G., Jung, K., **Lee, S.**, Jung, H., Lee, N., Kim, E., and You, H. (2017). Development of an ECG-Based Discriminant Model for Emotion Detection of Drivers. *In Proceedings of the 2017 Spring Conference of the Ergonomics Society of Korea*.
8. **Lee, S.**, Jung, H., Oh, G., Moon, S., Lee, H., Kim, M., Choi, S., and You, H. (2017). Development of Statistical Models for Predicting a Driver's Hip and Eye Locations. *In Proceedings of the 2017 Spring Conference of the Ergonomics Society of Korea*.
9. Lee, H., **Lee, S.**, Jeon, E., and You, H. (2017). Development of Statistical Models for Predicting a Driver's Hip and Eye Locations. *In Proceedings of the 2017 Spring Conference of the Ergonomics Society of Korea*.
10. Kim, M., **Lee, S.**, Jung, H., Oh, G., Moon, S., Lee, H., Kim, M., Choi, S., and You, H. (2017). The Effect of a Seat Motion System on the Passive Mental Fatigue of Driver. *In Proceedings of the 2017 Spring Conference of the Ergonomics Society of Korea*.

11. **Lee, S.**, Oh, G., Jung, H., Lee, J., Lee, H., Moon, S., Ryu, J., Choi, S., and You, H. (2016). A Preliminary Study of the Effects of a Seat Motion System for Reduction of Driving Fatigue. *In Proceedings of the 2016 Fall Conference of the Ergonomics Society of Korea*.
12. Jung, H., Lee, W., **Lee, S.**, Gradiyan, B., Edwina, D., Lee, H., Moon, S., and You, H. (2016). 3D Deformable Template Human Body Model for Ergonomic Product Design. *In Proceedings of the 2016 Spring Conference of the Ergonomics Society of Korea*.
13. Lee, N., **Lee, S.**, Jung, H., Park, B., Choi, H., and You, H. (2016). Ergonomic Bus Seat Design Method Based on 3D Seating Body Scan Data. *In Proceedings of the 2016 Spring Conference of the Ergonomics Society of Korea*.
14. **Lee, S.**, Jung, H., Lee, N., Park, B., Choi, H., and You, H. (2016). Evaluation of Sitting Comfort and Preferred Hardness for 3D Body Shape-based Bus Seat. *In Proceedings of the 2016 Spring Conference of the Ergonomics Society of Korea*.
15. Jeon, E., Park, S., Jung, D., Lee, W., **Lee, S.**, Kim, S., You, S., and Kim, H. (2014). Development of hip protector design process for Korean elderly people. *In Proceedings of the 2014 Fall Conference of the Korean Institute Society of Fashion & Textile Industry*.
16. **Lee, S.**, Park, S., Jung, D., Jeon, E., Kim, H., Kim, S., Lee, W., and You, H. (2014). Recommendations for biomechanical testing of hip protectors: Systematic literature review. *In Proceedings of the 2014 Fall Conference of the Ergonomics Society of Korea*.
17. Lee, B., **Lee, S.**, Jung, H., Lee, J., Choi, T., Lee, M., Kim, H., Kim, E., Jeon, H., Cho, Y., Seo, S., and You, H. (2014). Development of a design factor quantification method to increase a grip comfort of outside door handle (ODH). *In Proceedings of the 2014 Fall Conference of the Ergonomics Society of Korea*.
18. **Lee, S.**, Kim, K., Bang, S., Yeon, Y., You, H. (2014). Comparison of national and corporate take-back system to derive effective collection program of EOL mobile phone. In *Proceedings of the 2014 Spring Conference of the Korean Institute of Industrial Engineers*.
19. Lee, J., Lee, B., **Lee, S.**, You, H., and Kang, J. (2013). A study on personalized visual field testing methods for improving the efficiency and accuracy. In *Proceedings of the 29th Annual Meeting of Korean Glaucoma Society*.
20. Kim, S., Lee, J., **Lee, S.**, Yeon, Y., Batbileg, T., and You, H. (2013). A survey of eco product development methods and strategies. In *Proceedings of the 2013 Fall Conference of the Korea Society for Life Cycle Assessment*.
21. Jeon, E., Park, J., **Lee, S.**, Jung, D., Park, S., Ha, J., Kim, E., Park, S., and You, H. (2013). Wearing comfort evaluation of safety shoes with a ventilation system. In *Proceedings of the 2013 Fall Conference of the Ergonomics Society of Korea*.
22. Lee, W., Park, S., Jung, D., Jeon, E., Kim, H., Park, J., **Lee, S.**, and You, H. (2013). Development of a design process of hip protector for the elderly. In *Proceedings of the 2013 Fall Conference of Ergonomics Society of Korea*.
23. **Lee, S.**, Choi, Y., Lee, H., Lee, W., You, T., Ko, M., Park, J., Yu, M., and You, H. (2013). Development of a physical therapy system for enhancement of balance ability. In *Proceedings of the 2013 Fall Conference of Ergonomics Society of Korea*.
24. Park, H., Kim, M., **Lee, S.**, Lee, S., Lee, B., and You, H. (2013). Eco-friendly design for electric hair dryer through life-cycle assessment. In *Proceedings of the 2013 Spring Conference of Korean Institute of Industrial Engineers*.
25. **Lee, S.**, Park, H., Park, J., and You, H. (2013). Development of a muscle rigidity measurement system for an early diagnosis of Parkinson's disease. In *Proceedings of the 2013 Spring Conference of Ergonomics Society of Korea*.

26. Lee, J., **Lee, S.**, Lee, B., Kang, J., Jun, C., and You, H. (2013). Development of a diagnostic model for glaucoma. In *Proceedings of the 2013 Spring Conference of Ergonomics Society of Korea*.
27. **Lee, S.**, and Shin, C. (2012). Effect of Shoes on Anterior Tibial Translation during Landing. *In Proceedings of the 2012 Fall Conference of Korean Society for Precision Engineering*.
28. **Lee, S.**, and Shin, C. (2012). Gender Difference in Kinetic of Knee during Stair Descending. *In Proceedings of the 2012 Fall Conference of Korean Society for Precision Engineering*.
29. **Lee, S.**, and Shin, C. (2012). Knee Kinetics Differences between Shod and Barefoot Landing. *In Proceedings of the 2012 Fall Conference of Korean Society of Mechanical Engineering*.
30. **Lee, S.**, and Shin, C. (2012). Stress Concentration Patterns of Femoral Articular Cartilage during Single leg Landing. *In Proceedings of the 2012 Spring Conference of Korean Society for Precision Engineering*.
31. **Lee, S.**, and Shin, C. (2012). Effect of Frame Rates on Knee Kinetics during Side Step Cutting Maneuver. *In Proceedings of the 2012 Spring Conference of Korean Society of Mechanical Engineering*.

D. Patents

Issued

1. Kim, H., Kim, D., You, H., Jeon, E., Lee, S., Ko, M., Kim, G., Yoon, S., Yu, M. Hip protector. Registration number: 10-1979356, 2019. 5. 10.
2. Lee, B., Lee, S., You, H., Yang, G., Jeon, H., Hong, S., Lee, Y., Na, D. System for counting swallowing and method thereof. Registration number: 10-2016-0023345, 2016. 8. 30.
3. You, H., Lee, B., Lee, J., Park, H., Lee, S., Kang, J. Individual-based visual field testing method and device of the same. Registration number: 10-1654265, 2016. 8. 30.
4. You, H., Lee, S., Jung, H., Choi, Y., Park, J., Ko, M., Yu, M., Choung, W., Lee, E., Lee, S., Lee, C., Choe, J. Functional game system for balance training and quantitative evaluation. Registration number: 10-1521575, 2015. 5. 13.
5. Lee, J., Lee, B., Lee, S., Park, H., You, H., Kang, J. The measurement program of optic disc C/D ratio. Registration number: C-2013-0117718, 2013. 9. 9.

Pending

1. Lee, B., Jeong, D., Kang, T., Choi, S., Park, H., Lee, S., Park, S., Lee, Y., Kim, Y., You, H., **Lee, S**., Kim, M., Ko, J. System and method for reducing fatigue of driver in the seat of vehicle. Application number: 10-2019-0068958, 2019. 6. 11.

Research Grants

1. Establishment of a real-life usability testing center. Korea Institute for Advancement of Technology. 2017. 11 ~ 2018. 8
2. Development of a novel evaluation method for seat comfort evenness, Hyundai Motor Group. 2017. 5 ~ 2018. 6
3. On-road evaluation of a motion seat system on passive driving fatigue. Hyundai Motor Group. 2017. 5 ~ 2018. 4
4. Advancement of a swallowing monitoring system. National Research Foundation. 2016. 10 ~ 2020. 7.

5. Anthropometric analysis of pilots and cockpit layout design for KF-X. Korea Aerospace Industry. 2016. 4 ~ 2018. 2
6. Development of a seat motion system for reduction of driving fatigue. Hyundai Motor Group. 2016. 3 ~ 2017. 2
7. Ergonomic evaluation of ultrasonic probe PUI. Samsung Medison. 2016. 3 ~ 2016. 5
8. An explorative study of in-vehicle risk analysis using ECG signals. Hyundai Motor Group. 2015. 11 ~ 2016. 4.
9. Ergonomic evaluation of excavator designs. Hyundai Heavy Industry. 2015. 12 ~ 2016. 5.
10. Design technology of product design shape based on analysis of human-product deformation. National Research Foundation. 2015. 5 ~ 2018. 6.
11. Development of ergonomic bus seat design using 3D sitting body shape data and cushion density preference. Hyundai Motor Group. 2015. 4 ~ 2016. 3.
12. Development of ergonomic handle designs for vacuum cleaners. LG Electronics. 2014. 8 ~ 2015. 3.
13. Development of a design factor quantification methodology for optimal grip fit of car door handles. Hyundai Motor Group. 2013. 9 ~ 2014. 9.
14. Development and validation of an ergonomic guideline for the control panel design of home appliance. Samsung Electronics. 2013. 6 ~ 2013. 8.
15. Development of a hip fracture prevention product based on 3D body shape and biomechanical analyses. National Research Foundation. 2013. 6 ~ 2016. 5.
16. Development of a muscle rigidity measurement system for early identification of Parkinson's disease. Korea Science Academy. 2013. 3 ~ 2013. 12.
17. Evaluation of a ventilation structure at the midsole of shoe. Kyungdo, Inc. 2012. 12 ~ 2013. 8.

Honors & Awards

1. International Awards

1. World Intellectual Property Organization Special Prize (WIPO Secretary General Award) with $3,000 at the University Creative Invention Contest, Korea Invention Promotion Association (KIPA). Invention: Swallowing number measurement system and method thereof. Nov. 2014.

2. Korean Awards

1. Best Paper Award at the *2019 Fall Conference of the Ergonomics Society of Korea*. Oct. 2019.
2. Hyundai NGV Automobile Ergonomics Best Paper Award at the *2017 Fall Conference of the Ergonomics Society of Korea*. Nov. 2017.
3. Best Paper Award at the *2012 Fall Conference of Korean Society of Mechanical Engineering*. Nov. 2012.