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Evaluation of driver's discomfort and postural change using dynamic body pressure distribution

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Abstract

The main objective of this study is the application of body pressure distribution measurements for the prediction of the driver's posture and its change. This requires quantitative analyses of dynamic body pressure distribution, which is the change of body pressure distribution with time. To investigate the relationship between dynamic body pressure data with driver's posture, 16 male subjects performed a simulated driving task for 45 min in a seating buck. During driving, the body posture and body-seat interface pressure were measured continuously, and the discomfort ratings were surveyed at the prescribed interval. For the statistical analyses, driving period, stature group, and lumbar support prominence were selected as independent variables, whereas subjective ratings of driver discomfort, driving posture, and body pressure values were selected as dependent variables. In this study, newly defined dynamic body pressure distribution variables were proposed, and the relationship between these pressure variables with subjective discomfort ratings were analyzed. The close correlations between the body pressure change variables and subjective discomfort ratings supported the possibility of using dynamic pressure data as a tool for the assessment of driver discomfort.

Relevance to industry

Since dynamic body pressure distribution data provide quantitative and objective indices in measuring driver's postural changes and discomfort while driving, the proposed method can be used for more effective automobile seat design and its evaluation.

Keywords: Dynamic body pressure distribution; Seat design; Driving posture; Driving movement; Driving discomfort

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1. Introduction

Drivers' comfort is as important as the functional and aesthetic design of automobiles since consumers are more and more concerned about safety and comfortable driving. Progress in car seat development depends on the ergonomic research for seat design and on the assessment criteria used to analyze the interactions between driver and car (Yamazaki, 1992). One of the most important contributions that ergonomics can provide to the automobile design process is information of the physical size of driver, and his/her preferred postures (Porter and Gyi, 1998). The objective measures or indices affecting driver's comfort and related posture are needed to investigate (Gyi et al., 1998; Guenaelle, 1995).

Many researchers have been interested in drivers' preferred postures. Porter and Gyi (1998) conducted an experiment to investigate observed optimum driving postures and positions and they developed the guidelines for optimum postural comfort. The study of Park et al. (2000) investigated the relationships among Korean drivers' body dimensions, their driving postures and preferred seat adjustments after collecting data concerning the preferred driving postures and adopted seat adjustment levels. Reed et al. (2000) collected data on 68 subjects' preferred driving postures in 18 combinations of seat height, steering wheel position, and seat back angle. Andreoni et al. (2002) used an optoelectronic system to capture the driving postures. However, these experiment times were not over 15 min. It would not be long enough to investigate postural changes and drivers' discomfort that happen often in real driving situations. Hence, in this study, we investigated drivers' discomfort and movement using dynamic body pressure distributions measured for a relatively long time, about 45 min.

The information of the pressure patterns are very useful for the design of seats (Andreoni et al., 2002). However, a clear and consistent relationship between interface pressure and driving comfort was not identified (Gyi and Porter, 1999). Lee and Ferraiuolo (1993) evaluated 16 car seats with 100 subjects. The author concluded that the results did not show enough correlation between subjective comfort and body pressure distributions. Andreoni et al. (2002) analyzed sitting posture and interaction of the driver body pressure with the cushion and the backrest. In this study, postures are measured by motion capture camera. Koyano et al. (2003) analyzed the static seating comfort of motorcycle seats using seated body pressure distribution data. These studies were performed in the static situation and used the body pressure distribution measured only at specific time. To investigate the pressure patterns, the body pressure distribution at specific times could provide enough information. However if the body pressure distributions are analyzed serially, it might provide more valuable information.

Lee et al. (1995) stated that the driver tends to move more frequently when he/she feels discomfort in order to adjust the posture and improve the discomfort situation. Previous studies relating to drivers' movements used 3D motion cameras and CCTV's to measure the frequency of postural change. However, the application of these methods in small simulators or real cars is not practical. Therefore Park et al. (2001) limitedly checked the movement of the left leg in a passenger car with the automatic transmission.

The body pressure distribution is sensitive to movements and is relatively simple to measure even in a small space. Therefore, this study suggests the analysis method using serial or dynamic body pressure distribution to investigate the driver's movement.

The main objectives of this study are (1) to propose a method for using body pressure distribution data in order to measure driver's postural change during driving and (2) to investigate the relationships among the dynamic body pressure distribution and driver's postural changes and discomfort. For the prediction of drivers' posture and its change using body pressure, dynamic data regarding changes over time in body pressure distribution and driving posture should be captured and analyzed. In this study, we suggest new body pressure variables by using the dynamic body pressure distribution, and investigate the relationship between these variables and changes in driver's posture.

2. Method

2.1. Subjects

Sixteen healthy college students, all paid volunteers, participated in the experiment. All had driving experience and none had a history of musculoskeletal diseases. All subjects were male to minimize anthropometric differences. Their mean (SD) age, height, weight and driving experience were 25.5 (2.6) years, 172.8 (5.4) cm, 72.3 (9.8) kg, and 2.38 (2.4) years, respectively.

2.2. Experimental environment

The experiment was conducted in a seating buck. The seat of a mid-size sedan in Korean automobile market was used. The actual design parameters of the car's relationships among accelerator heel point(AHP), steering wheel point (SWP) and hip-point (H-Point) were used to make the seating buck (Fig. 1).

In the seating buck, the well-known high-fidelity game, Grand Turismo 2 (Polyphony, 1999) was used on PlayStation^{tm} (Sony, 1998) hardware. The maximum velocity of the vehicle controlled by the software was 140 km/h. The driving was done on a simulated track course that consisted of two straight parts and two curved parts.

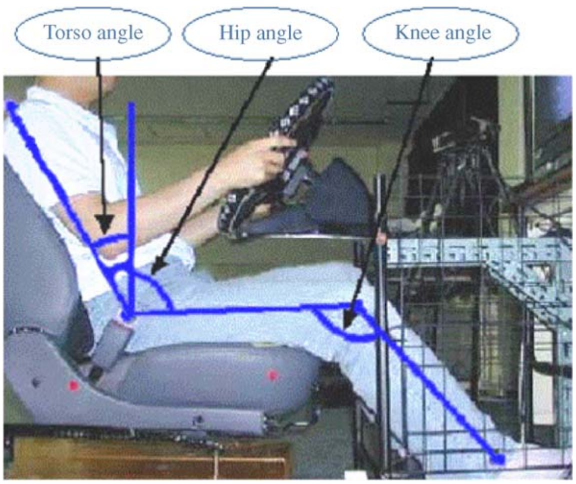


Fig. 1. Seating buck and driving posture.

The body pressure distribution was measured using flexible body pressure mat (FBPM) which is composed of two matrices for the seat pan and the seat back (Park et al.,1992). Each matrix contains 16×16 force sensing resistor (FSRs). The body pressure distributions were measured during the entire driving period and sampled at 32 Hz.

Before the experiments, a subject took a seat on which FBPM were fitted, adjusted the seat position by himself and then practiced driving on the same track as the main experiment laps for more than 10 min. The seat back-angle was fixed because the seat back-body pressure was sensitive to the seat back-angle. The mean trunk–thigh angle of Korean male is 115.9 ($\pm$7.63)° (Park et al., 2000). The fixed seat back-angel was 115°.

In the experiment, subjects drove a simulated track course consisting of 15 laps of 3 min per lap. While driving, the subject's motions were recorded by the 8 mm camcorder (Samsung, SV-L380).

2.3. Independent variables

The independent variables of this experiment were driving period, stature group, and lumbar support prominence. Driving periods had 7 levels as shown in Table 1: a pre-driving period, 5 periods during the driving task, and a post-driving period. The middle of driving period was equivalent to the starting time of subjective discomfort ratings.

Subjects were divided into 2 stature groups at the 50th percentile of the height data (171.1 cm) of the National Anthropometric Survey of Korea (KRISS, 1997) because stature may affect driving

Table 1
Driving period

Period	Approximated time (the middle on the driving period) (min)
Before	Before driving
1	1–9 (starting point of 2nd lap)
2	10–18 (starting point of 5th lap)
3	19–27 (starting point of 8th lap)
4	28–36 (starting point of 11th lap)
5	37–45 (starting point of 14th lap)
After	After driving

postures. The mean statures were 177.3 cm for the taller subject group, and 168.3 cm for the shorter subject group.

Lumbar support prominence had 2 levels: 1and 3 cm. The driving seat used in the experiment had 4 levels of lumber support prominence. The lowest level was 1 cm and the highest level was 3 cm. Lumbar support prominence was chosen as an independent variable to investigate the effect of lumbar support on driving posture and driver's discomfort.

A mixed factor design was adopted for the experiment. Driving period and lumbar support prominence were within-subject variables and stature group was a between-subject variable. The experiment was repeated for the same participant for each lumbar support prominence level (1 and 3 cm). The lumbar support treatment was randomized.

2.4. Dependent variables

Dependent variables were divided into three groups: subjective discomfort ratings, driving postures and body pressure distributions. Subjective discomfort ratings and driving postures were measured at each driving period defined in Table 1. At each driving period, subjective discomfort ratings were measured on a seven point scale for whole body discomfort and discomfort of six body parts: neck, shoulder, back, lumbar, hip and thigh.

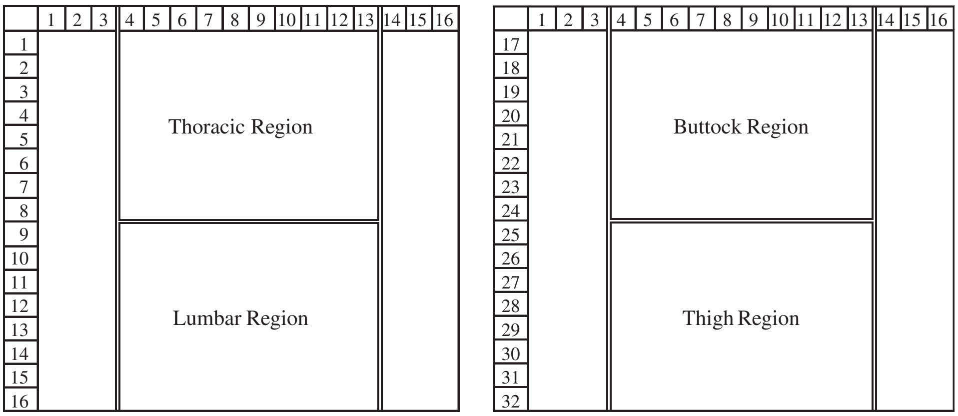
Reflective markers were attached to acromion, greater trochanter, lateral condyle and lateral malleolus of each subject for recordings of driving posture using a camera (Fig. 1). Pictures were taken right after performing the subject ratings. The camera was located at the right side of the seating buck. Definitions of the postural angles are as follows (See Fig. 1):

- Knee angle: the angle between the line across the greater trochanter and the lateral condyle and the line across the lateral condyle and the lateral malleolus.
- Hip angle: the angle between the line across the acromion and the greater trochanter and the line across the greater trochanter and the lateral condyle.
- Trunk angle: the angle between the line across the acromion and the greater trochanter and the vertical line across the greater trochanter.

2.5. The body pressure distribution

The body pressure distributions measured before or after the driving are different from the body pressure distributions measured during the driving (Lim et al.,2000). Hence, the body pressure distribution variables were analyzed only during driving (driving period: 1, 2, 3, 4, 5).

The 16 × 32 body pressure distribution data matrix was divided as shown in Fig. 2. to define



(a) Seat back (b) Seat pan

Fig. 2. Body pressure division.

the body pressure ratio variables. The definitions of the body pressure ratio variables are shown in Tables 2 and 3.

Body pressure change variables came from dynamic body pressure distribution. The definitions of body pressure change variables are shown in Table 4. The difference between the total pressure of the seat back or the seat pan and that of the previous measurement was defined as a pressure change. Body pressure change variable is the count of pressure changes that exceeded 15% of the average total pressure of the seat back and 5% for the seat pan. These definitions were made from the pilot test results that were performed to observe the pressure change when movements occurred. Validation of these variables was performed with video in this study.

Body pressure change variables indicate the number of subject's movements. This study concerned movement which occurred to prevent numbness or to find a more comfortable position, however, the total body pressures also differed due to small movements like breathing, moving the steering wheel or pedal, and so forth. Because of this, thresholds were needed. The pilot test was performed to determine these thresholds. The percentages differ since the body pressure of the seat back is more sensitive than that of the seat pan.

Table 2
The variables used in the body pressure ratio variables

Variable	Definition
Lum	The sum of body pressures in lumbar region
Total	The sum of body pressures in seat back and seat pan
Back	The sum of body pressures in seat back
Butt	The sum of body pressures in buttock region
Pan	The sum of body pressures in seat pan

Table 3
Body pressure ratio variables

Ratio variables		Defintion
Seat back	Lum/total	The ratio of Lum to total
	Lum/back	The ratio of Lum to back
Seat pan	Butt/total	The ratio of Butt to total
	Butt/pan	The ratio of Butt to pan

Table 4
Body pressure change variables

	Definition
Seat pan	The count of pressure changes which exceeded 15% of the average total pressure of seat back
Seat back	The count of pressure changes which exceeded 5% of the average total pressure of seat pan

3. Results

3.1. Subjective discomfort ratings

ANOVA analysis was performed for whole body discomfort and the six body part discomforts. The summary of ANOVA results about subjective discomfort ratings is shown in Table 5 ($\alpha = 0.05$). Driving period was found to have a systematic effect on all subjective discomforts. All subjective discomfort ratings increased as the driving period increased. Fig. 3(a) shows the change of whole body discomfort according to the

Table 5
The summary of ANOVA results about the subjective discomfort

Subjective discomfort	Significant effects
Whole body	Driving period, stature group × lumbar support prominence
Neck	Driving period, stature group
Shoulder	Driving period, stature group
Back	Driving period, stature group × lumbar support prominence
Lumbar	Driving period, stature group × driving period
Hip	Driving period, stature group, stature group × driving period
Thigh	Driving period, stature group, stature group × driving period

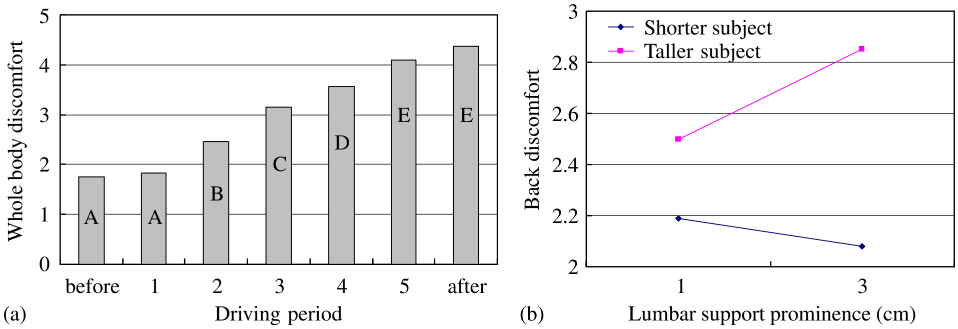


Fig. 3. The effects on subjective discomfort: (a) whole body discomfort and priving period; (b) interaction effect on back discomfort.

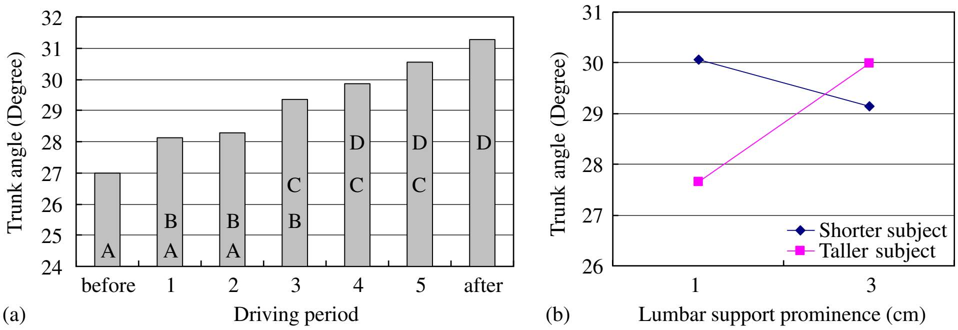


Fig. 4. The effects on trunk angles: (a) driving period; (b) stature group and lumbar support prominence.

driving periods and letters in the bar indicate Student–Newman Keuls test results ($\alpha = 0.05$). Stature groups showed significant effects on the body part discomforts of neck, shoulder, hip and thigh. The instances of body part discomfort of the taller subjects were larger than those of the shorter subjects.

The interaction of stature group and lumbar support prominence showed significant effects on whole body discomfort and back discomfort. The back discomfort of taller subjects increased as the lumbar Support prominence increased (Fig. 3(b)). Whole body discomfort showed the same tendency.

3.2. Driving postures

ANOVA was performed for driving postures. Driving period, stature group $\times$ lumbar support prominence and stature group $\times$ driving period showed significant effects on trunk angle ($\alpha = 0.05$). Trunk angles increased as the driving period increased (Fig. 4(a)). The trunk angle of shorter subjects decreased as lumbar support prominence increased and trunk angle of taller subjects increased as lumbar support prominence increased (Fig. 4(b)).

Hip angles were affected by driving period ($\alpha = 0.05$). The Student–Newman Keuls test ($\alpha = 0.05$) showed that the hip angle before driving was smaller than the others (Fig. 5(a)).

Knee angles were affected by driving period and the interaction of stature group and lumbar support prominence ($\alpha = 0.05$). The Student–Newman Keuls test results showed that knee angles during driving (driving period: 1, 2, 3, 4, 5) were larger than before/after driving. The interaction effect of stature group and lumbar support prominence showed that knee angle of the shorter subjects increased as lumbar support prominence increased and knee angle of the taller subjects decreased (Fig. 5(b)).

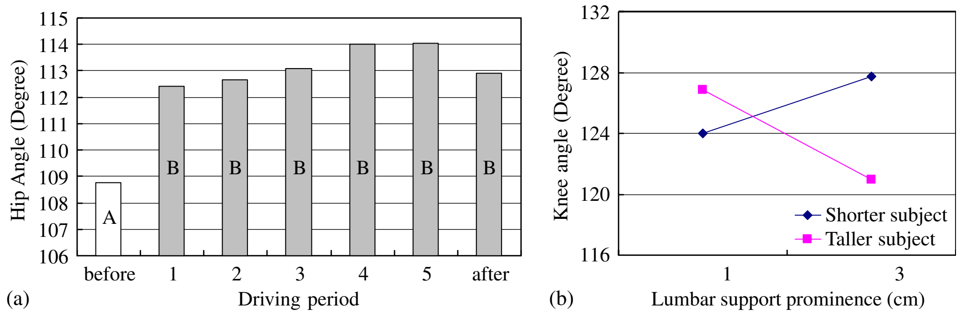


Fig. 5. The effects on hip and knee angles: (a) hip angle and driving period; (b) interaction effect on knee angle.

3.3. The body pressure distribution

Table 6 shows the summary of ANOVA results of the body pressure ratio variables. All body pressure ratio variables related to the seat back were affected by driving period and lumbar support prominence ($\alpha = 0.05$). The body pressure of the lumbar region decreased as the driving period increased (Fig. 6(a)). This tendency was caused by taller subjects rather than shorter subjects (Fig. 6(b)). The body pressure of the lumbar region increased as the lumbar support prominence increased. The mean body pressure ratio of Lum/Back was 0.51 when lumbar support prominence was 1 cm and 0.63 when lumbar support prominence was 3 cm.

All body pressure ratio variables for the seat pan were affected by driving period, and decreased as the driving period increased (Fig. 7(a)). For taller subjects, the pressure on the buttock region decreased as the lumbar support prominence increased (Fig. 7(b)).

The main effects upon the body pressure change variable on the seat back were found in the driving period and the lumbar support prominence, whereas they did not show any interaction effect ($\alpha = 0.05$). The Body pressure change variable on the seat back increased as driving period increased (Fig. 8(a)). When lumbar support prominence was 1 cm, the mean of body pressure change variable was 21.52, while it was 14.01 when lumbar support prominence was 3 cm.

Driving period and the interaction between stature group and lumbar support prominence showed significant effects on the body pressure change variable on the seat pan ($\alpha = 0.05$). As in the case of the seat back, the body pressure change variable on the seat pan also increased as driving period increased (Fig. 8(b)). The interaction effect showed that body pressure change variable increased as lumbar support prominence increased for the taller subjects. However, the body pressure change variable for the smaller subjects decreased (Fig. 9).

Table 6
The summary of ANOVA results about the body pressure ratio variables

Body pressure ratio variables	Significant effects
Lum/total	Driving period, lumbar support prominence
Lum/back	Driving period, lumbar support prominence, stature group × driving period
Butt/total	Driving period, lumbar support prominence
Butt/pan	Driving period, stature group × lumbar support prominence, stature group × driving period

3.4. Video record analysis

Body pressure change variables are assumed to reflect the subject's movement. To verify this assumption, the occurrences of "recognizable body movement" during driving in the recorded video tapes were counted and compared with the body pressure change variables. Definition of "recognizable movement" was a movement that could be recognized by human eye through the TV monitor. The movements were divided in three

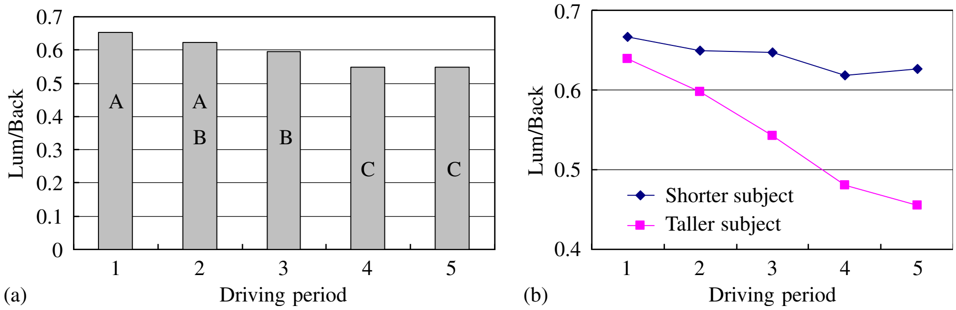


Fig. 6. The effects on Lum/Back: (a) driving period; (b) stature group and driving period.

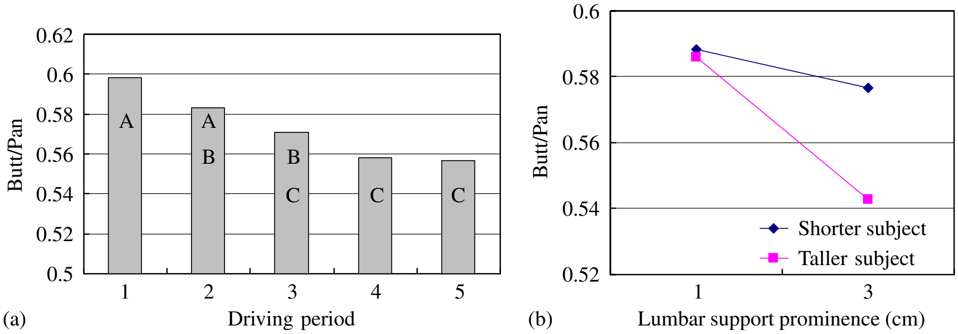


Fig. 7. The effects on Butt/Pan: (a) driving period; (b) stature group and driving period.

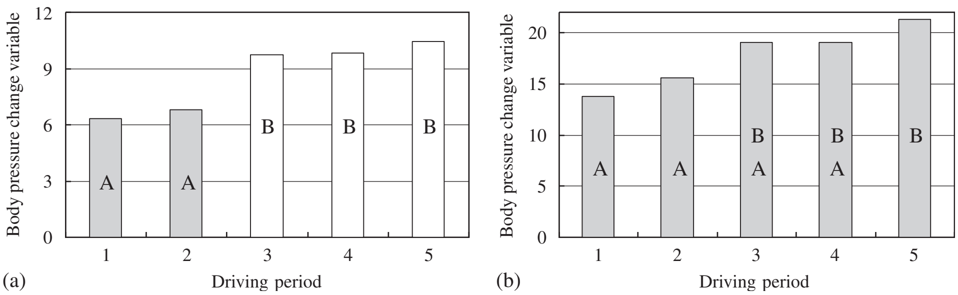


Fig. 8. The change of body pressure change variables: (a) seat pan; (b) seat back.

categories: Upper body movement, lower body movement, and whole body movement. Body pressure change variables of the seat back were compared with the sum of upper body movements and whole body movements. Similarly, body pressure change variables of the seat pan were compared with the sum of lower body movements and whole body movements.

Fig. 10 shows the relation of body pressure change variables and the results of the video record analysis. R^2 values were high and the body pressure change variables were slightly higher than the observed movements.

4. Discussion

The result of ANOVA for subjective discomfort showed that along with whole body discomfort, all body part discomfort levels increased as the driving period increased. The mean whole body discomfort before driving was 1.78, and that after driving was 4.37. El Falou et al. (2003) evaluated driver discomfort during 150 min of car driving. Despite the subjective increase in discomfort level, performance and SEMG did not show a significant effect. The mean peak discomfort at the end of the experiment was just over two on the 10-point scale. This discomfort level may be too low to cause any noticeable change in performance or SEMG. In this study, driving time was 45 min. It could not be long enough to cause discomfort, but the result showed the discomfort levels increased to 4.37 on seven-point scale. The driving task may cause discomfort. In the study of El Falou et al. (2003), there was no driving task.

The instances of part discomforts in taller subjects were larger than those of smaller subjects.

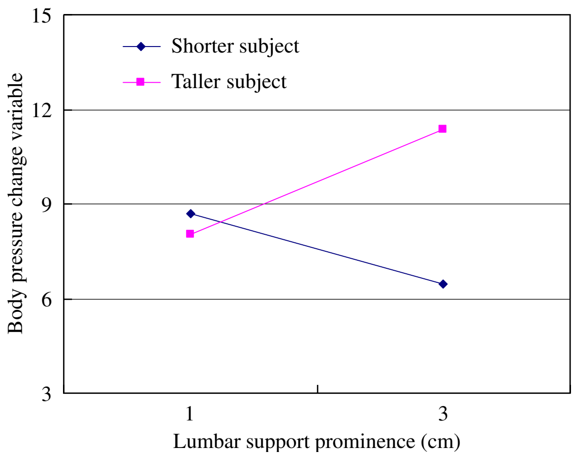


Fig. 9. Interaction of stature group and lumbar support prominence seat back body pressure change variable.

Neck, shoulder, buttock and thigh discomfort was affected by stature group. This result suggests that the design of the seat used in this experiment was more uncomfortable for taller subjects.

In the case of whole body discomfort and back discomfort, interaction effects of lumbar support prominence and stature group were found. Back and whole body discomfort increased as lumbar support prominence increased for taller subject, but for shorter subjects the back and whole body discomfort decreased. The lumbar support has been regarded as the essential design element for automobile seat design (Ng et al., 1995; Thomas et al., 1991; Udo et al., 1996). The study of Andersson et al. (1974) showed back extensor muscle activity and intradiscal pressure decreased as lumbar support prominence increased up to 5 cm. However, in this study, taller subjects felt more discomfort when the lumbar support prominence was 3 cm. This result showed that the design of lumbar support of the seat used in the study was not suitable for tall people.

The result of SNK comparison tests on knee and hip angles showed that knee and hip angles before driving and after driving were different from these angles while driving. This result agrees with the result of Lim et al. (2000), in which the body pressure of non-driving periods is different from the body pressure of a driving period. Postures should be measured during driving because they differ from those of non-driving periods.

As the lumbar support prominence increased, taller subjects' torso angle increased and knee angle decreased, however shorter subjects' torso angle decreased and knee angle increased. This result seemed to reflect that some tall subjects did

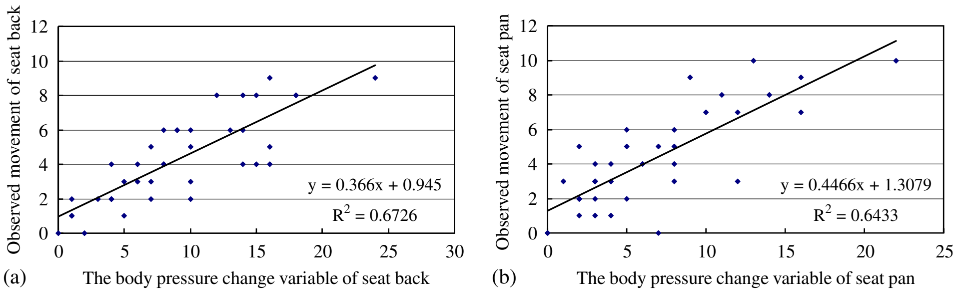


Fig. 10. Video analysis results: (a) seat pan; (b) seat back.

not attach their hips to the seat back adequately. Therefore they could not use lumbar support well and felt more discomfort when the lumbar support prominence was 3 cm. This result implies that the lumbar support height was too low for taller subject to use. Height and prominence are the main design parameters of lumbar support, but the lumbar support height was fixed in this study because the driving seat could not adjust it. For more comfortable seats, lumbar support height along with prominence needs to be adjustable.

As the driving period increased, the body pressure ratio variables decreased and trunk angle increased (Fig. 11). In other words, the body pressure of the lower region of seat back (Lum) decreased and the body pressure of the seat pan region near the seat back (Butt) decreased as the driving period increased. The increasing of torso angle suggested that subjects' hips slid to the front, which could be confirmed by the photos that were taken to capture driving posture (Fig. 12). That sliding state could be predicted by the body pressure ratio variable. Because the hip slid forward, the pressure of lower region of the seat back and seat pan region near the seat back decreased.

Body pressure change variables were affected by the driving period, and increased as the driving period increased. Body pressure change variables counted the number of large changes of the body pressure. The video analysis showed the relation between observed movement and body pressure change variables. Increasing of the body pressure change variables means that subjects moved more frequently, and the tendencies of body pressure

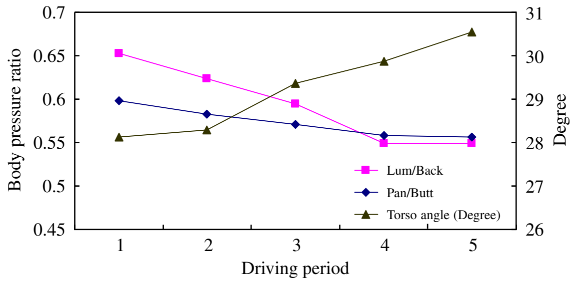


Fig. 11. The relation of the body pressure ratio variables and torso angle.

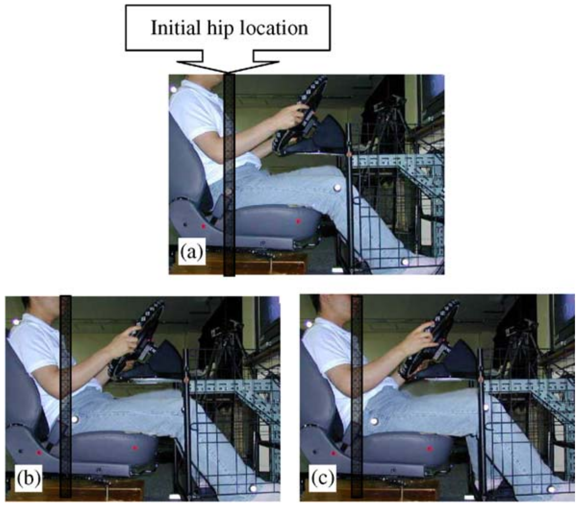


Fig. 12. The change of driving posture: (a) driving period 1; (b) driving period 3; (c) driving period 5.

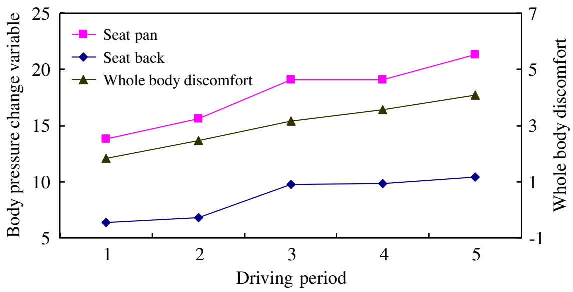


Fig. 13. The relation of the body pressure change variables and whole body discomfort.

change variables during driving were similar to the whole body discomfort level (Fig. 13).

The interaction effect of stature group and lumbar support prominence was found on the body pressure change variable of the seat pan, which affected whole body discomfort and back discomfort. For a taller subject, as lumbar support prominence increased, body pressure change variables of the seat pan increased. However, body pressure change variables of the seat pan decreased for shorter subjects. In other words, when lumbar support prominence was 3 cm, taller subjects moved more frequently, and shorter subjects moved less frequently. The same tendency was found in whole body discomfort. These results show that the driver's moving frequency could be used as a quantitative and objective measure to evaluate the driver's discomfort. Furthermore, the dynamic body pressure distribution could be used as a tool that predicts the driver's movement frequency.

Previously, body pressure distribution has been recorded as a static measure. In this study, the dynamic body pressure distribution was defined and analyzed. This study showed the possibility of using the body pressure distribution dynamically and its utility as a tool that can evaluate driver's discomfort.

The experiment was performed in simulated driving situations. For a precise and accurate study, the experiments should be performed in a real vehicle on real roads. The body pressure ratio variable may show similar results by measuring the average value of several data. However body pressure change variables could very likely be affected by vibrations.

5. Conclusion

The objective of this study was the application of body pressure distribution data for the prediction of the driver's posture and its change. We suggested new body pressure variables, to which the dynamic body pressure distribution was applied, and investigated their relationship to the driver's posture and its change. body pressure change variables and subjective discomfort ratings were found to increase as the driving period increased. The driver tends to move more frequently when he/she feels discomfort. The frequency of the movement of subjects could be estimated with the suggested body pressure change variables. As the driving period increased, whole body discomfort as well as the body pressure change variable increased. This study supports the usefulness of body pressure distribution for discomfort evaluation.

The body pressure ratio variables were used to evaluate the driving posture. As the driving period increased, Lum/Back and Butt/Pan decreased and torso angle increased. Increasing of torso angle leads to decreasing the pressure on the buttock region and the lumbar region. The body pressure ratio variables were influenced by driving postures. Hence, with the body pressure ratio variables, we could evaluate the driving posture. In a real driving situation, the evaluation of the driving posture is difficult with CCTV or motion analysis systems. However body pressure distribution could be used in actual driving situations.

In this study, the change of total body pressure on the seat pan and seat back were analyzed. In future studies, intensive and manifold analyses of dynamic body pressure distributions are needed in real driving situations.

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