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Development of a Feedback Stimulation for Drowsy Driver Using Heartbeat Rhythms

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Abstract—**We investigated the physiological response of a vibratory stimulation, which has the rhythm of heartbeats, and examined whether it is useful for the feedback stimulation for drowsy driving. We evaluated the efficiency of 4 types of vibratory rhythms for stimulation by using the sleepiness level estimated by the multiple linear regression model made from the indices of ECG and respiration. As the result, the vibratory rhythm, which has the real time heartbeats of subjects themselves, had an effect of inducing their physiological condition closer to the condition when they were struggling against the drowsiness. We concluded that the stimulation might be useful to prevent a drowsy driving if we could give it to the driver before he or she gets the severe drowsiness.**

Index Terms—**Drowsy driving, heartbeat, synchronization, vibratory stimulation, sleepiness.**

I. INTRODUCTION

THE amount of traffic accidents happen in Japan is showing tendency to decrease in recent years. This appearance is brought by the developments of technologies on safe driving and enlightenment activities, such as fasten seat belts or not to drive a car under the influence of alcohol. Though there are still more than 7 hundred thousands of traffic accidents happen in Japan and more than 9 hundred thousands of people got injured by the accidents [1]. This fact indicates that there are still severe situations remain in this matter. According to the traffic accident situation in 2009 investigated by the national police agency, 73.3% of the traffic accidents were done by driver's violation of safe driving obligations, such as drowsy driving and inattentive driving. It is reported that the death rate of drowsy driving is more than 9 times higher than the general accidents [2].

The technologies of preventing driver’s drowsy driving are now highly on demand and extensive studies have been carried out by many of the automobile manufacturers or research institutes [3][4][5]. Some systems made by TOYOTA [6] and DYMLER [7] have been already put to practical use. However the feedback stimulations used in these cases are alerting by audible sound, or flashing up warning messages on a display to urge driver to take a rest. There are no effective methods of leading driver to adequate conditions on driving physiologically. As widely known, arousal levels are strongly related to the balance of parasympathetic and sympathetic nervous system; therefore another type of additional stimulation is needed that can control it somehow.

Ogawa et al. reported that the rhythm of a subject's heart beats were synchronized to the rhythm of a sound [8], and Anischchenko et al. reported both audible sound and blinking monitor made a synchronization of rhythms among those stimulations and subject's heart beats [9]. As these preceding studies, the stimulation using the biological rhythms especially heartbeat rhythms are influential to human body.

The purpose of this study is to investigate the physiological response of a vibratory stimulation, which has the rhythm of heartbeats instead of sound or light pulses, and to examine whether it is useful for the feedback stimulation for drowsy driving. We compared 4 types of the rhythms for vibratory stimulations. All of the types were given to the subjects through a speaker and vibration transducers attached on bottom of a seat. We used a multiple linear regression model to investigate the physiological response of the 4 types of vibratory stimulations in cooperation with 5 volunteers.

The model was made from the measured data of 46 subjects whom we given one hour driving task. The model estimates defying level of the drowsiness by using 14 parameters obtained from ECG (electrocardiography) and respiration curve. As a result, the vibratory rhythm, which has the real time heartbeats of subjects themselves, induced physiological conditions closer to the conditions when they were defying drowsiness. We concluded that the stimulation might be useful to prevent a drowsy driving if we could give it to a driver before he or she gets the severe drowsiness.

II. MATERIALS AND METHODS

We implemented two experiments, A and B in this paper. The experiment A was done for the purpose of making a multiple linear regression model for the investigation of the physiological response of 4 types of vibratory stimulations in the experiment B.

The experiment A was done with a driving simulator and in cooperation with 46 subjects. We measured ECG, respiration curve and the sleepiness level during the subject’s driving task. The sleepiness level was graded according to five levels. The stronger drowsiness is felt, the value graded larger. We used ANOVA (analysis of variance) to see whether there are

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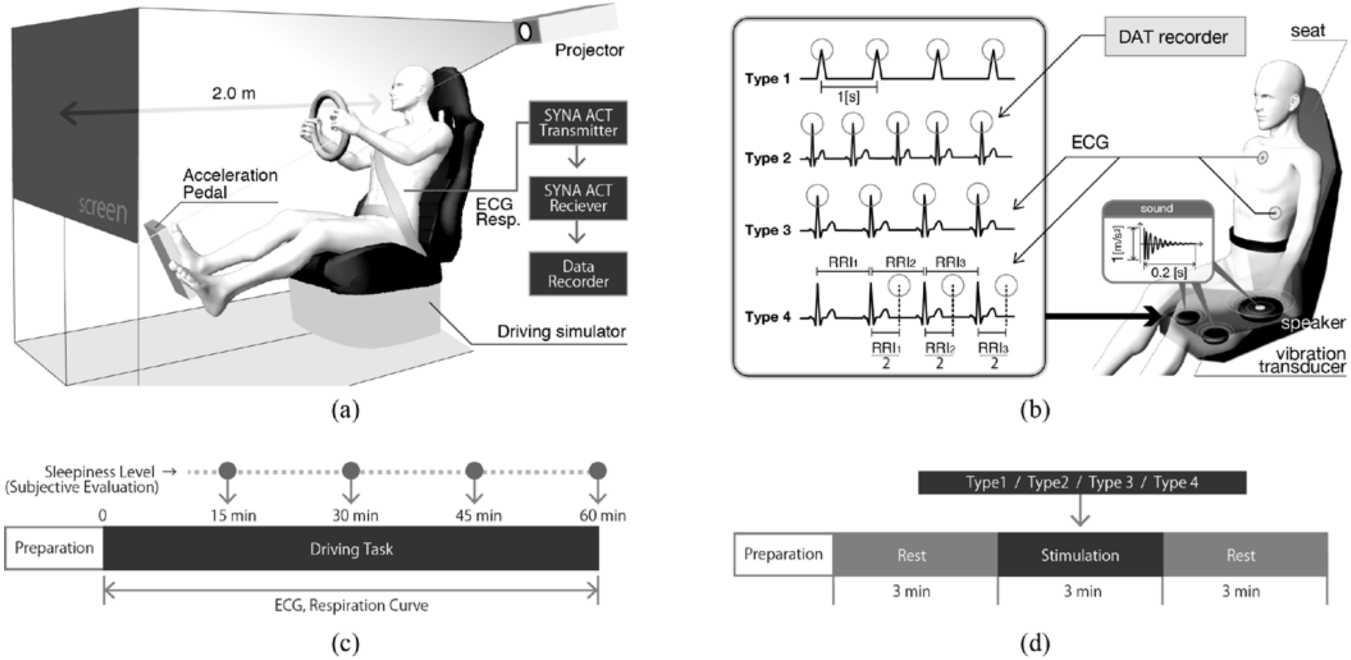


Fig. 1. Environment and schedule of the experiment A and B. (a) Driving environment in the experiment A. (b) Four types of vibratory rhythms used in the experiment B. Type1: 1[s] constant beat. Type 2: rhythm of other's heartbeats. Type 3: rhythm of the subject himself. Type 4: rhythm of the subject with a half interval delay of RRI. (c) Schedule of the experiment A. (d) Schedule of the experiment B.

differences between each value of the indices obtained from ECG and respiration curve, and the levels of sleepiness. Be based on the results, we considered the relations between those indices and the levels, and what does the levels implying about the physiological conditions.

A. Equipment and Methods used in the Experiment A

The first experiment was done with 46 healthy subjects (Avg:31.5 SD:7.4 years, males) and provided written informed consents. We used a driving simulator called DS Racer to create a driving situation (Fig.1 (a)). We assigned the subject to track the eight-shaped course, which length is 1 [km] per track, for an hour with a speed of 50 [km/h] (Fig.1(c)). During the task of driving, we measured ECG by bipolar leads and respiration curve from strain gage bandaged at the abdominal region. ECG and respiration were measured through the bio-amplifier (SYNA ACT MT11, NEC) and were recorded into data recorder (LX110, TEAC). The sleepiness level was measured orally every 15 minutes.

B. Equipment and Methods used in the Experiment B

We implemented the experiment B with 5 healthy volunteers (Avg:22.2 SD:1.1 years, males) and provided written informed consents. During the experiment, the subject sat on the seat at rest with eyes closed and no constraints like paced respiration or mental workload were used. The examinations were done with 4 types of vibratory rhythms to see the differences of physiological response of the stimulations (Fig.1 (b)). Type 1 is the 1 [s] constant beat that has no fluctuation. Type 2 is the rhythms, which has heartbeats of other's. Type 3 is the rhythm, which has the real time heartbeats of subject himself. Type 4 is similar to type 3, but has a half interval delay of every heartbeat. We set the type 1, which has no heartbeat rhythm to see the difference of physiological response among the other types.

All the stimulations were given to the subject after the 3 minutes rest and continued giving it for 3 minutes. Then we kept the subject as is for 3 minutes again to see how does the affection of the stimulation last after those were given to the subjects (Fig.1 (d)). During the examination, the ECG was recorded by bipolar lead and respiration was measured by a strain-gage bandaged at the abdominal region. ECG and respiration were measured through the bio-amplifier (SYNA ACT MT11, NEC) and were recorded into DAT recorder (PC216Ax, SONY Precision Technology). The recorded signals were digitized with 1.5 kHz sampling frequency by A/D converter and were taken into PC.

We implemented the experiment by using equipment shown in Fig.1 (b). In this equipment, the recorded ECG and the subject's ECG measured from the electrodes were taken into the PC (CPU: Intel Core2Duo 2.53GHz, memory: 4GHz). The former ECG was used for creating the stimulation type 2, and the latter was for type 3 and type 4 stimulations. Every time when the timings were calculated, a short vibrating stimulation was given to the subject from the vibration transducers (BODYSONIC, SCP-6018) and a speaker (diameter: 130 mm, Input [Max] 60W, Imp. 4Ω) attached on a seat. These vibrators were settled on the place of driver's backside and both thighs to conduct the vibrations efficiently.

III. ANALYSIS

For the analysis, we obtained 14 indices from the experiment A, and investigated the relations between the indices and the sleepiness level. Then, we made a multiple linear regression model with those indices to evaluate an efficiency of the 4 types of vibratory rhythms for the feedback stimulation.

A. Indices obtained from ECG and respiration curve.

The human cardiovascular and respiratory systems do not act independently and both activities are strongly interacted with autonomous nervous. Based on that, we detected 14 indices from ECG and respiration curves to estimate the activity of autonomous nervous from composite way. These indices were estimated from the 5 minutes complex data just before the sleepiness levels were measured orally.

We detected 10 indices from ECG: HR (Heart Rate), CVRR (Coefficient of Variation (CV=SD/mean*100) of R-R intervals), rMSSD (root Mean Square of Successive Differences), AC (Acceleration Capacity), DC (Deceleration Capacity), RRAT (R-R interval Acceleration Trend), RT (R-T interval), RT/$\sqrt{\ }$RR, LF (Low Frequency), and HF (High Frequency). These indices are estimated from 1 [kHz] R-R interval time series, which de-noised and interpolated by cubic spline.

HR, CVRR, and rMSSD are typical indices used for estimating the autonomous nervous activities. During the sympathetic nervous activities are predominant, generally HR decreases and the other two indices increase.

RRAT is an index that characterizes an intermittent acceleration-related heart-rate variability, which often observed in the situation when a driver is defying drowsiness [10]. RRAT is calculated as shown in formula (1).

$$
\begin{aligned}
&\mathrm{RRAT} = \Big(\sum_{i=1}^{n} \mathrm{X}i\ \mathrm{meanRRI}^2\Big) / 60000 \\
&\mathrm{meanRRI} = \frac{1}{n}\sum_{i=1}^{n} \mathrm{RRI}(i) \\
&\begin{cases} \mathrm{RRI}(i) - \mathrm{RRI}(i-1) > 0 \cdots\cdots \mathrm{X}i = 0 \\ \mathrm{RRI}(i) - \mathrm{RRI}(i-1) \le 0 \cdots\cdots \mathrm{X}i = 1 \end{cases}
\end{aligned}
\tag{1}
$$

AC and DC are indices of deceleration-related and acceleration-related heart-rate variability. We calculated these indices by following the directions refer to A. Bunde et al. [11]. With the predomination of the cardiac para-sympathetic modulation, there is a decrease in AC and an increase in DC.

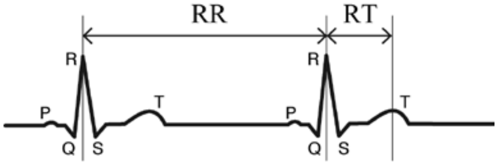
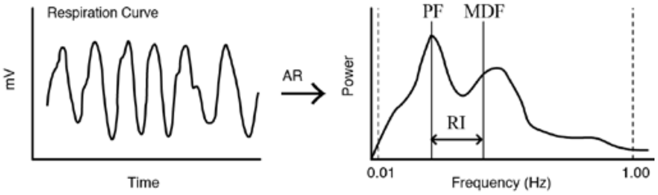


Fig. 2. Positions of RR interval and RT interval on ECG

RT is often used for the clinical test of the heart conditions [12] [13]. It is the interval of R-wave peak and T-wave peak on the ECG as shown in Fig.2. R-wave marks the beginning of ventricular contraction, and T-wave marks the ending of ventricular contraction. Which means that the RT interval represents the ventricular systole. RT/$\sqrt{\ }$RR is the index, which corrects RT interval according to RR cycle lengths. We used this standardization to see the changes of the ventricular systoles that are not influenced by the RR intervals.

HF and LF were estimated with the power spectrum analysis of heart rate variability by using the autoregressive model. LF is the component of low frequency band (0.04-0.15Hz), and was used as an index of cardiac sympathetic modulation. HF is the component of high frequency band (0.15-0.40Hz), and was used as an index of cardiac parasympathetic modulation [14][15].



(a) (b)

Fig. 3. Respiration indices. (a) Respiration curve. (b) Power spectrum of the respiration curve using autoregressive model.

Respiration changes drastically with the arousal conditions. We used frequency analysis to detect the speeds of the respiration, and obtained 4 indices: PF (peak power frequency), MDF (median power frequency), MNF (mean power frequency), and RI (respiration instability) by using autoregressive model. The frequency band of PF, MDF, and MNF are 0.01[Hz] to 1.00[Hz]. RI is the absolute difference between PF an MDF, and it stands for the instability of respiration. If the respiration is stable, RI become smaller by occasion of PF and MDF stays in almost same level. However, if the respiration becomes unstable by yawns or deep breathings, it indicates opposite way.

We investigated the relations between each of these indices and sleepiness levels by using ANOVA, and considered what does the sleepiness levels implying about the physiological conditions of the subjects.

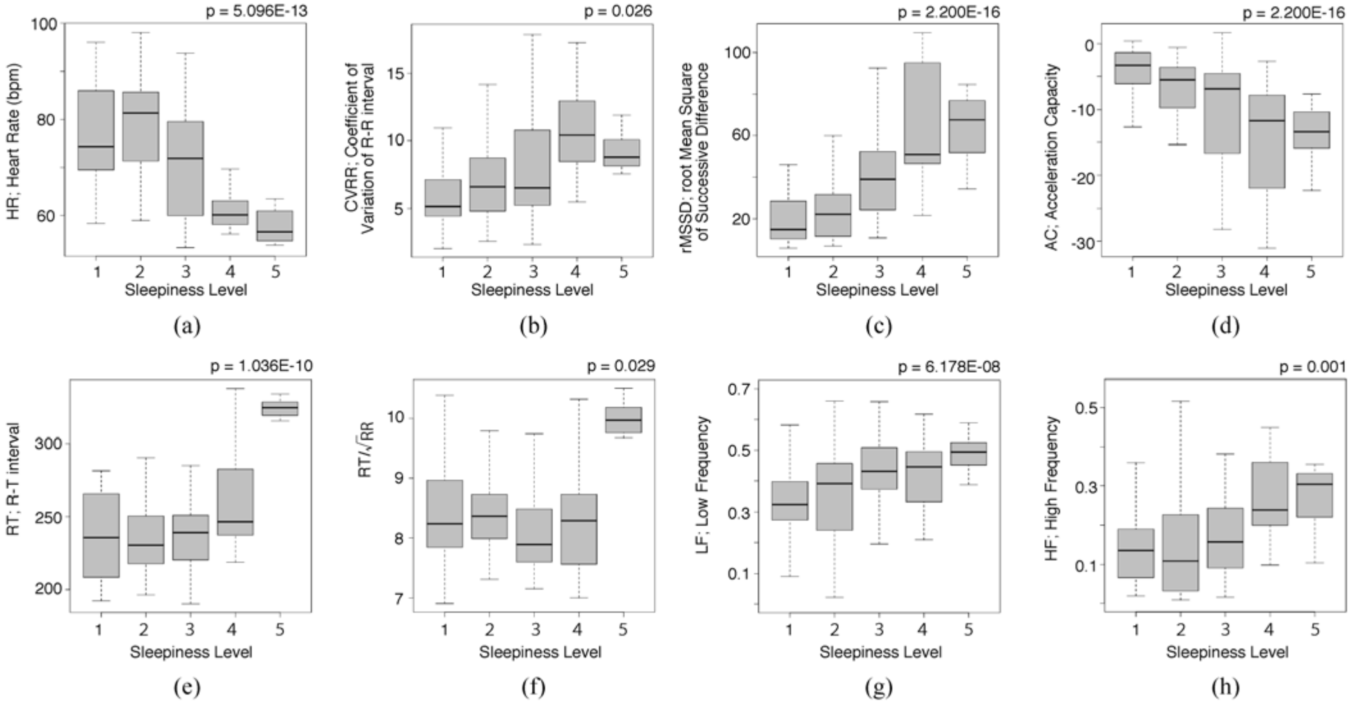


Fig. 4. Boxplots of the sleepiness level and indices obtained from ECG. (a) HR; Heart Rate (b) CVRR; Coefficient of Variation of RR intervals (c) rMSSD; root Mean Square of Successive Differences (d) AC; Acceleration Capacity (e) RT; RT interval (f) $RT/\sqrt{RR}$ (g) LF; Low Frequency (h) HF; High Frequency . The "p" on upper right of each graph stands for the p-value.

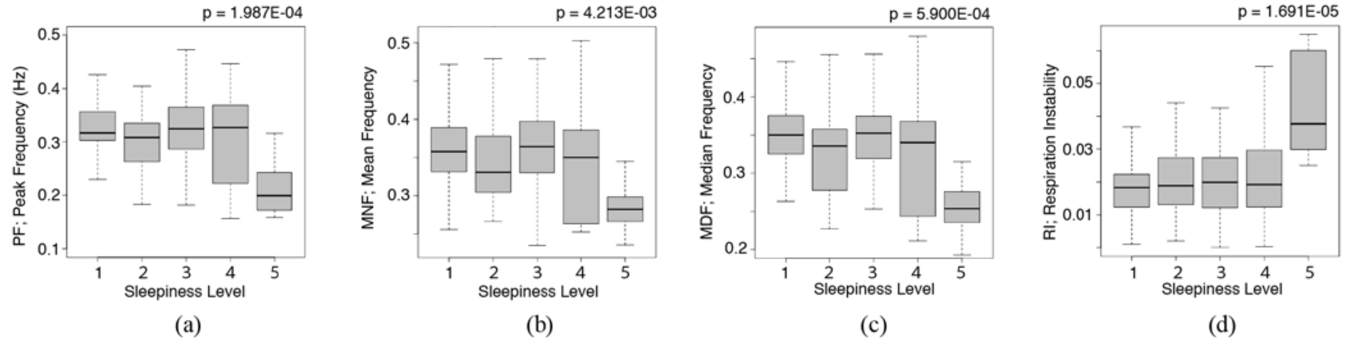


Fig. 5. Boxplots of the sleepiness level and indices obtained from respiration. (a) PF; respiration Peak power Frequency (b) MNF; respiration MeaN power Frequency (c) MDF; respiration MeDian power Frequency (d) RI; Respiration Instability

B. Evaluation of the stimulations using a model

After the investigation of the relations between each index and the sleepiness levels, we made a multiple linear regression model, which estimates the sleepiness levels of each occasion in the experiment B. This model was used for the datum point for the evaluation of the stimulations in the experiment B. We used three fourth of the data in the experiment A for building the model, and rest of them for the evaluation of the fitting. The fitting was evaluated by the R-square and correlation coefficient between the predicted sleepiness levels and the observed sleepiness levels. We applied all of the ECG and respiration indices obtained from the experiment B to the model and estimated the sleepiness levels of the subjects in each occasion: before and while the stimulations are given to the subjects. Then we used a t-test for the investigation of significant differences between the two occasions.

IV. RESULTS

Fig.4 shows the results of ANOVA and boxplots of the ECG indices and the sleepiness levels. Most of the ECG indices except RRAT and DC had significant differences ($p<0.05$) between each index and sleepiness levels. The indices: HR, CVRR, rMSSD, and HF (Fig.4 (a)(b)(c)(h)) indicated the tendency that sympathetic nervous activity got predominant on proportion to a rise in the sleepiness level. However, the other indices showed the opposite way. With the drop of AC (Fig.4 (d)) and the rise of LF (Fig.4 (g)), the sleepiness level rose higher. Generally, these indices are used

TABLE I
RESULTS OF THE LINEAR REGRESSION MODEL

Index	Coefficient	Pr(>|t|)	
(Intercept)	-9.443	3.36E-03	**
HR	0.123	1.01E-03	**
CVRR	-0.011	4.32E-01	
LF	-0.317	6.42E-01	
HF	-0.704	3.20E-01	
rMSSD	0.040	4.45E-06	***
DC	0.058	1.47E-02	*
AC	0.010	7.24E-01	
RRAT	0.004	5.19E-02	.
RT/$\sqrt{RR}$	-1.771	7.48E-03	**
RT	0.063	5.85E-03	**
RPF	9.049	1.85E-01	
RMDF	1.535	7.79E-01	
RMNF	-11.782	1.12E-02	*
RI	23.040	1.30E-02	*

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Fitting of the model	train data	test data
Correlation Coefficient	0.748	0.719
R-square	0.560	0.397

as an index of cardiac sympathetic modulation, so that it is inconsistent with the increase of the sleepiness level. The results of RT and RT/$\sqrt{RR}$ (Fig.4 (e)(f)) also supported this fact. RT and RT/$\sqrt{RR}$ increased when the sleepiness level got close to 5. This trend suggests that the interval of ventricular systole is enhanced and it thought to be brought out the increase of cardiac output.

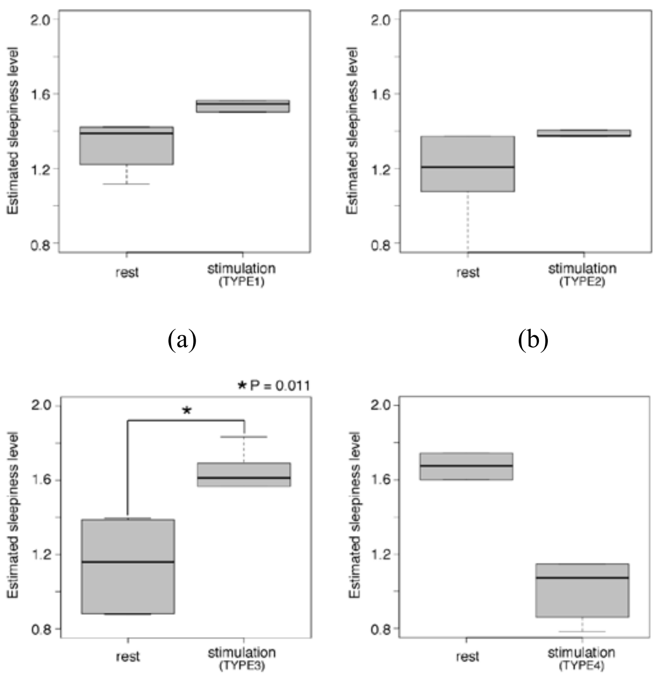
Fig.5 shows the result of the indices obtained from respiration curve. With the drop of PF, MNF and MDF (Fig.5 (a)(b)(c)), the sleepiness level decreased. RI (Fig.5 (d)) showed the opposite result to these three indices. These results represent that yawns or deep breathings appeared frequently when the subject felt drowsy. The frequent appearance of yawns or deep breathings and decrease of the breathing speed is thought to be a physiological phenomenon of getting more oxygen into the body and is a reaction of defying drowsiness.

These results of ECG and respiration indices provide evidence that there is mental state of not to fallen asleep among the subjects when they were implementing the task, accordingly the level of sleepiness can be interpreted as the level of defying drowsiness. The fluctuations of the ECG and the respiration indices were showing the different ways of tendency compared with general conditions of feeling drowsy. It fluctuated the way when the sympathetic nervous activities are predominant. This fact supports our interpretation of the levels of sleepiness.

By using these indices and sleepiness levels obtained from the experiment A, we made a linear regression model, which estimates the level of defying the drowsiness. We used three fourth of the data for training set and the rest of them for test set. The coefficient and the fitting result of the model are shown in table 1.

The R-square of both train and test data indicated low value. It means that the model is not fitted well. However, the correlation coefficient of the estimated value and both train and test data got more than 0.700, so that the model thought to be well enough to estimate approximate trend of the sleepiness level.

We applied 14 indices of ECG and respiration, which measured at the experiment B, to the model and estimated sleepiness levels of the subjects in each occasion: before and while the stimulations given to the subjects. Then we compared the levels between these two occasions by using t-test.



(a) (b)

(c) (d)

Fig. 6. Boxplot of the sleepiness level estimated from the model and the occasions in the experiment B. (a) Type 1 (b) Type 2 (c) Type 3 (d) Type 4

Fig. 6 shows the results of the sleepiness level between two occasions: before (Fig.6, rest) and while (Fig6, stimulation) the stimulation is given to the subjects. As a result, only the stimulation type 3 had a significant difference between the occasions. The estimated sleepiness level increased when the type 3 is given to the subjects. This result implies that the stimulation type 3 induced the subject's physiological conditions closer to the condition when they compete with the drowsiness.

V. DISCUSSION

We implemented two experiments: A and B in this study. The experiment A was done for the purpose of making a multiple linear regression model for the investigation of the physiological response of 4 types of vibratory stimulations in the experiment B. The experiment A was done with the driving simulator and in cooperation with 46 subjects. We measured ECG, respiration curve and the sleepiness level during the driving task. We used ANOVA to see whether there are significant differences between each value of the indices obtained from ECG and respiration curve, and the levels of sleepiness. Then we described the relations between each index and sleepiness levels.

As a result, HR, CVRR, HF, and rMSSD showed the tendency as generally observed when the parasympathetic activity is predominant. However the other indices showed the opposite way. It fluctuated the way when the sympathetic activities are predominant. Based on this results, we interpreted the sleepiness level as the defying level of the drowsiness and made an aim to make a stimulation that has an effect which enables to induce a driver's condition to the condition when he or she is defying drowsiness. This standpoint was brought by the idea that if we could make a driver's condition that compete with the drowsiness before the driver gets the severe drowsiness, it will be effective to prevent a drowsy driving.

To make a datum point for the evaluation of the stimulation, we made a multiple linear regression model that estimates this sleepiness level from the data obtained from the experiment A. Then we investigated which type of vibratory stimulation induces the driver to the condition that competes with the drowsiness effectively. The R squared of the model indicated 0.560 on train data, so that the fitting of the model was not so reliable. However, the correlation coefficient of predicted values and train data got 0.748, and test data got 0.719. Therefore the model thought to be capable to predict the approximate trend of the sleepiness level. As a result, type 3 had a significant increase of sleepiness levels during the stimulation is given to the subjects. This result implies that the vibratory rhythm, which has the real time heartbeats of subject himself, has an effect of inducing the physiological condition of defying drowsiness.

VI. CONCLUSION

In this paper, we investigated the physiological response of a vibratory stimulation, which has the rhythm of heartbeats, and examined whether it is useful for the feedback stimulation for drowsy driving. We evaluated the efficiency of 4 types of vibratory rhythms for stimulation by using the defying level of drowsiness calculated by the multiple regression model made from the indices of ECG and respiration. As a result, the vibratory rhythm type 3, which has the real time heartbeats of subject himself, had an effect of inducing the physiological condition of defying the drowsiness. Based on this, we conclude that this stimulation might be useful to prevent a drowsy driving if we could give it to the driver before he or she gets to the severe drowsiness.

However, the efficiency of the type 3 is not clarified enough to apply it to the practical use. We need to investigate the mechanism of this physiological response observed in the experiments. Also an alternation of patterns and strength of the stimulation might be affect to the results. We should increase the number of the subject to clarify these matters as our further study.

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