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論 文 内 容 の 要 旨

Development of a Drowsy Driving Prevention System Based on Cardio-Respiratory Phase Synchronization

1. Introduction

The global status report on road safety by the World Health Organization (WHO) presented statistics on road safety from 182 countries in 2013 [1]. The report indicated that the worldwide total number of road traffic deaths goes up to 1.24 million per year. According to the current trends, road traffic fatalities will become the fifth leading cause of death by 2030 unless urgent action is taken. Among the traffic accidents, drowsy driving is one of the main causes leading to the death. Connor et al. claimed that approximately 15–20% of the fatal accidents can be ascribed to drowsiness and fatigue [2]. Considering these backgrounds, antidotes against drowsy driving have been gaining greater attention during the recent years [3]. Countermeasures of the drowsy-driving are for example antilock brakes, forward collision warning, adaptive cruise control, or lane keeping systems. These systems work efficiently when the distracted driver is near to accidents. To improve the safety, it is desirable to prevent a driver before he or she become in serious situations. The majority of the research focuses on warning drowsy drivers about their dangerous states, and suggesting them to take countermeasures such as to take a break, short nap or, caffeine intake, by using auditory [4], visual [5], and tactile [6] stimuli. However, it is not always accessible to take a rest while driving and not all the drivers take the warnings in the desired manner. There is the fact that even when they were warned of their states, they often force themselves not to take a rest but to go on driving [7]. Although there are some trials using fragrance [8] or an air conditioner [9] for an alerting method, they are brought by empirical methods; therefore, the efficiency varies by a driver's preference, driving conditions or environment. Thus it is required to have a method that not only warns a driver's state, but also to reduces driver's drowsiness physiologically before he/she continues to drive at a dangerous state. The key to overcome drowsiness is to maintain oxygenation of the blood. It is commonly known that deoxygenation of the blood deteriorates activities of the brain and distract driver's attentiveness. Sung et al. reported that drowsiness got severed while oxygen rate is lowered and is weakened while high-rate of oxygen is

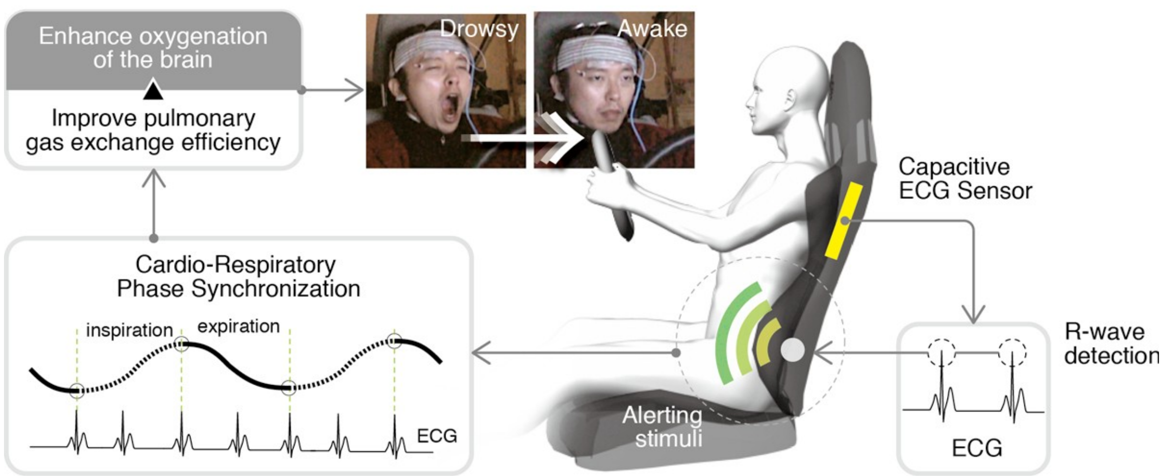

Figure 1. Outline of the drowsy driving prevention system based on Cardio-Respiratory Phase Synchronization.

Table I
Procedure of the feasibility study for the alerting stimuli

	Investigation	Method	Result
i)	Is it possible to induce CRPS by pulse sounds coupled with heartbeats?	Quantified the strength of CRPS (σ) during the rest and PB by using the Synchrogram. - Protocol: Rest (5min) → Pace breathing (PB) with the pulse sound coupled with heartbeats (5min). - Subject: 16 males, 22.6±3.4 years old (average±SD)	Significant increase of σ was observed at the PB with the pulse sound. (Paired t-test, $p<0.05$)
ii)	Is it certain that the pulse sounds coupled with heartbeat induced CRPS? (Any rhythm of pulse sound that is close to heartbeats might leads to CRPS.)	3 types of pulse sound rhythms are compared: 1s fixed interval, random interval, and R-R interval. - Protocol: (Rest (5min) → PB with the pulse sound (5min)) × 3 types. - Subject: 16 males, 22.6±3.4 years old (average±SD)	Significant increase of σ was observed only at the PB with the R-R interval pulse sound. (Paired t-test, $p<0.05$)
iii)	Does SpO2 increase by the induced CRPS?	Measured SpO2 from the forehead - Protocol: Rest (5min) → PB with the pulse sound coupled with heartbeats (5min). - Subject: 16 males, 22.6±3.4 years old (average±SD)	Significant increase of SpO2 was observed at the PB. (Paired t-test, $p<0.05$)
iv)	Increase of respiration rate (RR) and ventilation (VE) also brings an increase of SpO2. Is it certain that the result of iii) is brought by the CRPS?	3 patterns of PB are compared: inspiration and expiration at ratios of 1-to-1(increase RR), 2-to-2 (normal breath pace), and 3-to-3 (increase VE) beats. - Protocol: (Rest (5min) → PB (5min)) × 3 patterns. - Subject: 16 males, 22.6±3.4 years old (average±SD)	Significant increase of SpO2 was observed only at the PB with inspiration and expiration at ratios of 2-to-2 beats. (Paired t-test, $p<0.05$)
v)	Does the induced CRPS realize a sufficient amount of SpO2 increase for drowsiness reduction?	Detected a state when a drowsy driver overcomes drowsiness by using 5 drowsiness references → Compared increase amount of SpO2 at the detected states and at the induced CRPS. - Protocol: 1-hour driving task with a driving simulator. - Subject: 7 males & 9 females, 20.9±1.6 years old (average±SD)	The increase of SpO2 at the induced CRPS is significantly larger than that of the detected states in the 1-hour driving task. (Paired t-test, $p<0.05$)

Details are referred to: Achievements 1)

supplied [10]. Deoxygenation of the blood is also used as a drowsiness detection in the literature [11][12]. The study focuses on Cardio-Respiratory Phase Synchronization (CRPS), which improves gas exchange efficiency, to recover from the deoxygenation.

2. Purpose

The purpose of the study is to develop the drowsy driving prevention system as shown in the Figure 1. The developed alerting stimuli induce CRPS in order to reduce drowsiness by enriching the oxygen supply to the brain at drowsiness symptom phase before a driver gets to severe driving state. The CRPS is induced by synchronizing the timing of cardiac systole and switching point of the expiration and inspiration by using heartbeat synchronized vibratory stimuli. Since the stimuli require to have a bio-sensor that collect ECG sustainably while driving, the capacitive ECG sensor is also developed.

3. Development of the alerting stimuli

It is conceivable that CRPS, different from respiratory sinus arrhythmia (RSA), improves pulmonary gas exchange efficiency [13], and helps oxygen intake of a drowsy driver. Positioning the diastolic phase of the cardiac cycle at inspiration increases the venous return, and with the Starling mechanism, transmission of blood volume to the pulmonary circulation increases when abundant oxygen exists in the lungs. In contrast to inspiration, positioning the systole of the cardiac cycle within the expiratory period may facilitate the transmission of arterial blood, because vascular resistance decreases by the relaxation of respiratory muscles. Following this physiological mechanism, it can be hypothesized that CRPS may have an effect to cure drowsiness if it can be intentionally induced. The feasibility study of the stimuli using the CRSP was conducted with 5 gradual steps. Then the study verified the hypothesis by investigating the efficiency of the stimuli at a

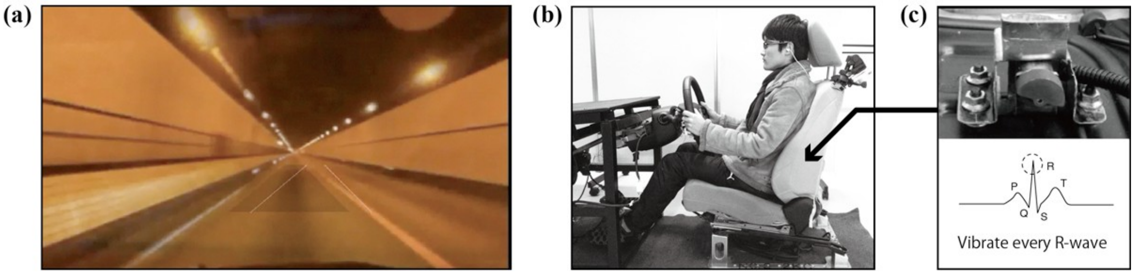

Figure 2. The alerting stimuli and a driving simulator (DS) used in the experiment v) and the investigation of the alerting stimuli for the practical uses
(a) Highway tunnel drive for the DS (b) Driving simulator used in the experiment (c) Heartbeat vibratory stimuli by a vibration motor

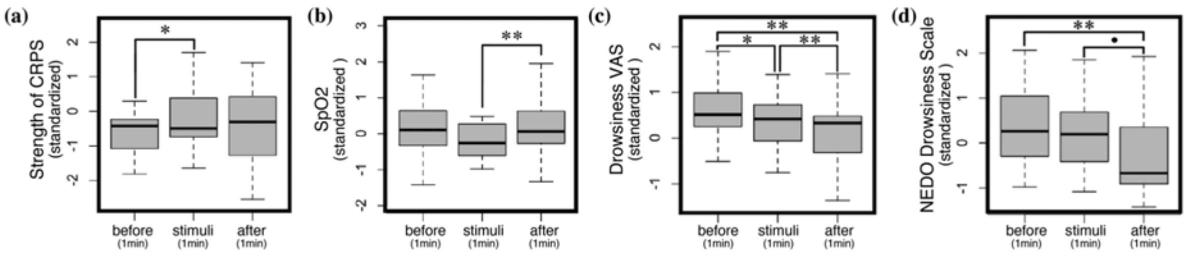

Figure 3. Responses of CRPS strength, SpO2, VAS, and NEDO by the alerting stimuli using the vibration motor
(a) CRPS strength (b) SpO2 (c) VAS (d) NEDO (N=16, Paired t-test, ・$p<0.1$, *$p<0.05$, **$p<0.01$, Standardization: $Z_i = (X_i-\mu)/s$, X_i: data, μ: Average, s: standard deviation)

simulated driving condition.

3.1. Feasibility test of the alerting stimuli

Table I indicates an outline of the five gradual steps conducted in the feasibility test of the alerting stimuli. The experiment i) was conducted on purpose of verifying the feasibility of CRPS inducement, which uses paced breathing (PB) that synchronizes timing of expiration and inspiration to the heartbeat pulse sound. The pulse sound was generated every R-wave on the ECG collected from adhesive electrodes on the chest, and given to a subject through earphones. The strength of the CRPS during the rest and PB were quantified by using the Synchrogram [14], and were compared. As the result, the CRPS significantly strengthened during the PB. The fact insists that it is possible to induce the CRPS by this method. The experiment ii) verified that the CRPS was not induced accidentally by comparison between the 3 patterns of PB with heartbeat, random and fixed 1-second interval pulse sounds. The purpose of the experiment iv) is to confirm the result of the experiment iii) was not brought by the increase of respiration rate (RR) nor ventilation volume (VE). Three patterns of PB were compared in the test: 1-beat, 2-beats, and 3-beats intervals of expiration and inspiration. Then the response of the SpO2 was observed under these three PB patterns. These conditions were settled because the 2-beats PB keeps almost the same pace as normal breathing, whereas the 1-beat and 3-beats PB leads increase of RR and VE, respectively. As the result, SpO2 increased significantly only at the condition of 2-beats PB; therefore it was verified that the result of the experiment iii) was not brought by the increase of RR and VE. The last feasibility test, experiment v), was conducted in order to investigate how much increase of SpO2 would suffice for drowsiness reduction. Since there is no criterion for this in the literature, the increase of SpO2 by the CRPS was compared with the situation when the drowsiness reduced by him/her-self such as deep breath or yawns. Drowsiness was induced by conducting a monotonous highway tunnel-driving task for one hour by using a driving simulator (DS) (Figure 2(a)(b)) with cooperation of 16

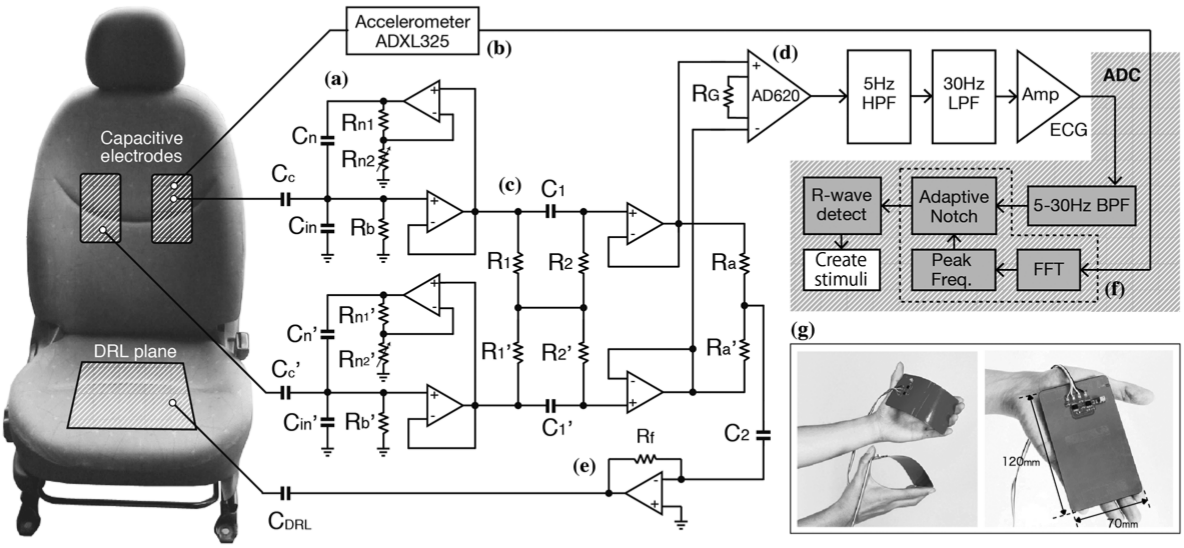

Figure 4. Configuration of the capacitive ECG sensor
(a) Neutralization circuit (b) Accelerometer of the adaptive notch filter (ADXL325) (c) AC coupling circuit (d) Differential amplifier (AD620)
(e) Driven-right-leg (DRL) circuit (f) Adaptive notch filter (g) Capacitive electrodes

subjects. The self-drowsiness reduction was observed by the visual analog drowsiness scale (VAS), NEDO drowsiness scale (NEDO), percentage of eye closure (PERCLOS), and autonomic nervous activity indices calculated from R-R intervals of ECG. The result showed that the SpO2 increase by the CRPS were larger than the increase by the self-drowsiness reduction. The fact insists that a driver's drowsiness can be effectively reduced by the CRPS inducement.

3.2. Investigation of the alerting stimuli for the practical uses

After the 5 gradual steps of the feasibility test, investigation of the alerting stimuli were conducted toward the practical uses. The investigation was aimed to verify whether the stimuli effectively reduces drowsiness while driving by CRPS inducement. Sixteen subjects (7males, mean±SD=20.9±1.6 years old) were participated in the test. Subjects drove for one hour on a DS with the same task applied in the experiment v) (Figure 2(b)). Drowsiness were induced in the first 30-minute, and the vibratory stimuli, correlated with the subjects' heartbeats (Figure 2(c)), were given to the subjects at 30-munite and 45-minute from the beginning. The stimuli were intended to induce CRPS in order to reduce drowsiness by recovering SpO2. Although the feasibility test i) through v) used pulse sounds from earphones for CRPS inducement, it makes a driver uncomfortable, and interrupt auditory information of driving; therefore, vibratory stimuli were used instead of it. The heartbeats used for the stimuli were collected from the adhesive electrodes on the chest, and CRPS were monitored from the ECG and respiration acquired from a strain gauge band attached on the abdominal region. SpO2 were monitored from a pulse oximeter on the left fore-head, and drowsiness were observed by VAS and NEDO. The Figure 3 shows the results of the test. Strength of the CRPS significantly strengthened during the stimuli (Figure 3(a)) and SpO2 significantly increase just after the stimuli were given to the subjects (Figure 3(b)). Drowsiness scale, VAS and NEDO, also significantly reduced by the stimuli. The conclusion of the test is that the alerting stimuli meet to requirement of the practical uses. The results obtained in the feasibility tests i) through v), and the investigation conducted toward the practical uses verified the hypothesis that it is possible to reduce drowsiness by the CRPS

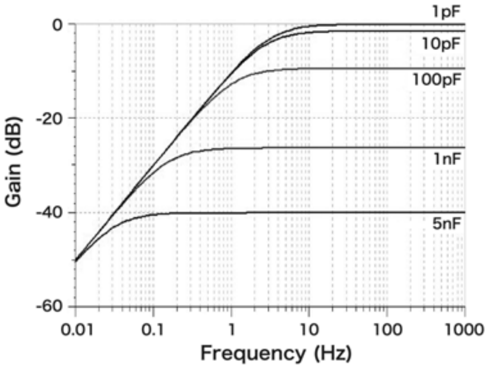

Figure 5. Signal attenuation by the parasitic capacitance inducement.

4. Designing of the bio-signal sensor

It is essential to have a sensor that continuously collects ECG in order to realize the alerting stimuli. The sensor needs to be non-intrusive and non-constrained metric through clothing that is robust to body movements, engine or road vibrations, and collect signals as precise as possible. The study developed a capacitive ECG sensor that suffice the requirements. The Figure 4 shows the configuration of the sensor. The flexible electrodes and the neutralization circuit (Figure 4(a)) [15] are designed as to prevent signal attenuation, and alternating current (AC) coupling circuit (Figure 4(c)) [16] and driven-right-leg (DRL) circuit (Figure 4(e)) [17] are settled in order to reduce noises. The Figure 4(g) shows the electrodes of the capacitive ECG sensor. The flexibility of the electrodes enlarges the capacitive coupling by touching the electrodes face to the body torso effectively, and improves the signal quality. The high input impedance bias circuit, the neutralization circuit, and an accelerometer for an adaptive notch filter (Figure4 (b)) are placed on the back side of the electrode face.

The unique characteristics of the structure is the neutralization circuit and the adaptive notch filter. One of the most leading studies in the field reported that clear ECG signals were obtained during a highway drive with 100[km/h] [18], and R-wave detections were achieved over 95% during a city drive [19]. However, neither of them uses

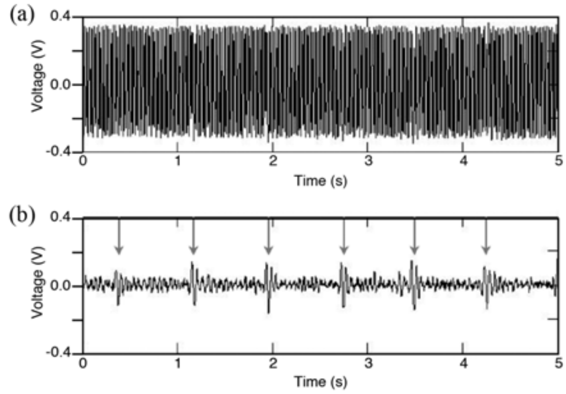

Figure 6. Effect of the adaptive notch filter at an engine speed of 800-1200rpm (a) Non-filtered ECG (b) Filtered ECG

the neutralization circuit and the adaptive notch filter. In general, parasitic capacitance exist between the electrode face and the noise blocking shield, and it largely attenuates the signal. The Figure 5 indicates the attenuation of the signal by the parasitic capacitance. The electrode developed in the study has approximately 5nF of parasitic capacitance; therefore, the signal attenuates about -40dB at the ECG frequency band (5-30Hz). The study attempted to minimize this effect. The installed neutralization circuit makes the signal attenuation to theoretically zero, so that the signal distortion can be avoided.

The reason why the adaptive notch filter is applied is because engine derived noises, which fluctuates at the same frequency as ECG (5-30Hz), that cannot be eliminated by a filter with fixed cut-off frequency. Since the adaptive notch filter makes it possible, ECG can be measured stably during low engine speed state such as city drive or under a traffic congestion. The Figure 6 shows the difference of filtered and non-filtered signals. The ECG signal is hidden under the noise and R-wave cannot be recognized when the filter is not applied (Figure 6(a)). In contrast, the noise is reduced enough to recognize R-waves on the ECG when the filter is applied (Figure 6(b)).

The feasibility test was done in Kitachikusa Campus of Nagoya City University using an actual car (Sunny, Nissan) with the configuration shown in the Figure 4. Twenty seven years old male subject with BMI of 28.6kg/m2 drove the car with 2-layers of T-shirt. The Figure

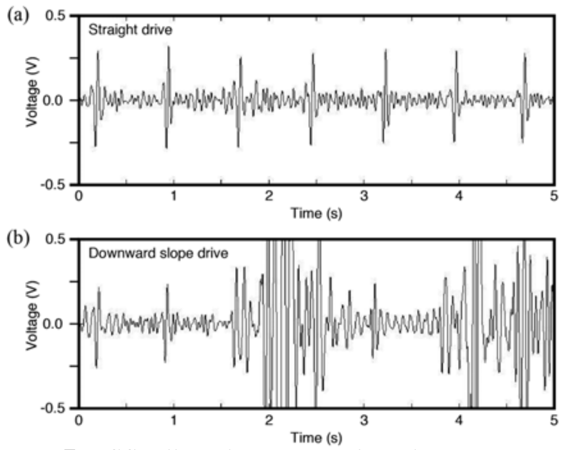

Figure 7. ECG collected on an actual car drive
(a) ECG at straight drive (b) ECG at downward slope drive

7 indicates a representative ECG during the test. R-waves of the ECG are clearly seen at the straight drive (Figure 7(a)). At this driving condition, the signal has sufficient quality for R-wave detection; therefore, the developed sensor meets the requirement for the practical uses. However, it is also revealed that large noise contaminates into the ECG by body movements at cornering or peculiar road conditions. Especially the downward slope largely deteriorated the signal quality. R-waves on the ECG were totally hidden under the noise. It happens because the electrodes faces detach from a driver's body. It is a weakness of the capacitive measurement needs to be solved. One of a prospective solution for the signal-loss is to use wearable devices that has a pulse-wave sensor on nose pad of eyeglasses or earphones. The nose bridge and the ear canal have less affection towards body movements, and are relatively easier to capture the arteries than the other body parts [20]. It has a potential to resist peculiar road conditions such as the cornering or downward slope. The further study will be dedicated to develop these devices.

5. Conclusion and prospects

The study developed the alerting stimuli aiming toward the practical uses by experimental feasibility test of drowsiness reduction using CRSP. Then the drowsy driving prevention system in the Figure 1 is formed with the capacitive ECG sensor, which used for generating the stimuli. The sensor was designed in order to collect ECG through clothing while driving with non-constrained metric. The originality of the system is to reduce drowsiness physiologically by recovering from de-oxygenation using CRPS, which induced by the vibratory stimuli from a car seat correlated with driver's heartbeats. Reducing drowsiness using CRPS is a unique trial never attempted in the literature. It is not based on mental nor empirical method used in the previous studies, but is based on physiological mechanism that is another peculiarity of the study. In addition, the feedback indicator uses the driver's own heartbeats; therefore it realizes a driver to have a great affinity to the stimuli.

However, the system has not reached to the practical level yet. There are many problems remained need to be solved. The investigation of exposition site and strength for the alerting stimuli are not conducted enough. Since various vibrations get on to the driver's seat, there is a potential that a driver cannot perceive the timing of the cardiac systole indicated by the vibratory stimuli during an actual car drive. In addition, the alerting stimuli are not tested in an actual drowsiness state on a public road. Moreover, the age of the subjects in the study are all twenties, so that it is essential to confirm the efficiency of the stimuli for middle age or older generations.

The signal quality of the bio-signal sensors needs to be improved further. An actual car-drive test is essential to investigate patterns of noises and signal losses in various road conditions. Then appropriate solutions need to be conducted to the problems extracted by the investigation. On top of that, careful investigation is required to quantify efficiency of the signal loss compensation by the wearable pulse oximeters. The protocol of integrating the bio-sensors needs to be designed based on the investigations.

The other topic for the further study is a development of drowsiness detection. Since the conventional sensors had been playing a bottleneck for bio-signal acquisition, video capturing or driving characteristics were used for drowsiness detection. The study found that it is feasible to collect bio-signals while driving. The capacitive ECG sensor enables to collect ECG and respiration, and the wearable pulse oximeters collect SpO2 as well. By using these signals, CRPS and SpO2 can be monitored at whole driving moments. It contributes to improve the efficiency of the alerting stimuli, because the stimuli can be triggered at an appropriate timing by this. These investigations and developments will be conducted in the further studies.

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論文審査の結果の要旨

提出論文では、振動刺激により心拍位相同期を誘発し、それにより自動車運転中の覚醒度を向上させる独創的な居眠り運転防止手法を提案するとともに、その効果評価と提案方法を応用した居眠り運転防止システムの開発に関して記述している。論文は、１章から６章までの構成となっている。

第１章「Introduction」では、研究背景と研究目的、提案システムの概要を述べている。世界的に重要な課題である居眠り運転防止対策として、眠気の兆候が検出された早い段階で、生理的に眠気を緩和する働きかけを運転者に施す方法は殆ど提案されていない。本研究では、生理的な眠気緩和のためには、脳への酸素供給量を増やすことが必要であり、その手段として心拍呼吸位相同期を振動刺激により誘発することにより､肺への血液流入と吸気による酸素補給のタイミングを合わせることができ、血中酸素濃度を高め眠気を緩和することを提案し、実験によりその効果を実証することを目的とする。

第２章「Literature review of the study」では、自動車事故に関する統計、居眠りの定義、居眠り運転を推定する方法、居眠り運転検出時の安全運転支援や警告システムの最新動向など、先行研究の調査結果をまとめている。

第３章「Driving simulator and drowsiness references」では、本研究における基礎実験と提案方法の評価に使用している自動車運転シミュレータの機器構成と機能を記述している。加えて、提案手法の眠気緩和の効果を評価する際に使用する、従来研究で報告、あるいは、実用化レベルに達している眠気度の定量化指標（主観評価、顔表情からの判定、瞬き検出による定量化、心拍から推定する自律神経活動バランス指標）の算出方法を記述している。

第４章「Development of the alerting stimuli」では、本研究で提案している心拍呼吸位相同期による眠気緩和方法の原理、吸気と心拍動のタイミングを合わせることで、心拍呼吸位相同期が誘発され、それにより血中酸素飽和度が上昇し、また、心拍動と同期した振動刺激を付与することでも、心拍呼吸位相同期が誘発され、結果として血中酸素飽和度が増加することで、眠気が緩和したことを、５種類の段階的に実施した実験により確認した結果を述べている。この眠気緩和方法は、血中酸素飽和度が増加することで眠気が緩和することと、心拍呼吸位相同期は肺のガス交換効率を向上させるとの先行研究による生理学的知見に基づき提案している。最初の実験では､心拍動と同期したパルス音により吸気のタイミングを合わせる呼吸統制により心拍呼吸位相同期が誘発されることを 16 名の被験者実験により確認している。二番目の実験では、心拍動と同程度の周波数で非同期となる一定間隔やランダム間隔のタイミングによる呼吸統制を行った場合と比較して､心拍同期パルスによる統制の場合のみ心拍呼吸位相同期が誘発されることを、16 名の被験者実験で確認している。三番目の実験として、心拍呼吸位相同期が誘発される前後の血中酸素飽和度を比較することで､心拍呼吸位相同期の誘発により血中酸素飽和度が統計的に有意に増加することを 16 名の被験者実験で確認している。四番目の実験では、ダグラスバッグを装着することで呼気に含まれる酸素と二酸化炭素濃度の分析による換気量も測定し､呼吸１周期に対して心拍動が４拍（拍数比 2:2）においてのみ、1:1 と 3:3 と比較して、統制呼吸前後で統計的に有意に血中酸素飽和度が増加することを確認している。最後の実験で、ドライビングシ

ミュレータを用いた１時間の運転タスクにおいて、運転開始 30 分後と 45 分後に心拍に同期したタイミングの振動刺激付加を行うことで、心拍位相同期が誘発し、誘発前に比べて誘発後に血中酸素飽和度が向上し、かつ、主観評価、顔表情、瞬き何れの眠気判定指標からも刺激前後において眠気緩和効果を統計的に実証している。心拍同期振動刺激を用いた居眠り防止システム提案の概要は、J. Human Ergology に査読論文として掲載され、眠気緩和方法の提案と上記の実験結果と考察は、IEEE Trans. Intelligent Transportation System (IF2.47)に査読論文として掲載されている。

第５章「Designing of the bio-signal sensors」では、眠気緩和刺激付与に必要となる心電図を着衣状態で測定するための容量結合型生体信号センサーの設計と実装について記述している。センサーについては、測定信号の電位レベルを減衰させないための寄生容量除去回路の設計・組み込みと、エンジンの振動などに起因するノイズ除去のための適応型ノッチフィルタの組み込みを行う改良を加えている。

第６章「Discussion」では、提案システムを実車に搭載するために解決すべき課題を述べている。

第７章「Conclusion」では、本研究のまとめと新規性を述べている。

以上より、本申請論文は生理学的知見に基づき独創的な眠気緩和方法を構築し、方法の妥当性を基礎実験で確認し、さらに、自動車運転シミュレータを用いた運転動作時への適用実験でその効果評価までを実施した結果に基づき、眠気緩和システム開発への展開を図ったものであり、博士（芸術工学）の学位授与論文に値するものと認められる。