Helmet based physiological signal monitoring system

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Abstract A helmet based system that was able to monitor the drowsiness of a soldier was developed. The helmet system monitored the electrocardiogram, electrooculogram and electroencephalogram (alpha waves) without constraints. Six dry electrodes were mounted at 5 locations on the helmet: both temporal sides, forehead region and upper and lower jaw strips. The electrodes were connected to an amplifier that transferred signals to a laptop computer via Bluetooth wireless communication. The system was validated by comparing the signal quality with conventional recording methods. Data were acquired from 3 healthy male volunteers for 12 minutes twice a day while they were sitting in a chair wearing the sensor-installed helmet. Experimental results showed that physiological signals for the helmet user were measured with acceptable quality without any intrusions on physical activities. The helmet system discriminated between the alert and drowsiness states by detecting blinking and heart rate variability (HRV) parameters extracted from ECG. Blinking duration and eye reopening time were increased during the sleepiness state compared to the alert state. Also, positive peak values of the sleepiness state were much higher, and the negative peaks were much lower than that of the alert state. The LF/HF ratio also decreased during drowsiness. This study shows the feasibility for using this helmet system; the subjects' health status and mental states could be monitored without constraints while they were working.

Keywords Helmet · Dry electrodes · ECG · EOG · EEG · Alpha wave · Drowsiness

Introduction

During their military careers, soldiers are exposed to mental and physical stress, and threats to their health (Scherrer et al. 2008). They are trained mentally and physically during the day, and at night they patrol the boundary of their base. These activities are tiring and difficult for an individual, and sometimes compromise a soldier's condition and may prove fatal. Thus, it is important to monitor their health. Also, their availability, mobility and reliability should be considered (Zieniewicz et al. 2002). In order to meet these requirements, a lightweight, wireless, unconstrained helmet system was developed. This research is a pilot study for monitoring a soldier's health without physical constraints.

Electrooculography (EOG) is based on potential differences between the retina and cornea. The eye is a dipole with the positive cornea in the front and the negative retina in the back. This dipole can be used to measure eye position by placing surface electrodes to the left and right of the eye, on the nose and at the temple. When the eyes are gazing straight ahead, the EOG output is zero. When the eyes move in a certain direction, the change of potential is measured by the surface electrodes (Webster 1998).

Blinking can be determined by EOG measurement. Blinking results from the relationship between the innervation patterns of the levator palpebrae superioris (LP) and the orbicularis oculi (OO) muscles (Bour et al. 2002). Blinking has been extensively studied and is considered to be a reliable indicator of fatigue and alertness level (Hyoki et al. 1998; Stern et al. 2001). Blinking has also been used to detect sleepiness during work time or while driving (Caffier et al. 2003; Galley et al. 2004; Papadelis et al. 2007; Svensson 2004; Takeyama et al. 2005; Verwey and Zaidel 2000). To measure blinking in these studies, a camera, infra red sensor or surface electrodes, like Ag/AgCl were used. Blinking has several parameters, including duration, closing time, reopening time, blink interval and peak amplitude. The mean blink duration is about 300-400ms and increases as drowsiness increases. The reopening time has the same characteristics as duration and is more closely related to the duration properties than the closing time. The blink interval is subject to characteristic modifications with drowsiness (Caffier et al. 2003).

Heart rate variability provides useful information regarding the autonomic nervous system (ANS). HRV analysis provides information on sympathetic nerve and para sympathetic nerve activity (Acharya et al. 2006). Within the power spectra of HRV, a high frequency (HF) peak appears at 0.15-0.4Hz and a low frequency (LF) peak at 0.04-0.15Hz. The HF reflects the degree to which RR intervals are affected by parasympathetic activity and the LF is affected by sympathetic activity. HRV has been used for evaluating sleep stages. HRV during REM sleep is significantly higher than in stages 2 and 4 of non-REM sleep. (Kleiger et al. 2005; van den Berg et al. 2005).

Electroencephalography (EEG) is the most reliable index to detect drowsiness. Several patterns are evident in an EEG. Alpha, Beta, Theta and Delta waves have usually been used for sleep studies. Among these, alpha waves (8-13Hz) are found in almost all normal persons when they are awake in a quiet, resting state. They arise in the occipital region, but can also be recorded in the parietal and frontal regions. When the subject is asleep, the alpha waves disappear completely (Webster 1998). Because of this characteristic, alpha waves can be used as an indicator of drowsiness (Andreassi 2000; Gillberg et al. 1994).

This study had two functional aim for a biomedical system utilizing helmet. The first was to develop a helmet system to monitor a soldier's condition, and the second was to detect physiological state changes when a subject was sleepy.

Methods

Helmet system

To obtain physiological signals, dry electrodes (electrical tape, 3M, New Zealand), which do not cause skin rash or itching problems and are reusable were attached to the Korean standard army helmet. Fig. 1 shows a helmet diagram with installed electrodes. Six electrodes were used for recording the ECG, EOG and EEG alpha waves. For the acquisition of the ECG, EEG alpha waves and horizontal direction signal of the EOG, 3 electrodes were fixed to the left-temporal region (+), the forehead (ref) and right temporal region (-). The electrodes for monitoring the vertical direction EOG signal were fixed to the left temporal region (+), upper jaw strip (ref) and lower jaw strip (-). The raw signal from a sensor was sent to an amplifier on the helmet. The raw signal was amplified 30 times and was then sent to analogue filters. To minimise the high frequency distortion, a high pass filter cut-off frequency was set to 0.5Hz. Although it was difficult to observe the duration of eye movement direction, it was able to detect blinking. A low pass filter cut-off frequency was 35Hz. The filtered signal was amplified by an adjustable gain. The filtered and amplified signal was then, sent to a microcontroller. In the microcontroller, it was converted from an analogue signal into an 8-bit digital signal and sent to a Bluetooth module. The sampling frequency was 200Hz. Using a laptop computer, an acquisition program was developed with Visual Studio 2005 (Microsoft, USA) and TeeChart pro (SteeMa Software, Spain) that received signals in real time. The received signals were digitally filtered based on their characteristics and analysed by post processing. Fig. 2 shows the basic concepts used for the helmet system.

Experiment I: System validation

In order to check the reliability and accuracy of the helmet system, a conventional physiological signal acquisition system (Biopac MP-150, Biopac Systems Inc., Goleta, CA) was used to record reference ECG, EOG and EEG signals. To compare the helmet system with the Biopac system during the validation process, the influence of other sources needed to be removed. Thus, wired communication, rather than wireless, was used. Five healthy male volunteers who had a crew cut hairstyle participated in the experiment. Seven minutes were spent for recording: 6 minutes for recording a resting heartbeat, 30 seconds for recording eye movement and 30 seconds for measuring alpha waves. Because blinking had a high, clear peak and waveform, it was classified without difficulty. In contrast, the ECG signal was easily affected by various sources. Therefore, during the validation process, more effort was concentrated on ECG validation. For the ECG signal, the raw signal was filtered @ 8~25Hz. Then, an R peak detection algorithm was used. To check the reliability of the helmet system, the time delay between the two systems was analysed. The time delay was calculated by subtracting the Biopac system's R peak time from that of the helmet system. For comparisons, EOG signals from the conventional system and proposed system were measured simultaneously. During recording, subjects were instructed to move their eyes, in order, to the right, left, up and down directions. Afterwards, waveforms of both systems were compared. For the EEG alpha waves, experiments with eye opening and closing were performed to compare alpha wave power.

Experiment II: Sleepiness elicitation

Among the 5 subjects who participated in the validation, 3 healthy male volunteers participated again in the study. They had no prior diseases or family history related to ECG, EOG or EEG recordings. The measurements were done at 2 times in a day: once in the morning (09:00) and once in the afternoon (16:00). During afternoon recording, for elicitation of sleepiness, the subjects sat down while wearing the helmet in a room lighted by an incandescent electric lamp and stared at one point on the wall. Total measurement time was about 12 min for each subject. In terms of validation, there have been several reports showing a relatively strong relationship between the Karolinska Sleepiness Scale (KSS) and the sleepiness state (Akerstedt and Gillberg 1990; Horne and Baulk 2004; Reyner and Horne 1998). Because KSS has been frequently used for evaluating subjective sleepiness, we employed KSS to compare subjective sleepiness and related signal changes. In order to assure blink detection, blinking was simultaneously recorded with a USB Digital Camera MPU-C30.

To detect blinking, the raw data acquired from the helmet were smoothed by 10% of its frequency (Kong and Wilson 1998). After smoothing, the signal was filtered by low pass filter (4Hz) to remove artefacts from the ECG or other sources. This was differentiated and upper and lower thresholds were set to zero. Each of these threshold values was determined as 0.8 times its max, min values during recording. By this method, the raw signal was simplified, so an eye blink with high amplitude could be detected using the eye blink parameter characteristics of duration, closing time, reopening time and peak amplitude.

To obtain the ECG signal, the raw signal was filtered at 8-25Hz, and then, an R peak detection algorithm was used as mentioned above. For HRV analysis, an RR interval was calculated and its power spectral analysis was performed to obtain a frequency parameter for HRV. The LF/HF ratio was used in this experiment to estimate the subject's drowsiness.

The alpha wave signal was analysed by power spectrum to check the subject's drowsiness. The signal was set at 1 epoch per 10 seconds and the alpha ratio within the total power was calculated.

Results

Tests for evaluation of helmet system

Fig. 3 shows the measured signal that contains combined eye blink and ECG signals. It was possible to acquire each signal by filtering. Table 1 shows the means and standard deviations of the R peak time delays. The helmet system had a very small time delay of about 1-6ms, which may be overlooked in a practical situation. Table 2 shows the correlations of RR intervals between the two systems. Overall, the two systems had a significantly high correlation.

The eye blink had a steep, high amplitude. There was no difficulty in detecting eye blinks. However, for the EOG signal, the helmet system had a different blink waveform compared with blinking detected by the standard ECO signal. Fig. 4 shows the helmet system's blink waveform and the standard EOG system's waveform. Although it had a different waveform, the time parameters-duration, closing time and reopening time-were the same. Therefore, the use of these properties for the eye blink parameters of the helmet system was redefined. Table 3 shows the eye blink parameters and the definitions used for the helmet system.

Fig. 5 shows the alpha wave detection result. The upper part of Fig. 3 shows the alpha waves when the eyes were closed, and the lower part shows the alpha waves when the eyes were open. The difference between the waves is around 10Hz and the amplitude in the eye closed section was much higher than in the eye open section. This indicates that the helmet system was able to detect the alpha waves.

Sleepiness and related signal changes

The hypothesis was that the subject's drowsiness state would be higher in the afternoon than in the morning as many people encounter physical and mental stress during daily life. Therefore, it would be expected that there would be differences between morning and afternoon in terms of alert and drowsy states. The helmet system used 6 blink parameters. Table 4 shows the results of the 6 blink parameters that were measured from the helmet system, and Fig. 6 shows the parameters' changes between morning and afternoon.

Eye blink parameters could be divided into increasing, decreasing and statistically non-significant parameters. In the helmet system, blinking duration increased as subjective drowsiness increased. The mean blink duration in the alert state was from 300 to 350ms, while in the drowsy state the mean blink duration became unstable and the duration, which was higher than 400ms, appeared to increase and became irregular. Fig. 7 shows one subject's blink duration. When the subject was in the alert state, the duration was stable. But, in the drowsy state, the length of the duration, which was higher than 400ms, increased and the waveform for the duration became unstable. The reopening time also increased significantly with increasing drowsiness. But, the closing time did not show significant results. The negative peak amplitude of a blink could be acquired from this system. The negative peak in the drowsy state had a higher value than in the alert state. The positive peak amplitude of a blink became smaller than in the alert state. The blinking interval did not show significant results. Two subjects showed statistically significantly increased results, while the third did not. This might have been because the blinking interval can be easily changed by various conditions. For example, the physical condition, humidity of the measuring place, mental state, personal differences, etc. can be factors in individual differences. So, the blinking interval was not an appropriate parameter to detect the drowsiness change.

The HRV was analysed in order to detect physiological state changes. Fig. 8 shows the decreasing LF/HF ratios when the drowsiness increased. The awake state's LF/HF ratio is higher than for the drowsy state, as the LF/HF ratio decreased in drowsy state. This was thought to arise because sympathetic nerves' activities decreased compared with the alert state. In the drowsy state, the alpha power decreased compared to the alert state. The data, which ranged from 9.5Hz-13Hz (middle alpha wave), were divided into 10 sec. intervals, with one epoch equal to 10 sec. The alpha power for each epoch was divided by the total power for that epoch. Many studies have shown that alpha waves decrease in the sleepy state. We hypothesised that if an epoch was found that had a smaller power ratio than other epochs, then the drowsiness section could be found. After finding a small power ratio section, it was compared with the camera recording. But, in our experiments, the small power epoch did not match the drowsiness section. Also, the drowsy/alert alpha power ratio did not decrease.

Discussion

The purpose of this study was to unobtrusively monitor physiological signals without constraints and detect changes in those signals using a helmet system when the subject's physiological state changed, especially for the detection of drowsiness. For this purpose, dry electrodes were used for sensing and Bluetooth was used for wireless communication.

Some previous studies for physiological information monitoring systems utilizing helmet construction were reported. These systems provide valuable health related information for the helmet user, but have some limitations for actual military or other working environment applications. In some cases, they were not designed for non-intrusive purposes (Litscher 1998) and other systems required additional devices, like ear pieces, to acquire some physiological signals (Kaefer et al. 2003). An accelerometer based motion monitoring helmet also had limitations because it did not provide any signals that originated from the human body (Anishkina et al. 1992).

Six parameters for an eye blink were used for detecting the subject's state changes. Among the time parameters, blinking, duration and reopening time increased significantly when the subject felt sleepy. However, the closing time did not show significant results. This was due to the fact that the duration's change was affected more by the reopening time than by the closing time, and this result was consistent with other studies (Caffier et al. 2003; Ohsuga et al. 2007; Ryu and Myung 2005).

Peak amplitudes could be used for detecting a subject's state change. When subjects were in the alert state, the positive amplitude was higher than in the drowsy state. But, the negative amplitude showed the opposite behaviour. This was because during the alert state, the eyelid moves faster than in the drowsy state, so the OO and VB muscles that generates the potential differences in blinking are able to have higher amplitudes than in the drowsy state. The blinking interval (BI) did not show a significant difference. BI is a subjective characteristic and is easily affected by other environmental factors, so it may not be appropriate as a drowsiness index.

During the drowsy state, the LF/HF ratio showed a significant decrease. The LF ratio is influenced by sympathetic nerve activity and when the subject is sleepy, this activity is diminished (Kleiger et al. 2005). The hypothesis for the alpha wave was that the alpha power would decrease with increasing drowsiness (Barbato et al. 1995; Cantero et al.

2002). The middle and fast alpha wave ranges (9.5-13Hz) were used for comparing the drowsy/alert ratio, as the alpha waves should decrease as drowsiness increased. But, there was no significant result. It was not certain whether or not this was caused by a motion artefact.

The possibility to discriminate the subject's state was shown by blinking and the LF/HF ratio. To ensure the reproducibility, a second experiment was done with 2 subjects (12min each). One epoch was set at 10 sec. If there was a duration that exceeded 400ms, it was highlighted as a drowsy section and was then compared with video recording results. Table 5 shows the comparison results for the systems. The agreement, sensitivity and specificity were 90.1%, 79.3% and 76.4%, respectively. Also, the LF/HF ratio showed decreasing results when the drowsiness increased. From this result, the reproducibility of the helmet system was well demonstrated.

Although drowsiness detection using a helmet system was possible, there were some limitations. First, in this study, the data that were transmitted from the helmet were analysed by post-processing. In a subsequent study, real time analysis will be used. Second, there were limitations with the subjects. To acquire a signal from the helmet, subjects were required to get a crew cut for successful signal acquisition. Although it was possible to obtain physiological signals from subjects with normal or long hairstyles, the quality of the signals was not good.

Conclusion

A helmet based unconstrained system for monitoring the health of military personnel and its application for detection of drowsiness was proposed. Although it was not completely automatic with real time processing, experimental results show that ECG, EOG and EEG alpha wave signals could be measured non-intrusively, and that some parameters extracted from the measured signals were changed according to the sleepiness state. Based on the present work, commander will be able to know the conditions of their men at all times and plan operations accordingly. Further, during a war, soldiers' locations and their fates can be easily determined by the command center. This study shows the lfeasibility of unconstrained health and condition monitoring not only for military personnel, but also various working people who use helmets during their work, such as fire fighters and mine works.

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Table. 1 Means and standard deviations (Std) of R peak time delays between the two systems. The accuracy indicates the percentage of detected peaks whose difference from the reference system was less than the mean value.

Subject	Mean	Std	Accuracy (%)
1	5.2381	14.005	97.2
2	6.0720	1.6725	94.3
3	1.3246	4.0321	99.4
4	5.4932	6.4501	99.1
5	6.4399	11.7170	98.2
Mean	4.9136		97.6

Table. 2 Correlation of RR intervals

Subject	Correlation	P value
1	0.9665	< 0.001
2	0.9877	< 0.001
3	0.9829	< 0.001
4	0.9540	< 0.001
5	0.9875	< 0.001

Table. 3 The helmet system's blink components were redefined for comparisons with the standard reference EOG waveform.

Variable	Definition
Duration	Time difference between blink start point and negative peak
Closing Time	Time difference between blink start point and positive peak
Reopening Time	Time difference between positive peak and negative peak
Positive peak Amplitude	Max point of blink waveform
Negative peak Amplitude	Min point of blink waveform
Blink Interval	Time interval between blinks

Table. 4 Blink parameter values when the subjects are in the alert state and the drowsy state. Duration, Reopening time, Negative peak amplitude increased during drowsy state.

Measures	State	
	Alert	Drowsy
Duration(ms)	350	398
Std	37	98
	P=0.0001	
Closing time(ms)	163	167
Std	25	51
	P=0.17	
Reopening time(ms)	187	231
Std	29	79
	P=0.0001	
Positive Peak(mV)	762	677
Std	91	79
	P=0.0001	
Negative Peak(mV)	295	352
Std	86	101
	P=0.0001	
Interval(sec)	18	26
Std	11	39
	P=0.09	

Table. 5 Comparison results with video system. The agreement, sensitivity and specificity are 90.1%, 79.3% and 76.4%, respectively.

		Helmet system		
		Drowsy	Normal	Total
Video system	Drowsy	73	8	81
	Normal	19	26	45
	Total	92	34	126

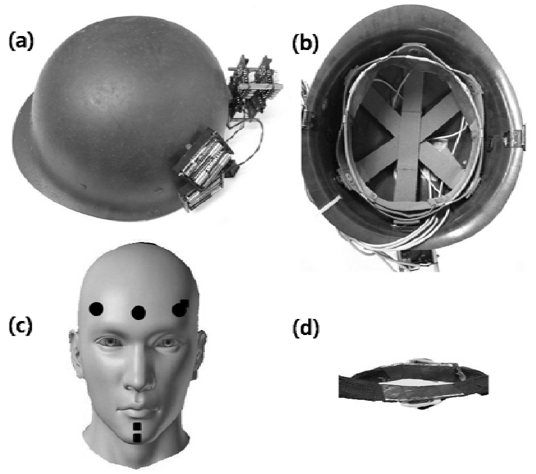

Fig. 1 A photograph of the proposed helmet based physiological monitoring system: (a) outside, (b) inside, (c) specific locations of dry electrodes. Circle marks indicate the locations for ECG, EEG alpha wave and horizontal direction EOG signal and square marks indicate the locations for vertical direction EOG signal, (d) jaw strip.

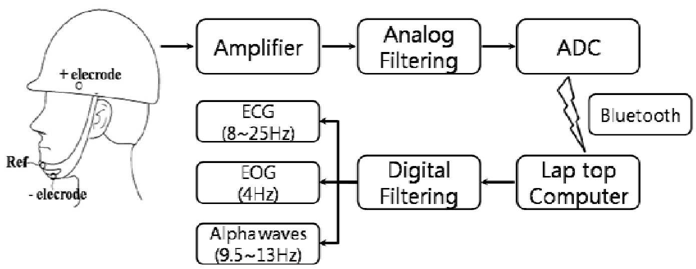

Fig. 2 Block diagram of the helmet system.

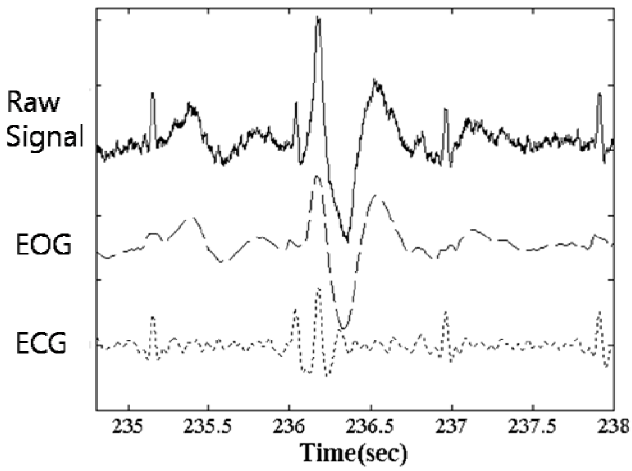

Fig.3 Measured and processed signals. The solid line is a raw signal with combined eye blink and ECG signals. Eye blink has a higher amplitude and larger waveform than the ECG. The dotted line (middle) is a low pass (4Hz) filtered signal. The ECG signal was removed and the eye blink waveform was emphasized. The dashed line (lower) is a band pass (8-25Hz) filtered signal. The ECG signal was emphasized.

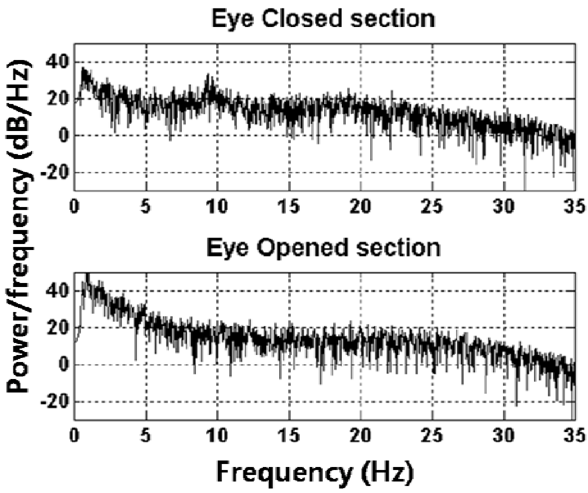

Fig.4 Alpha wave detection when eye is closed and open

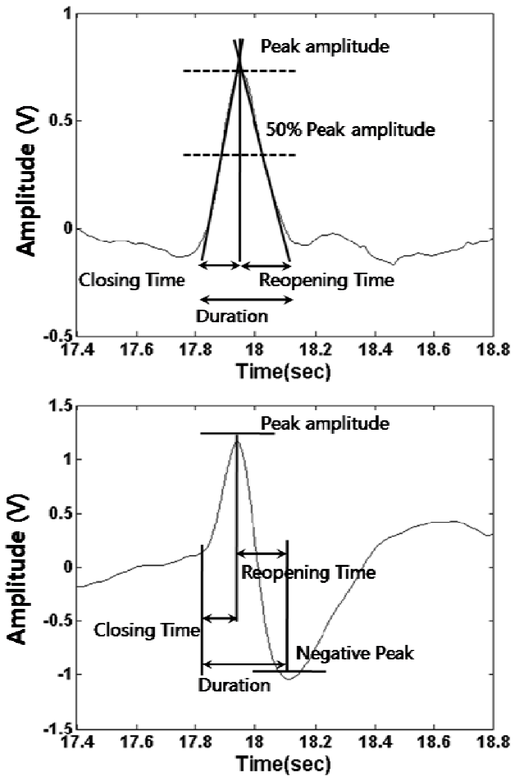

Fig. 5 Blink waveform of the standard vertical EOG measuring system (above) and waveform of the helmet system (below). The helmet system's waveform was equal to the standard system.

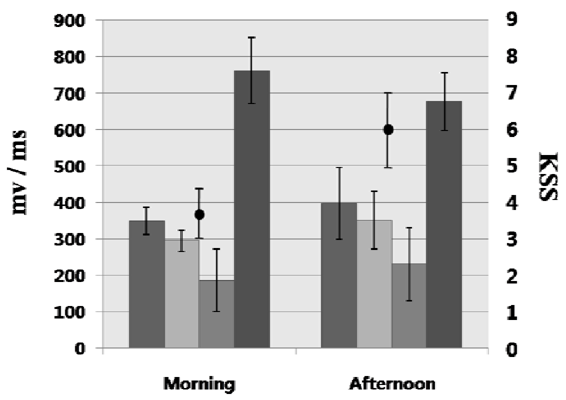

Fig. 6 The subjective sleepiness scale increased in the afternoon. The duration (first bar), negative peak (second bar), reopening time (third bar) increased. But the positive amplitude (fourth bar) decreased in the drowsy state.

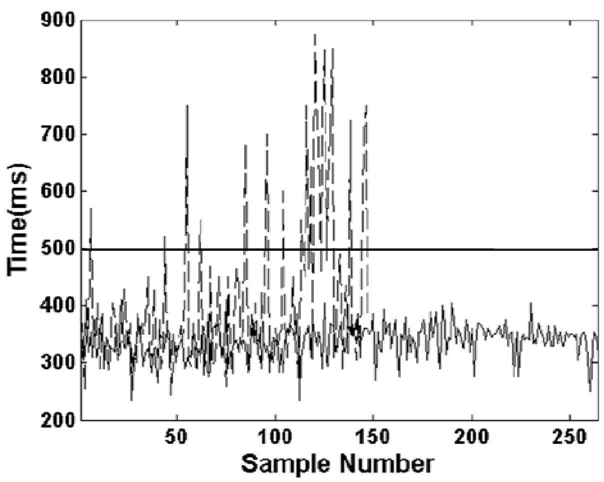

Fig. 7 Representive Blink Duration. The dotted line is the drowsy state and the solid line is the alert sate. In the drowsy state there are many blink durations that are higher than 400ms.

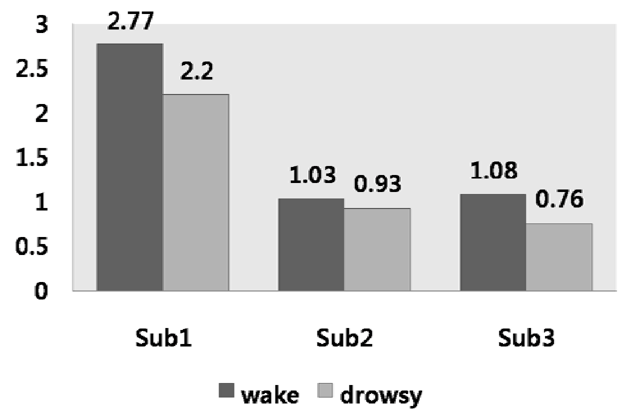

Fig. 8 The LF/HF ratio decreased when the subject's drowsiness increased.