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Biorhythm-Based Awakening Timing Modulation

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Abstract— **The purpose of the present study is to control human biological rhythm and life cycle by optimization of awakening timing. We developed a wearable interface for controlling awakening time named ”BRAC (Biological Rhythm based Awakening timing Controller)”. BRAC could estimate bio-rhythm by pulse wave from finger tip and send awake signal to user.**

An ordinary alarm clock operates according to set times that have to be set in advance. However, humans have a rhythm in their sleep, which affects one’s sleep depth and wake-up timing. We consider the simplest way to control or reset human’s bio-rhythm or life style is to optimize the awakening timing and the sleeping hours.

We examined the relationship between controlling awakening timing based on autonomous nerve rhythm and equilibrium function. Our findings suggest indicate that the prototype ”BRAC” could evaluate user’s biological rhythm and awakes user at the time optimized for physical function of equilibrium.

I. INTRODUCTION

TOday, many people have an irregular life cycle that is affected by the complex constraints of peoples’ work environments and the modern lifestyle; thus many find that they cannot get enough or regular sleep.

There are many people who have sleep problems, but there are few who aware of their own problems because often the problems that occur during sleep are not easily recognized by people themselves.

We have developing an wearable type human interface. This interface can observe a user’s biological rhythm from pulse wave and can control awakening timing based on the bio-rhythms (Fig.1). This paper introduces the algorithm installed in one component of the interface to estimate the sleep state and indicate the effect of awake timing control based on biological rhyhtm using BRAC.

II. BIOLOGICAL RHYTHM IN SLEEP

A. Sleep state and quality

Generally, sleep states can be classified on an electroencephalogram into REM sleep and four sleep stages. The periodical iteration of REM and NREM defines one of the biological rhythms in sleep termed the ”sleep cycle”. There are three requirements for a sound sleep; and people can not recover sufficiently even if we miss just one of them; suitable sleep length, a deep sleep generally defined as NREM, and having a periodical sleep cycle. Medical staff can estimate the sleep quality based on these three features.

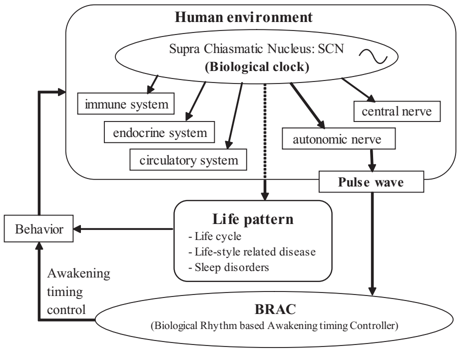

Fig. 1. System configuration of the biological rhythm control system

The check system commonly used in medical environments to categorize sleep disorders is polysomnography (”PSG”) .

The PSG system estimates the sleep stages based on many measured levels of data as explained above; however, this system gives stress tot eh subject monitoring due to the many attached electrodes and the unusual environment.

III. SLEEP CONTROL SYSTEM

A. Sleep control based on a wearable sensor

An ordinary alarm-clock operates based on a time preset by the user. However, those awakened by a set clock do so based on an economic system, one not necessarily suitable for the user’s health. In cases of rhythm disorders, the rhythm of the sleep-wake and sleep cycle is a very important factor.

In conventional research, light and medicines are used as stimuli to control biological rhythm. However, we focused on the wake-up timing to control the human biological rhythm.

We developed a sleep observation sensor device styled into wearable equipment so that we could observe long term human data.

The wake-up timing control system can estimate a human biological rhythm and can stimulate a person by sound or another approach.

B. Wearable interface for sleep observation

In our previous works[2], the sleep stage and biological rhythm are well estimated because of the relationship between autonomic nerves and heart rate.

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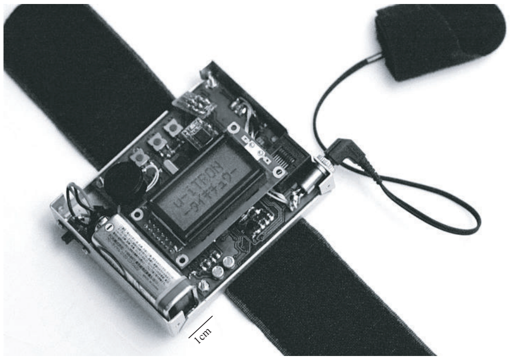

Fig. 3. Prototype of wearable sleep control system

In this paper, we propose a method for the correct estimation of sleep quality using a "pulse wave interval" measured by a system that is simpler than measuring heart rate.

The pulse wave interval data using a prototype wearable sleep observer sampled data every 30 seconds. On the other hand, the R-R interval data from an ECG are measured using PSG and are adjusted to a mean value from raw R-R interval data to the 30sec sampling data to compare with that from the prototype in the experiments. Between pulse wave interval data and R-R interval data (heart rate), there is little difference in respect to the data level [indicates interval span msec], because the prototype was worn on a wrist and that the pulse wave signal was not stable depended on the wearer's position, and so at times the pulse wave feature was not obtained, and two pulsewave intervals were summed to make up the pulse wave interval data. Then mean values of pulse interval data using the prototype were higher than the R-R intervals; however, the data wave features are similar and the correlation is efficient at 0.980 from 738 samples (the average is 0.951 in 6 subjects).

The device has acceleration and pulse wave sensors. The pulse wave is picked up from a fingertip using an infra-red photo coupler. The pulse wave is considered to contain autonomic nerve and the other human information along with the heart rate, and we evaluated errors between heart rate and pulse wave during the sleep state.

Several ways can be considered for controlling human biological rhythm; for example, using light or temperature controls. However, we considered what we think is the simplest approach to control human sleep-wake rhythm, that is to control the timing of the wake up. Therefore, we developed a wearable sensor device with an alarm function to control human sleep based on long-term information.

This wearable system is able to estimate states not only while the user is sleeping but also under daytime conditions for biological circadian rhythm as the equipment is portable. We designed a second prototype of our wearable sleep control system BRAC (Biological Rhythm based Awakening timing Controller), the system is shown in fig.3.

Additionally, to design the multi-task system, a Japanese Operating System μ-iTRON was installed in the device. This is an OS derived from TRON for built-in equipment with a smaller kernel and standard functions. The result was an easiness of stable operation and real-time control.

TABLE I

HARDWARE DATA OF THE SECOND RSCS PROTOTYPE

Part	Spec or Purpose
One-chip MPU	H8/3048F [16MHz]
RAM	SRAM [512kByte]
Infra-red photo coupler	pulse wave measurement
Acceleration sensor[two-axis]	sleep-wake detection
Operating time	23 hours
Size	70x90x20 [mm]

C. Sleep state estimation

1) Previous works: There are various studies on sleep state estimations based on heart rate information[8],[16]. These studies infer a sleep state by estimating the activity of the autonomic nerve system by frequent analyses of heart rate variability (HRV analysis) for low stress measurement; this because the two factors have a close relationship. We researched chaos analysis for HRV in a previous workbut as there are many personal characteristic features reflected in the variability of heart rate, chaos analysis was not suitable for application in the developed wearable micro computer.

There is a related study on sleep stage estimation using an air-mattress type heart rate sensor[7]. In our research, we use a wearable style sensor with the aim to achieve a low stress and low cost measurement system that can be widely used in a domestic situation. However, there are some problems in respect to using a wearable system; such as limited battery capacity, and the calculation cost in the compact system.

2) Method for an estimation of the sleep state with low cost calculations: In order to calculate easily on an embedded micro computer, we utilized a simpler method to estimate the sleep quality using numerical analysis of the pulse wave interval.

The system must be able to observe the human state for a long time, at least for 1 day, to determine the biological rhythm containing the circadian rhythm and other long term rhythms. To reduce the calculation cost and data sets for longitudinal data, we designed our system obtain pulse wave interval data by sampling every 30 sec, that is a mean of 30sec pulse interval data RR_n (However this pulse interval data is differ from R-R interval of ECG, we write RR in this paper conventional usage of symbol).

Second, a micro computer cannot calculate complex analyses in real-time, for example chaos analysis. FFT an other frequency analyses are not suitable for estimations of long term biological rhythms as we require here because the reliability of rhythm estimation will be decline if for example using 1 hour data to estimate a 1 hour periodic pattern.

In this section, we detail sleep state estimation based on low cost calculations using a sinusoidal sleep cycle template.

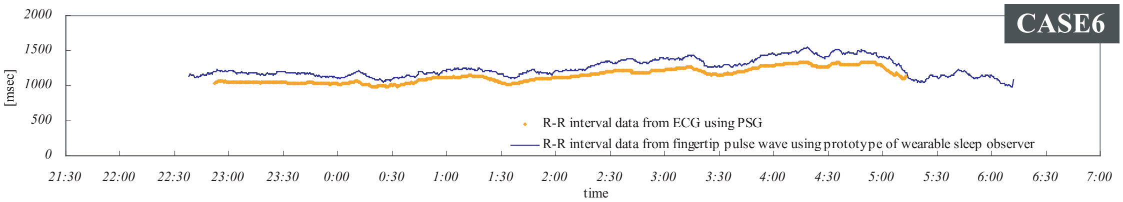

Fig. 2. Comparisons between overnight data of pulse wave intervals from fingertip and R-R interval data from ECG using PSG

We use a infra-red photo coupler sensor. Initially, we apply a three-stage moving average filter for 8 min (for 16 data), to eliminate breathing activity and high frequency noise in the pulse wave interval data. We define the mean of eight minutes of pulse interval data as the pulse interval rhythm data RR_{mean} containing ultradian biological rhythm[1] and circadian rhythm.

Next, we undertake template matching to find sleep cycle from RR_{mean}.

3) Sleep cycle estimation: The pulse wave interval data contains many frequency based on power spectrum of it. Sevral characteristic frequency of pulse wave interval data and R-R interval data are shown in Fig.4. The frequency of largest power spectrum of pulse wave interval data(30sec sampling) is 0.000152Hz(109.8minutes period). We estimate this characteristic frequency rhythm based on template matching using sinusoidal template of 100minutes period.

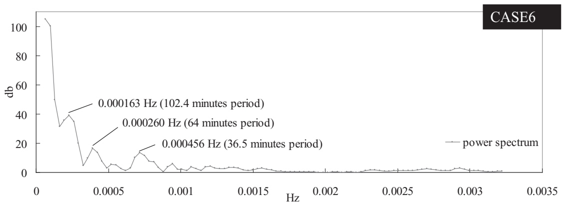

Fig. 4. Power spectrum of pulse wave peak-peak interval data

A template matching method has the advantage to being able to take no account of long term trends of pulse interval data, for example circadian(24 hour cycle) or circasemidian(12 hour cycle) rhythms. The template is defined in this paper as an expression of a half-period sinusoidal wave(50 minutes length) of time series data as follows.

$$T_j = sin(\frac{i\pi}{100}), (i = 1, 2, 3 \ldots, 100) \qquad (1)$$

Our reason for choosing the template sinusoidal wave was that there are several studies that define the rhythm as a sinusoidal oscillator in sleep-wake rhythm pattern modeling[21] and those model are fit with human biological rhythm dymanics well.

Additionally there are two reasons to define the template of sinusoidal wave as monotone decreasing data sets (graph-(a) in Fig.5). First, to find a peak on time. Second, the mean of a few minutes pulse wave interval data has many random small peaks or trough; so that if we use the dancette or trough shaped sinusoidal wave template graph-(b) shown in Fig.5, the result of sleep cycle estimation will be unstable experimentally. Using a monotone decreasing template equation1, we can find a long slope of the pulse wave interval rather than finding a peak as the sleep cycle rhythm.

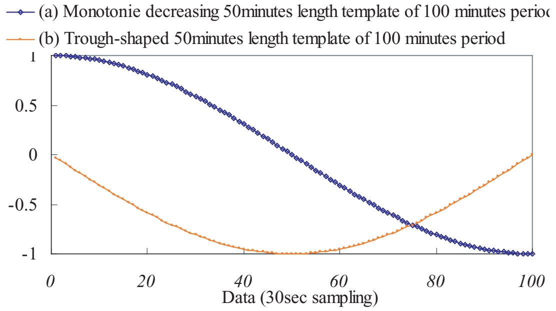

Fig. 5. 50 minutes template(100minutes period sinusoidal wave) data for sleep cycle estimation

We calculate the correlation coefficient between the sleep cycle template and RR_{mean}. The correlation coefficient rho is defined as the sleep cycle estimated from pulse interval data.

We computed the value of Pearson's correlation coefficient ρ_n between RR_{mean} and T_j at data number n by following equation.

$$\rho_n = \frac{C_n}{S_{n(Pulse)} S_{n(Template)}} \qquad (2)$$

Here, C_n is covariance between RR_{mean} and T_j, $S_{n(Pulse)}$ and $S_{n(Template)}$ are standard deviation defined as folows.

$$C_n = \frac{1}{n} \sum_{i=n-100}^{n} (RR_{mean(i)} - \overline{RR_n})(T_i - \overline{T}) \qquad (3)$$

$$S_{n(Pulse)} = \sqrt{\frac{1}{n} \sum_{i=n-100}^{n} (RR_{mean(i)} - \overline{RR_n})^2} \qquad (4)$$

$$S_{n(Template)} = \sqrt{\frac{1}{n} \sum_{i=n-100}^{n} (T_i - \overline{T})^2} \qquad (5)$$

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[1] ultradian rhythm is shorter than circasemidian rhythm and generally means a 90min rhythm

$RR_{mean(i)}$: Pulse wave peak-peak interval[msec]

In this form, a parameter is defined as follows.

$$\overline{RR_n} = \frac{1}{n}\sum_{i=n-99}^{n} RR_{mean(i)} \tag{6}$$

$$\overline{T} = \frac{1}{n}\sum_{i=1}^{100} T_i \tag{7}$$

Where, ρ_n is in this theory defined as a level of the sleep cycle rhythm.

IV. EXPERIMENTS WITH THE BRAC PROTOTYPE

A. Experimental settings

Generally, In development of medical equipment for evaluation of sleep state, it is needed to examine the reliability of equipment developed by comparing its results with those of PSG.

Therefore, we examined BRAC with PSG in 6 subjects at the Nagoya University Hospital.

The PSG system collects several kinds of data: electroencephalograms(C4A1, C3A2, O2A1, O1A2), eye movements(electro-oculogram : EOG) and Electromyography(EMG) of the chin and leg parts and R-R interval data(Fig.2) to construct sleep stage data.

On the other hand, BRAC obtains pulse interval data (Fig.2) and also estimates the sleep cycle and sleep stage based on our proposed method, and estimates the asleep or the awake state using the acceleration sensor. The estimated sleep stages are used for the comparisons.

Our experiments have two steps. First, we estimate the sleep cycle and sleep stage using BRAC and then compare these with the sleep stage estimated using PSG. Second, we investigate the reliability of the proposed method based on statistical analysis of the correlation coefficient between the estimated sleep stage and the sleep stage from the results of PSG.

B. Sleep cycle estimation using pulse waves

Raw pulse interval (interval of peak of pulse wave) data and heart rate interval(R-R interval) data for one night is shown in Fig.2.

The data ρ_n based on the proposed method are shown in the upper graph of Fig.6. The vertical lines in Fig.6 are flags of the estimated human biological cycle's peak and trough.

This is a normal case, where sleep starts with NREM and finishes with shallow sleep after NREM, via four periodical REM-NREM cycles.

A line like a square wave in the upper graph of Fig.6 shows the sleep stages using PSG. A line in the lower graph of Fig.6 shows the estimated sleep cycle using BRAC based only on pulse wave interval data. A glance at Fig.6 reveals that the proposed estimation results have commonality with the sleep stage obtained using PSG.

C. Correlation test between estimated sleep cycle using BRAC and stage determined by PSG

We studied the correlation coefficient between the sleep cycle estimated using BRAC and that using PSG as a statistical evaluation. The sleep stage estimated using BRAC $State(t)$ did not have the strong normality for distribution of stages. The sleep stage data using PSG did not have normality either. Thus, we uses Spearman's correlation coefficient as a non-parametric test for evaluating the correlation between two sleep indices. This coefficient assesses how well an arbitrary monotonic function describes the relationship between two variables, without making any assumptions about the frequency distribution of variables[6]. Raw scores are converted to ranks, and differences D between the ranks of each observation for the two variables are calculated for each case. ρ^{spear} is then given by:

$$\rho_n^{spear} = 1 - \frac{6\sum D^2}{N(N^2-1)} \tag{8}$$

where:

D : Difference between ranks of corresponding values for two stages.
N : Number of pairs of values.
n : Number of cases.

Results are given in Table II. We calculated Spearman's correlation coefficient using raw sleep cycle data from BRAC and PSG.

We also conducted a test of significance for the correlation coefficient for each case. The value of Spearman's correlation coefficient uses tested using the following criterion:

$$t_{cr} = \rho_n^{spear}\sqrt{\frac{N-2}{1-\rho_n^{spear2}}} \tag{9}$$

The sample size is large enough ($N \gg 30$), that T_{cr} can be compared to Student's t distribution (two-tailed) with $(N-2)$ degrees of freedom. t_{cr} for each case (Table II) greatly exceeds the critical value of $t_{0.01}$ ($t_{0.01} = 2.575$), which is given by the table of Student's t-distribution for a probability of 1% and for large degrees of freedom (two-tailed). Therefore, if we consider null hypothesis H_0 : $\rho_n^{spear} = 0$, this null hypothesis can be rejected at the 1% significance level in each case. Based on this significance test result, we concluded that each ρ_n^{spear} is significantly different from zero.

D. Summary

In this experiment, we have evaluated the estimation of sleep states in experiments using a wearable sleep observe device. Results demonstrated the high performance of our proposal in treating human information and sleep cycle estimation performs well enough to determine the peak time of the sleep cycle.

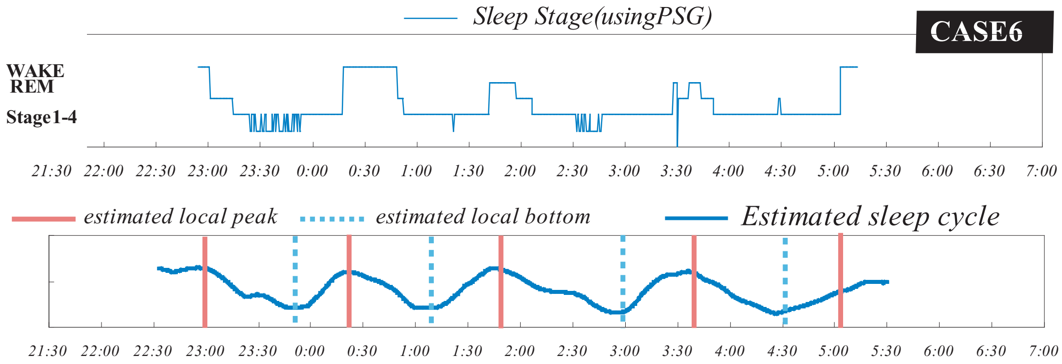


Fig. 6. Comparison between estimated sleep cycle using BRAC based on pulse wave interval analysis and sleep stage by PSG

TABLE II

CORRELATION COEFFICIENT BETWEEN ESTIMATED SLEEP CYCLE USING PULSE WAVE INTERVAL DATA AND USING PSG

n	Age	Gender	ρ^{spear}	N	t_{cr}
1	19	m	0.705	837	24.45
2	28	m	0.769	732	36.53
3	34	m	0.704	851	24.86
4	25	m	0.651	852	19.35
5	36	m	0.672	804	28.96
6	25	m	0.687	1024	40.51

n : Number of subjects.
ρ^{spear} : Spearman's correlation coefficient of sleep stage between PSG and BRAC.
N : Number of sleep stage data points sampled.
m : Male
f : Female

V. AWAKENING TIMING CONTROL USING BRAC

In the experiment, we use BRAC to control awakening timing based on sleep cycle, and examine balance function based on center of pressure using FootScan (RSscan International) after awake up.

In addition, we control sleep hours as four sleep cycles. We indicate the relationship between awakening timing based on biological rhythm and prevention of falling experimentally.

A. Evaluation of body sway based on COP of feet

As a index of body sway, we use orbit of COP(Center of Presure) of feet bottom by FootScan. FootScan could measure two dimensional distribution of pressure by 96x64 matrix pressure sensors in real time. We calculate center of output values of pressure sensors $F(x, y, t)(1 \leq x \leq 96, 1 \leq y \leq 48)$ to make coordinates $COP_x(t), COP_y(t)$. There are several discussion about evaluation of falling risk using COP, we use velocity of COP $V_{COP}(t)$ is given by following equation.

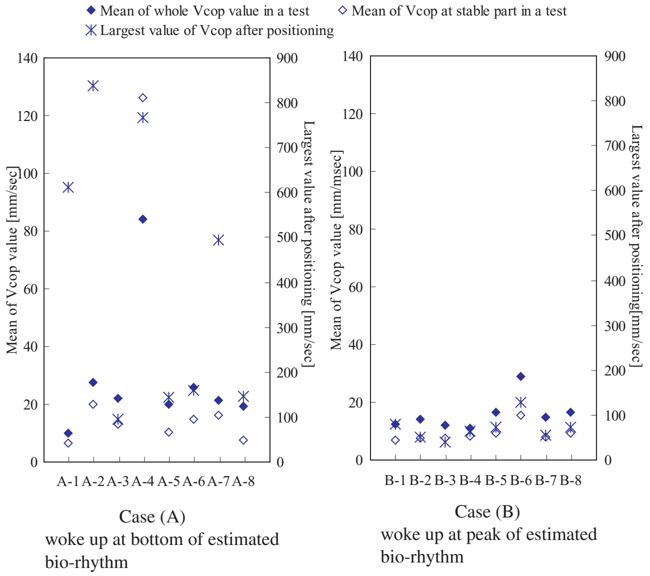
$$V_{COP}(t) = \sqrt{COP_x(t)^2 + COP_x(t)^2} \qquad (10)$$

B. Experimental result

The example of experimental result of COP orbit are shown in Fig.7. In the figure, left case is COP orbit of the subject awaken at peak of estimated biological rhythm, and right case's subject awaken at bottom of bio-rhythm. The sway of COP of case-2 is below than case-1 visually.

Additionally, subject get on FootScan at the time V_{COP} value started, and the value of V_{COP} in initial few seconds means subjects spend time to initial positioning of their feet. We except those unstable COP stage in initial 5 seconds for evaluation of body sway in this experiment because those values are different from the "body sway against subject's intent". In this paper, we use mean and largest value of V_{COP} for risk evaluation of falling.

The values of V_{COP} shown in Fig.8. Subjects are 20's four males and 16 cases. The case-A in Fig.8 means awake at bottom timing of biological rhythm estimated by BRAC, and the case-B means awake at peak.



Case (A)
woke up at bottom of estimated bio-rhythm

Case (B)
woke up at peak of estimated bio-rhythm

Fig. 8. Deference of velocity of COP between after woke up at peak and at bottom of bio-rhythm based on pulse wave interval

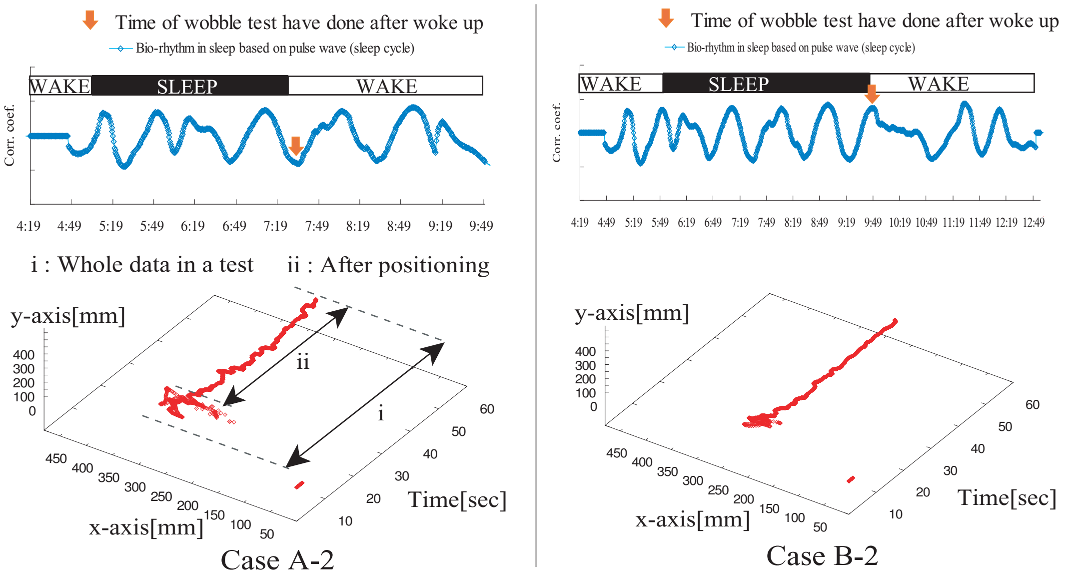


Fig. 7. Example of estimated bio-rhythm based on pulse wave interval and timing of wobble test after woke up

The case-A in Fig.8 is awake subject at buttom timing of biological rhythm, and case-B is awake at peak timing. Those graphs are indicate velocity of COPV_{COP} and mean value and largest value of V_{COP} are shown on left and right hand. According to the result, mean value of V_{COP} is lower in the case of awakening subject at peak of estimated bio-rhythm than the case awaken at bottom.

VI. CONCLUSION

In this paper, we proposed a wearable sensor device "BRAC" to estimate the sleep stage and sleep cycle. We proposed an estimation method using a pulse wave interval from a fingertip based on time series template matching with sinusoidal template of biological rhythms. We also indicated its reliability based on an experimental comparison with PSG. Additionally, we indicated effectiveness of biological rhythm based awakening timing control based on "body sway" in term of falling prevention.

We indicate that BRAC could awake user at peak of biological rhythm and prevent falling after wake up. provide by mentioned above.

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