Real-Time Sleep Stage Estimation from Biological Data with Trigonometric Function Regression Model

Tomohiro Harada
College of Information Science and Engineering, Ritsumeikan University
1-1-1, Noji-Higashi, Kusatsu, Shiga, Japan
harada@ci.ritsumei.ac.jp

Fumito Uwano and **Takahiro Komine** and **Yusuke Tajima**
Graduate School of Informatics and Engineering, The University of Electro-Communications,
1-5-1, Chofugaoka, Chofu, Tokyo, Japan
{uwano,tkomine,y_tajima}@cas.hc.uec.ac.jp

Takahiro Kawashima and **Morito Morishima**
Yamaha Corporation, Japan
{takahiro.kawashima,morito.morishima}@music.yamaha.com

Keiki Takadama
Graduate School of Informatics and Engineering, The University of Electro-Communications,
1-5-1, Chofugaoka, Chofu, Tokyo, Japan
keiki@inf.uec.ac.jp

Abstract

This paper proposes a novel method to estimate sleep stage in real-time with a non-contact device. The proposed method employs the trigonometric function regression model to estimate prospective heart rate from the partially obtained heart rate and calculates the sleep stage from the estimated heart rate. This paper conducts the subject experiment and it is revealed that the proposed method enables to estimate the sleep stage in real-time, in particular the proposed method has the equivalent estimation accuracy as the previous method that estimates the sleep stage according to the entire heart rate during sleeping.

Introduction

It is important to understand sleep behavior to promote psychological wellbeing. In particular, the demands on measuring the sleep condition in real-time recently increase for healthcare management or product development. Several researches proposed the sleep stage estimation method. Rechtschaffen and Kales (R&K) method, which is one of the most standard sleep stage measurement method, calculates the sleep stage by the brain wave from the electroencephalogram (EEG), electromyogram (EMG), or electrooculography (EOG) (Kales and Rechtschaffen 1968). This method, however, needs to wear an electric sensor to obtain the biological data, which is unsuitable for daily measurement of the sleep behavior. The previous research (Watanabe and Watanabe 2004) proposed the sleep stage estimation method based on the fluctuation of the heart rate obtained with a non-contact device. This method estimates the sleep stage based on the intermediate frequency component of the heart rate measured by a non-contact device. Takadama et al. improved its estimation accuracy by learning the band-pass filter for extracting the intermediate frequency component (Takadama et al. 2010). These previous researches enable to estimate to the sleep stage without any contact devices, which enables to measure daily sleep behaviour. Since these approaches, however, need whole biological data during sleeping to estimate the sleep stage, it is difficult to estimate the sleep stage in real-time from partially obtained heart rate during sleeping.

To tackle this issue, this paper proposes a novel method to estimate the sleep stage in real-time from partially obtained heart rate with a non-contact device. For this purpose, this paper employs the approach in the previous research (Watanabe and Watanabe 2004) based on the intermediate frequency component of the heart rate. Concretely, our approach constructs the trigonometric function regression model from the partially obtained heart rate and estimates the sleep stage based on the estimated intermediate frequency component of the prospective heart rate.

To investigate the effectiveness of the proposed method, we conduct the subject experiment that compares the sleep stage estimated by the proposed method in real-time with the one measured by PSG (Polysomnography), which is the standard method of measuring the sleep stage by medical specialists using data such as EEG or EMG of human. We evaluate the estimation accuracy of the proposed method by comparing it with that of the previous method proposed in (Watanabe and Watanabe 2004) as the baseline method.

The remaining of this paper is organized as follows.

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Firstly previous works related to the sleep stage estimation are introduced. The next section shows the proposed method that employs the trigonometric function regression model. Then the subject experiment is conducted and its result is shown. Finally the conclusion of this paper is given in the final section.

Related works

Sleep stage

The sleep stage is generally divided into six stages, wake stage, REM sleep stage, stages 1, 2, 3, and 4. Note that the stage 4 corresponds to the deepest sleep, while the wake stage corresponds to the lightest sleep. The main purpose of the sleep stage estimation is to accurately classify the sleep behavior into these six stages. Hereafter, this paper donates these six stages as WAK, REM, St. 1, St. 2, St. 3 and St. 4 respectively.

Rechtschaffen and Kales method

Rechtschaffen and Kales (R&K) method has been proposed in 1968 that calculates the sleep stage by the brain wave obtained from the electroencephalogram (EEG), electromyogram (EMG), or electrooculography (EOG) (Kales and Rechtschaffen 1968). Although R&K method is employed to calculate medically correct sleep stage, it cannot be used to measure the sleep stage in everyday life. This is because it does not only need to ware electric sensor such as EEG or EMG on a human head during sleeping but also has to be calculated by medical specialists.

Sleep stage estimation with a non-contact device

To estimate the sleep stage with a *non-contact* device, Watanabe et al. proposed the sleep stage estimation method that estimates the sleep stage based on the heart rate of human obtained with a non-contact mattress sensor (Watanabe and Watanabe 2004). This is based on the results of several articles suggesting that the heart rate has the strong relation to the sleep stage (Harper, Schechtman, and Kluge 1987; Otsuka, Ichimaru, and Yanaga 1991; Shimohira et al. 1998). Hereafter, this method is termed as the Watanabe's method in this paper. The Watanabe's method obtains the heart rate of humans with a non-contact mattress sensor during sleeping and estimates the sleep stage based on the intermediate frequency component of the heart rate, in particular the frequency component with a cycle between 135 minutes and 22 minutes.

Takadama et al. proposed more accurate sleep stage estimation method of improving the Watanabe's method to adjust the range of the intermediate frequency component for each person (Takadama et al. 2010). Concretely, this method improves the estimation accuracy of the Watanabe's method with the band-pass filter adjusted to each person. This band-pass filter is learnt from past sleep data of each person.

Proposed method

Overview

The previous methods (Watanabe and Watanabe 2004; Takadama et al. 2010) enable to estimate the sleep stage without giving excessive load or stress to humans by measuring the heart rate of human with a non-contact sensor. Since these methods, however, need whole heart rate during sleeping, it is difficult to estimate the sleep stage in real-time from partially obtained heart rate during sleeping. For this reason, these methods are not applied to the real-time sleep stage estimation.

To tackle this issue, this paper proposes a novel method to estimate the sleep stage in *real-time* only from partially obtained heart rate during sleeping. Figure 1 depicts an illustration of the proposed method. The proposed method constructs a model of the intermediate frequency component of the heart rate (the red line in Figure 1) during sleeping as the regression of the trigonometric function (the blue line in Figure 1). From this model, prospective heart rate is predicted from the partially obtained heart rate with the trigonometric function regression of the proposed method, and calculates the sleep stage in real-time from the estimated heart rate (the green line in Figure 1).

Trigonometric function regression model

The proposed method models the intermediate frequency component of the heart rate as follows,

$$h(t,\phi) = c + \sum_{n=1}^{N}\left(a_n \cos\left(\frac{2\pi t}{L/n}\right) + b_n \sin\left(\frac{2\pi t}{L/n}\right)\right), \tag{1}$$

where ϕ is the model parameter $\phi = \{a_i, b_i, c\} (i \in \{1, \cdots, N\})$, $h(t,\phi)$ denotes the estimated heart rate at time t with the model parameter ϕ, L denotes the maximum period of the intermediate frequency component, and N denotes the number of composed trigonometric functions. The model parameters ϕ are provided by the maximum likelihood estimation method that minimizes the following likelihood function;

$$J = \frac{1}{T}\sum_{t=1}^{T}\left(HR\left(t\right) - h\left(t,\phi\right)\right)^2 + \frac{\lambda}{N}\sum_{n=1}^{N}\left(a_n^2 + b_n^2\right), \tag{2}$$

where T denotes the elapsed time after falling asleep, $HR(t)$ denotes the obtained heart rate at time t, while the second term denotes the regularization term.

After calculating the parameters ϕ, the sleep stage is estimated by discretizing the predicted heart rate $h(t,\phi)$ according to the following equation:

$$\begin{aligned} s(t) &= \begin{cases} 5 & \left\lceil \frac{f(t)-ave.}{stdev.} + 2 \right\rceil > 5 \\ 0 & \left\lceil \frac{f(t)-ave.}{stdev.} + 2 \right\rceil < 0 \\ \left\lceil \frac{f(t)-ave.}{stdev} + 2 \right\rceil & otherwise \end{cases} \qquad (3) \\ ave. &= \frac{1}{max(T,L)} \sum_{t=1}^{max(T,L)} f(t) \\ stdev. &= \sqrt{\frac{1}{max(T,L)-1} \sum_{t=1}^{max(T,L)} \left(ave. - f(t)\right)^2} \end{aligned}$$

where $s(t)$ denotes the sleep stage at time t, $\lceil x \rceil$ denotes the ceiling function that returns the minimum integer value

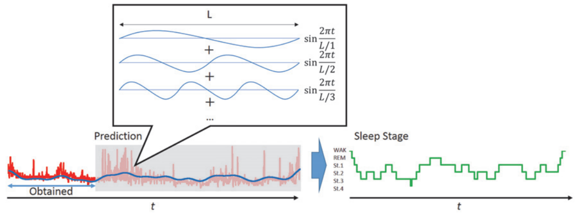


Figure 1: An illustration of the proposed real-time sleep stage estimation

equal to or grater than x, and from 5 to 0 correspond to WAK, REM, St. 1, St. 2, St. 3, and St. 4 respectively. This discretization formula is based on the previous research (Takadama et al. 2010).

To calculate the model parameters that minimize equation (2), the following simultaneous equation has to be solved:

$$\frac{\partial J}{\partial c} = -\frac{2}{T}\sum_{t=1}^{T}\left(HR\left(t\right)-h\left(t,\phi\right)\right)=0 \tag{4}$$

$$\frac{\partial J}{\partial a_i} = -\frac{2}{T}\sum_{t=1}^{T}\cos m_i t\left(HR\left(t\right)-h\left(t,\phi\right)\right)+\frac{2\lambda a_i}{N}=0 \tag{5}$$

$$\frac{\partial J}{\partial b_i} = -\frac{2}{T}\sum_{t=1}^{T}\sin m_i t\left(HR\left(t\right)-h\left(t,\phi\right)\right)+\frac{2\lambda b_i}{N}=0 \tag{6}$$

$$\left(m_i = \frac{2\pi}{L/n}\right).$$

Here we denote

$$P = \begin{pmatrix} c \\ a_1 \\ \vdots \\ a_N \\ b_1 \\ \vdots \\ b_N \end{pmatrix}, \mathbf{a} = \begin{pmatrix} 1 \\ \cos m_1 t \\ \vdots \\ \cos m_N t \\ \sin m_1 t \\ \vdots \\ \sin m_N t \end{pmatrix},$$

$$W = (w_{ij}) = \begin{cases} \frac{\lambda T}{N} & 2 \le i = j \le 2N+1 \\ 0 & otherwise \end{cases},$$

the model parameters are calculated by solving the following equation;

$$P = \left(\sum_{t=1}^{T} \mathbf{a}^{t}\mathbf{a} + W\right)^{-1}\left(\sum_{t=1}^{T} HR(t)\right)\mathbf{a}, \tag{7}$$

where ${}^{t}\mathbf{a}$ indicates transposed matrix of $\mathbf{a}$. This equation can be calculated in real-time by summing up $\cos m_i t$, $\sin m_i t$, $HR(t)\cos m_i t$ and $HR(t)\sin m_i t$ whenever the heart rate is measured, and solving inverse matrix of $(\sum_{t=1}^{T} \mathbf{a}^{t}\mathbf{a}+W)$.

Algorithm

The detailed algorithm of the proposed method is described in Algorithm 1. After detecting falling asleep, the heart rate $HR(t_{now})$ at time t_{now} is measured, and when

Algorithm 1 The flow of the proposed real-time sleep stage estimation

$t_{prev} = 0$
while Sleeping **do**
  $t_n ow = current\ time$
  Measure heart rate $HR(t_{now})$ at time t_{now}
  if $t_{now} - t_{prev} \ge t_{int}$ **then**
    Calculate parameters $\phi = \{a_i, b_i, c\}$ $(i \in \{1, \cdots, N\}$ from equation (7) to minimize J in equation (2)
    Estimate entire heart rate $h(t, \phi)$ from equation (1) according to the calculated parameters for $t = [0, max(T, L)]$
    Estimate sleep stage from equation (3) according to estimated $h(t, \phi)$
    Output current sleep stage from t_{prev} to t_{now}
    $t_{prev} = t_{now}$
  end if
end while

the predefined estimation interval term t_{int} has passed, the model parameter is calculated to minimize equation (2) by solving equation (7). Using these parameters, the prospective heart rate is predicted and the current sleep stage is calculated by discretizing the predicted heart rate according to equation (3). After estimating current sleep stage, these processes are repeated during sleeper awakes.

Experiment

Settings

To investigate the effectiveness of the proposed real-time sleep stage estimation method, we conduct the human subject experiment. Nine male subjects participate in this experiment. Each subject wares Alice PDx as a kind of the electro-encephalograph and his heart rate is measured with the EMFit sensor developed by VTT Technical Research Center of Finland for care support in the 1990's. The EMFit sensor, as shown in Figure 2 is a non-contact biosensor to measure human's heart rate, body movement, respiration of a person on a bed by being laid under a bed mattress, which are measured every one second.

Two types of the maximum period of the intermediate frequency component L are compared, $L = 2^{14}[sec] \approx 4.5[hour]$ and $L = 2^{13}[sec] \approx 2.25[hour]$. The number of model parameters N is set as 13 for $L = 2^{14}$ and 7 for $L = 2^{13}$. This is because these settings make the mini-

Figure 2: The EMFit sensor being laid under a bed mattress (the blue one in this image).

mum period of the intermediate frequency component approximate $22[min]$, which is the minimum periods used in the Watanabe's method. The parameter λ of the regularization term is set as one. The estimation interval term t_{int} is set as one minute, which means the sleep stage is estimated every one minute during sleeping.

Evaluation criteria

The estimation accuracy of the proposed real-time sleep stage is measured by comparing its estimated sleep stage with one of PSG (Polysomnography), which is the standard method of calculating the sleep stage by medical specialists using data of humans obtained by Alice PDx. This approach is based on the R&K method (Kales and Rechtschaffen 1968) as described in the previous section and can measure the sleep stage with high accuracy.

The estimation accuracy of the proposed method is compared with that of the Watanabe's method, which estimates the sleep stage by using all data of the heart rate during sleep, unlike the proposed method uses partial data. Since it is important for the proposed method to estimate the approximate sleep stage, we evaluate the estimation accuracy that allows difference of one sleep stage (*e.g.*, difference of St. 1 and St. 2). The sleep stage is estimated from falling asleep till sleeper awakes, which is determined from the measured sleep stage by PSG.

Result

Figure 3 shows the estimation accuracy of each method. The horizontal axis indicates each subject, while the vertical axis indicates the estimation accuracy that allows difference of one sleep stage. The dark gray bars indicate the result of the Watanabe's method, the light gray bars indicate the result of the proposed method with $L = 2^{13}$, while the white bars indicate that of the proposed method with $L = 2^{14}$. The rightmost group in this figure indicates the average accuracy of all subjects and the error bars indicate their standard deviations.

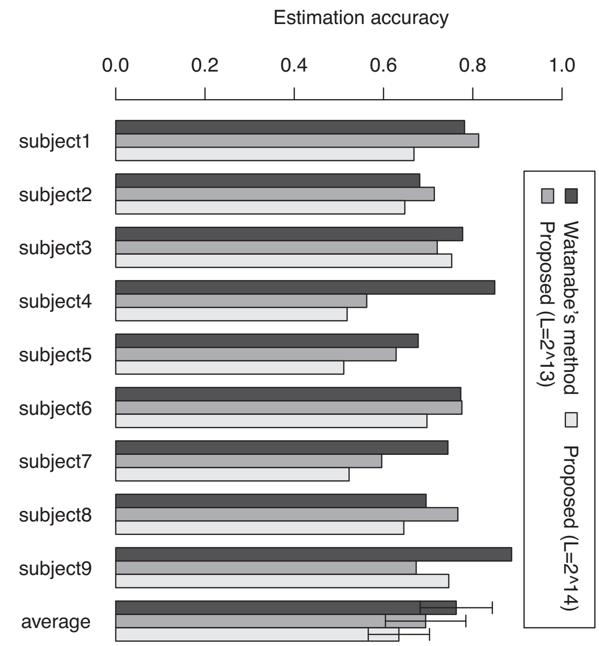


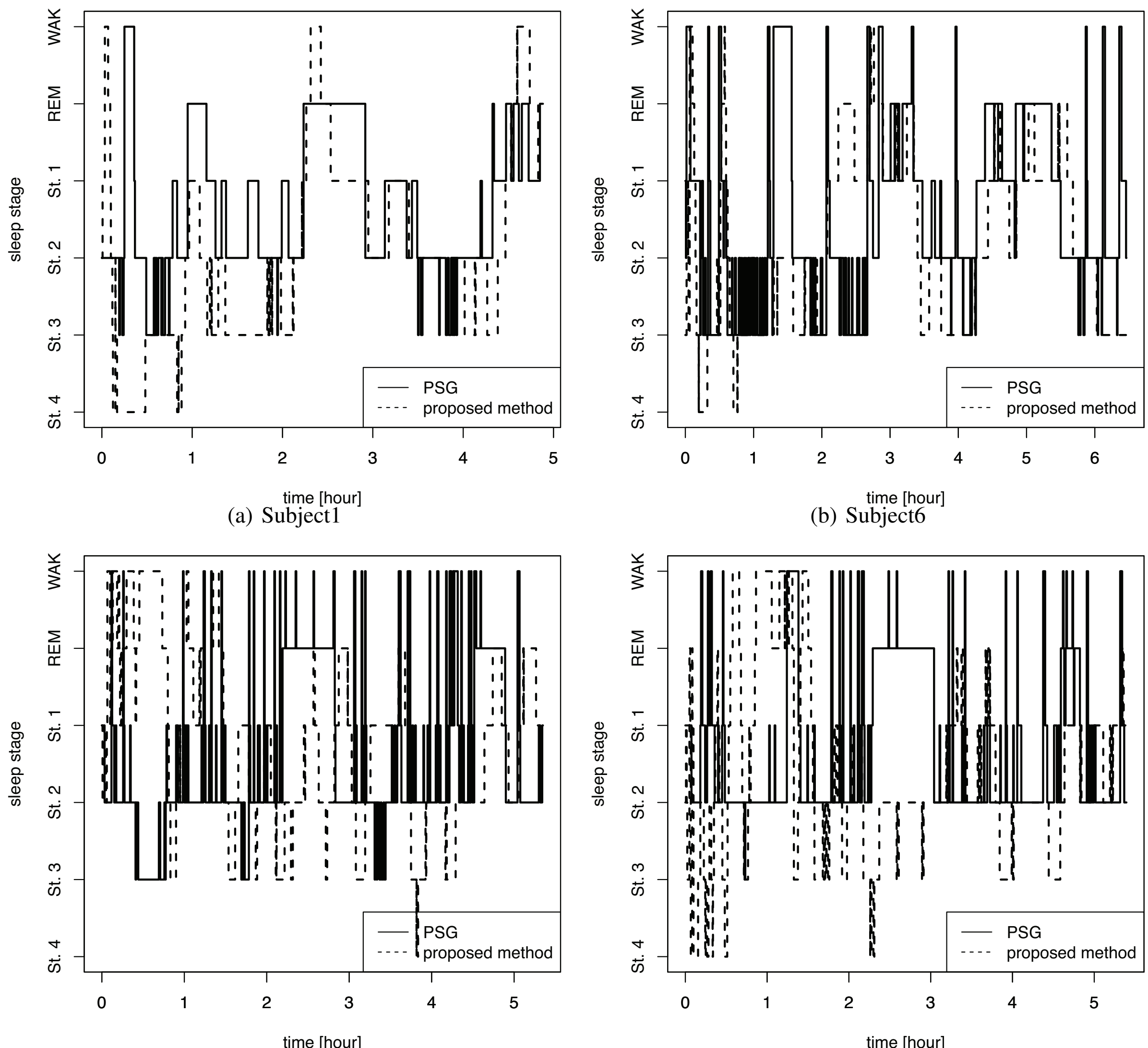
Figure 3: The estimation accuracy of each method

Figure 3 shows that the proposed method with $L = 2^{13}$ averagely outperforms that with $L = 2^{14}$, in particular, it performs higher accuracy in 7 out of 9 subjects. In comparison with the Watanabe's method and the proposed method with $L = 2^{13}$, although the proposed method is not averagely better than the Watanabe's method, its estimation accuracy is close to that of the Watanabe's method. In fact, in some subjects the proposed method outperforms the Watanabe's method, and significant difference between them is not found by the paired t-test with the significant level $\alpha = 0.05$. What should be noted here is that even though the proposed method estimates the sleep stage from the *partially* observed heart rate in real-time, it has the equivalent estimation capability with the Watanabe's method, which estimates the sleep stage from *all* observed heart rate after sleeping.

From this result, it is revealed that the proposed method enables to estimate the sleep stage in real-time, in particular the proposed method can estimate the sleep stage immediately after falling sleep nevertheless much heart rate are not obtained.

Discussion

Figure 4 shows the fluctuation of the sleep stage measured by PSG and that estimated by the proposed method with $L = 2^{13}$. The horizontal axis shows elapsed time after falling asleep, while the vertical axis shows the sleep stage and each scale indicates WAK, REM, St. 1, St. 2, St. 3 and St. 4 from the top to the bottom respectively. The solid line indicates the sleep stage measured by PSG, while the dashed line indicates the sleep stage estimated by the proposed method. Figures 4(a) and 4(b) are chosen from the subjects 1 and 6 who have the best two estimation accuracy, while Figures 4(c) and 4(d) are chosen from the subjects 4



(a) Subject1 (b) Subject6

(c) Subject4 (d) Subject7

Figure 4: The sleep stage with PSG and the proposed method. Top two figures shows the best two estimation accuracy, while the bottom two figures shows the worst two estimation accuracy.

and 7 who have the worst two estimation accuracy.

In Figures 4(a) and 4(b), it is indicated that the estimated sleep stage of the proposed method approximately follows the one measured by PSG. On the other hand, if the subject frequently awakes, i.e., WAK frequently appears, it is hard for the proposed method to follow such rapid change of the sleep stage. This causes to decrease the estimation accuracy of the subjects 4 and 7. From these results, it is revealed that although the proposed method does not follow the rapid change of the sleep stage, the proposed method approximately follows the correct sleep stage in real-time.

Conclusion

This paper proposes a novel method to estimate the sleep stage in real-time from partially obtained heart rate with a non-contact device during sleeping. The proposed method constructs the trigonometric function regression model from the partially obtained heart rate and estimates the sleep stage depending on the predicted intermediate frequency component of the prospective heart rate. The model can be calculated in real-time by summing up the heart rate whenever it is measured.

To investigate the effectiveness of the proposed method, we conduct the subject experiment. We compare the sleep stage measured by PSG (Polysomnography) with the sleep stage estimated by the proposed method and the Watanabe's method. The experimental result revealed that the proposed method achieves the equivalent estimation accuracy as the Watanabe's method even though the proposed method estimates the sleep stage by using the partially obtained heart rate unlike the Watanabe's method uses the entire heart rate.

What should be noted here is that further improvement of the proposed method is needed to apply this method to the real world applications. This improvement has to be pursued in the near future in addition to the following tasks: (1) A verification of the proposed method with more human subjects; and (2) an implementation of the real-time sleep stage estimation system.

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