Verification of Sleep/Wake Detection Algorithms for Kindergarten Support System Based on Activity Recognition

Sounosuke HIKOSAKA *, Shuhei KURASHIMA *, and Satoshi SUZUKI *

Abstract: Practical application of a human monitoring system draws increasing attention with the high developments of information & communication technology and robot technology. Utilizing these technologies, a kindergarten support system for children, parents, and childminders using the activity recognition (AR) has been studied in author’s previous studies. In this paper, several wake/sleep identification algorithms for infants as an additional AR were verified by using orthodox algorithms that were used for adults. Investigating combinations of sensor position to infant’s body (arm or leg), sampling frequency (5 Hz to 50 Hz), threshold for acceleration detection (0.1 m/s² to 0.9 m/s²), and types of wake/sleep detection algorithms (count-scaled, Cole, Sadeh, and zero-threshold algorithms), it was confirmed that the count-scaled algorithm could obtain highest identification accuracy as high as 89.0% under adequate measurement condition.

Key Words: sleep detection, wake detection, human monitoring, infant, activity recognition.

1. Introduction

Lifestyle diseases such as diabetes, stroke, hypertension, and obesity, became social problem; hence, people take a lot of interests in health care of their daily life. Generally, getting appropriate exercise, having appropriate meals, and sleep can help us for prevention of these diseases. In order to objectively know the amount of exercise and the sleep rhythm, several health care products have been developed such as JAWBONE (JawBone Co., Japan), Sleepmeter/SleepDesign (OMRON Co., Japan), and JINS MEME (JIN Co., Japan). Main users of these products are, however, adults or aged persons, not children. Although similar types of monitoring systems have been developed for children, They are so-called of surveillance system for elementary school students, and there is few health care systems for children. Rather for children, the health monitoring is more required than for adults because it is quite difficult for child to manage own health and it depends on mostly his/her parent’s lifestyle. Such undesirable circumstance is severe in Japan; for instance, only 1.3 percent Japanese young children (0-3 years old) can go to bed till seven p.m. while 36 percent German children can do. Further there is no difference in their wake-up time between Japanese and German children [1], that is, Japanese children cannot get enough sleep. It is well known that a lack of sleep not only decreases motivation for learning but also has a significant negative impact on their physical and mental developments [2]. Therefore, proper management of sleep for young children is quite important.

With above-mentioned background, a concept of KinderGuardian (KGR) was proposed in author’s previous study [3],[4]. In the KGR system, activity recognition (AR) technique is used to estimate status of child’s activities to check his/her health and growth. That AR method utilized for 3-5 years old children, however, was not sufficiently useful for infants since they spend almost time by sleeping in bed. Therefore an alternative method to check status of infant’s health is required.

On the other hand, several algorithms of sleep/wake detection using an acceleration sensor have been presented by Cole [5], Sadeh [6], and Marschollek [7]. These methods are, however, for adults (20-88 years-old), and a pendulum mass acceleration sensor is used for them. From point of view of AR in the KGR system, it is desirable to use same three axis digital sensor for the sleep/wake detection, and a threshold of acceleration count has to be adequately selected for better sleep/wake detection. Moreover, an attachment position of the sensor to child’s body in the KGR system differs from other case for orthodox sleep monitoring studies by same reason which will be described in Section 2.1. In addition, low sampling rate in the acceleration measurement is desirable to save memory capacity of the data logger for long time measurement. Thus, summarizing these conditions and constraints, the following points have to be clarified:

P1. Can sleep/wake detection using arm’s acceleration work as well as orthodox methods that use leg’s acceleration? And which algorithms can obtain best accuracy for sleep/wake detection?

P2. How much lower can sampling rate be decreased by keeping enough identification accuracy?

P3. Can similar good sleep/wake detection result be obtained in case of infants by considering above-mentioned two items?

The points are also contribution of this paper.

An organization of the paper is the followings: Section 2 introduces the KGR concept and its AR briefly. In Section 3, four algorithms to detect sleep/wake status are explained. Section 4 shows results of analyses and gives comprehensive discussions. Last Section 5 is a conclusion.

* Department of Robotics and Mechatronics, School of Science and Technology for Future Life, Tokyo Denki University, Tokyo, Japan
E-mail: hikosakas@mail.suzulab.fr.dendai.ac.jp
(Received September 20, 2014)
(Revised November 24, 2014)
2. Concept of Kinder-GuaRdian

2.1 System Overview

A kindergarten support system for children, parents, and childminders has been studied in author’s previous study [3], as shown in Fig. 1, and the concept or its system structure was named Kinder-GuaRdian. The minimum system consists of a sensor node attached to child (angel bands) and a child-care data analyzer (guardian management system).

Fig. 1 Overview of Kinder-GuaRdian system.

Angel bands is assumed to be equipped with an acceleration sensor, an electromyogram (EMG) sensor, a RFID tag, and microphone. Building a sensor network using multiple angel band devices, signals to estimate each child’s behavior and emotional change are measured. All measured data are stored in guardian management system, and status of each children’s health, mental, and social status are analyzed from the data. Unlike other existing AR studies, targets of this AR are young children from infants to six years old, and only one sensor device for the AR is attached to his/her upper arm, because a part of electencephalogram signals to estimate his/her emotion can be detected from the EMG signal at the upper arm [8]. This is the reason that a sleep/wake detection method using one device at the upper arm is required.

2.2 AR in KGR and Sensor Device

In the KGR system, activities of each child are identified using the data clustering technique after computing several features from acceleration data. In author’s previous study [4], it was shown that six types of child activities (sleeping, walking, running, hand motion, playing, and sitting) could be classified adequately using a two-step classification by combining several types of classifiers. Through the experiment and studies, a three-axis acceleration logger MSR145 (MSR Electronics Co., Switzerland. size: 20 mm × 15 mm × 52 mm, mass: 16 g) was used. In this study, same acceleration logger was used for investigation of sleep/wake detection for infants. The acceleration sensor unit in this device is a digital acceleration sensor and it differs from an orthodox sleep/wake sensor which utilizes a pendulum mass acceleration sensor. This is another different point from the existing studies concerning sleep/wake applications.

3. Identification of Sleep/Wake Status

3.1 Sensor Position to Child’s Body

In general, the more sensor devices are attached to the body, the better identification result is obtained; however, it will be troublesome for childminders to attach sensors to many children. Therefore, it is desired that only one sensor device is attached to child’s body, and moreover it is preferred that sleep/wake detection works well when the sensor was attached to the upper arm as explained in Section 2.1. Barbara’s study has a similar idea with us and he showed that leg was best position to obtain good identification accuracy [9]. Since in case of our child AR the measurement at upper arm is preferable, acceleration of both arm and leg were measured and investigated in order to investing we the differences in our experiment.

3.2 Algorithms to Detect Sleep/Wake Status

Sleep/wake detection was compared using the following four algorithms. Although sleep/wake status are computed from binary information in these algorithms, information obtained by our experiment is acceleration signal because of difference of sensor. Thus, for these algorithms, binary information converted from the accelerate signal using some threshold is required. This binary information is called “acceleration counter” simply, and it is computed as follows:

\[ C[i] = \begin{cases} 1 & (S'[i] \geq \zeta) \\ 0 & (S'[i] < \zeta) \end{cases} \]

where \( C \) is the acceleration count, \( i \) is an index counter per sampling rate, and \( S' \) is a difference between some current data and the previous data. Here \( \zeta \) is a threshold.

3.2.1 Count-scaled algorithm

In this algorithm, the number of counts accumulated by comparing measured acceleration value with a pre-determined threshold. Next after the total counts are divided by average of the non-zero element in order to eliminate zero value, the sleep/wake status is discriminated by checking whether the weighted accumulated count is larger than one. The accumulated count \( C_a \) is computed as

\[
C_a[s] = 2.7(C_s[s - 4] + 2C_s[s - 3] + 3C_s[s - 2] + 4C_s[s - 1]) + 5C_s[s] + 3C_s[s + 1] + C_s[s + 2])
\]

\[
C_s[s] := \frac{C}{M}
\]

where \( s (= 1, 2, \cdots) \) is a counter index per fifteen seconds [9], \( C \) is a sum of counts for the case that the acceleration value is larger than the pre-determined threshold, and \( M \) is an average of the counts eliminated with non-zero elements during each fifteen seconds interval. Coefficients in Eq. (2) are determined by experimentally in [9]. Finally the sleep status is determined when \( C_a[n] < 1 \) is satisfied.

3.2.2 Cole algorithm

As the former case of the count-scaled algorithm, this cole algorithm computes a weighted sum of counted value similarly. This algorithm uses the counter value accumulated in every minute. The states of sleep value \( S_C \) is computed using total seven counters from past four minutes to future two minutes as follows [3]:

\[
S_C := \sum_{n}^{7} C_a[n] / 7
\]


\begin{equation}
S_C = 0.0033(1.06 \cdot a[m - 4] + 0.54 \cdot a[m - 3] \\
+ 0.58 \cdot a[m - 2] + 0.76 \cdot a[m - 1] \\
+ 2.3 \cdot a[m] + 0.74 \cdot a[m + 1] \\
+ 0.67 \cdot a[m + 2]),
\end{equation}

where \( m (= 1, 2, \cdots) \) is a counter index per minutes, \( a[m - 4] \) means a sum of counts in the past four minutes and others are in same manners. Similarly, the sleep status is determined when \( S_C < 1 \) is satisfied.

3.2.3 Sadeh algorithm

Sadeh algorithm utilizes standard deviation of counter values in past five and future five minutes intervals, respectively, \( S_a \) and \( C_i \) give by Eq. (1).

\begin{equation}
PS_t = 7.601 - 0.065 \cdot \sigma_w - 1.08 \cdot S_a \\
- 0.056 \cdot \sigma_c - 0.073 \cdot A,
\end{equation}

where \( \sigma_w \) and \( \sigma_c \) are standard deviation of acceleration data in past five and future five minutes intervals, respectively, \( S_a \) is a sum of acceleration counts for total 11 minutes, and \( A \) is a sum of counts during future one minute. Finally the sleep status is determined when \( PS_t < 0 \) is satisfied. As shown above, Sadeh algorithm identifies the current sleep/wake status by considering not only past but also future data; hence, it is expected that this method is robust to disturbance for case that infant is moved exogenously by other person.

3.2.4 Zero-threshold algorithm

By this algorithm, after accumulating the count by comparing the measured acceleration counts with the threshold, the sleep/wake status is distinguished as follows:

\[
Z = \begin{cases} 
\text{wake} & (C' > 1) \\
\text{sleep} & (C' = 0) 
\end{cases}
\]

where \( C' = \sum_{t=n}^{n+14} C[t] \), and \( C \) is given by Eq. (1), \( t (= 1, 2, \cdots) \) is a counter index per one second.

4. Measurement and Analysis

4.1 Experimental Scene and Methods

Figure 2 shows an experimental circumstance of measurement when infants are napping. During the experiment, infant’s movement was recorded using a video camera by synchronizing with the acceleration sensor measurement. And Fig. 3 shows sensor position of infant’s body (arm or leg). The scene of the nap was recorded for 90 minutes to each infant participant. Participants were eight infants and they were two boys and six girls (2-17 months old). The experiment was approved by the university’s ethics committee and both parents of their infants and childminders gave informed consent before the experiment.

In this study, their wake-up status was judged when the infant’s eyes were open or he/she pushed oneself up by an expert experimenter who watched the recorded video and had gained enough experience on observing infant’s nap. One example of the measured data and identification results are shown in Fig. 4. Figure 4(a) show the raw data. In Fig. 4(b), estimated two statuses, that are wake-up and sleep, are plotted by high or low binary value, respectively, the right axis shows true sleep/wake status on, and the left axis shows the others distinguished by algorithms. The figure shows that correct status and adequate timing can be discriminated by the algorithm.

4.2 Verification of Identification Results

Identification accuracies \( \alpha \) of each algorithm under various parameter settings were investigated through computing ratio of normal detection of sleep status against true sleep circumstances by

\[
\alpha = \frac{N_p}{N},
\]

where \( N_p \) is the total number of counts which are estimated as sleep by each algorithm, and \( N \) is the total counts of all data. \( N \) became about 270,000 when the sampling frequency was specified as 50 Hz.

Figure 5 summarizes identification accuracies \( \alpha \) for each algorithm in cases of the arm and leg sensor conditions. Statistical test (wilcoxon rank sum test) found significant differences between the count-scaled and Sadeh algorithm and between the count-scaled and zero-threshold algorithm (\( p < 0.05 \)), as shown in the figure. Although statistical significance was not
and it is found that accuracy of sleep frequencies are approximately over than 85.0% when thresholds are changed. It is found that accuracy of all arm is similar to in case of leg.

Concerning detection algorithms, the following four types were investigated: the count-scaled algorithm, Cole algorithm, Sadeh algorithm, and zero-threshold algorithm.

As a result, it was found that there is no significant difference \((p < 0.05, N = 2,400)\) in sensor positions between arm and leg among four algorithms, that is, measurement of arm's acceleration is also effective to estimate infant's sleep/wake detection. Concerning the sampling rate condition, best identification accuracy as high as 89.0% could be obtained when the sampling rate was 50 Hz with acceleration threshold 0.2 [m/s²]; however, almost same good result (88.7%) could be obtained under 10 Hz sampling rate with threshold 0.4. Further to know the best algorithm, a wilcoxon rank sum test against an average of identification results computed by those four algorithms was performed, and it was confirmed that count-scaled algorithm is significantly better than both Sadeh algorithm and zero-threshold algorithm \((p < 0.05, N = 2,400)\). To sum up with these results, it was concluded that the count-scaled algorithm could obtain highest identification accuracy from the arm's acceleration, and that sampling rate can be decreased to almost 10 Hz by adjusting the acceleration threshold.

Generally in medical science like American Academy of Sleep Medicine, the gold standard test to distinguish sleep status is polysomnography (PSG) which has to measure various bio signals such as electromyogram of the brain, the eyeball movement, mandible, breaths, and electrocardiograms. The present authors would like to compare our approach with the above-mentioned approach in future work.

**5. Conclusion**

In order to enhance a kindergarten support system for children, parents, and childminders using the activity recognition (AR) technique, an additional AR algorithm for infant’s sleep was verified by modifying the existing nap detection algorithms, which use a pendulum mass acceleration sensor, for our AR scheme using a three axis acceleration sensor. Specifically the identification accuracies of the infant’s sleep were investigated by changing the combination of the following conditions: sensor position to infant’s body, sampling frequency, threshold of acceleration detection, and types of sleep/wake detection algorithms. Concerning detection algorithms, the following four types were investigated: the count-scaled algorithm, Cole algorithm, Sadeh algorithm, and zero-threshold algorithm.

Many infants, their parents, and childminders with Benesse Hiyoshi kindergarten cooperated with this experiment. The authors would like to appreciate their kind cooperation.

**Acknowledgments**

Many infants, their parents, and childminders with Benesse Hiyoshi kindergarten cooperated with this experiment. The authors would like to appreciate their kind cooperation.

**References**


---

**Sounosuke Hikosaka**

He is B.S. with Department of Robotics and Mechatronics, School of Science and Technology for Future Life, Tokyo Denki University. His research interests are activity recognition and human monitoring.

---

**Shuhei Kurashima**

He is B.S. with Department of Robotics and Mechatronics, School of Science and Technology for Future Life, Tokyo Denki University. He interests in the data clustering and health care system design.

---

**Satoshi Suzuki (Member)**

He received his B.S. degree in Control Engineering, M.S. degree in Department of Systems Science, and Ph.D. in Department of Mechanical and Control Engineering from Tokyo Institute of Technology in 1993, 1995, and 2004, respectively. He is now an associate professor in Department of Robotics and Mechatronics with Tokyo Denki University. His major research interests are human-machine system, control theory and robotics. He is a member of IEEE, IEEJ (Institute of Electrical Engineers of Japan), Society for Serviceology, SICE, and RSJ (Robotics Society of Japan).