Estimation of Sleep Posture using a Patch-type Accelerometer based Device

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***Abstract*—In this study, we developed a sleep posture estimation algorithm using 3-axis accelerometer signals measured from a patch-type sensor. Firstly, we inspected the characteristics of accelerometer signals for different sleep postures. Based on the results, we established decision rules to estimate 5 postures containing supine, left, right lateral, prone postures, and non-sleep postures such as sitting and standing. The algorithm was tested by the data from thirteen subjects during night time PSG. As a result, the algorithm estimated sleep postures with an average agreement of 99.16%, and cohen's kappa of 0.98 compared with reference sleep postures determined by position sensor and video recording. The proposed method with the device could be used as supportive purpose in routine PSG study and out-of-hospital environment.**

I. INTRODUCTION

Sleep plays an important role in human life, allowing us to recover from physical and mental fatigue, grow based on hormone secretion, and consolidate memories [1]-[3]. Sleep is highly related to daily life that is, inadequate sleep causes excessive daytime sleepiness, degrades cognitive function, and increases unintended injuries [4]-[6]. Various factors influence on the insufficient sleep such as sleep environment, psychophysiological state, and sleep-related disorders.

Obstructive sleep apnea syndrome (OSAS) that is characterized by complete or partial blocking of upper airway during sleep is one of major sleep-related disorders which causes sleep disturbance. Although patients with OSA have higher potential of developing cardiovascular diseases, almost 85% of the patients are not diagnosed [7], and even approximately 1-3% of children suffers from OSA [8]. Many studies reported that changing sleep posture can reduce the severity of OSA. Lee *et al.* showed that sleeping with lateral posture alleviates the disorder for patients with mild and moderate OSA [9]. Additionally, Oksenberg *et al.* researched the relationship between sleep postures and sleep-related breathing disorders, and discovered that supine posture increases detrimental effects on breathing. Moreover, apnea-hypopnea index (AHI) was more than 50% higher in supine posture than in lateral posture. Finally, they concluded that postural change is a simple therapy for the majority of patients suffering from OSA [10].

Monitoring sleep posture is also necessary to prevent immobile patients and the elderly from pressure ulcers. Pressure ulcers are localized injuries to the skin, developed over a bony prominence caused by long-term pressure and lowered blood circulation [15]. It is necessary to change patient's posture regularly to prevent pressure sores, because it is less harmful and expensive than treating after they have been progressed far enough [11]. In fact, the cost of treating bed sores in the United States was estimated at $11 billion in 2006 [12].

Thus, it is important to monitor patients' sleep posture for both clinical and patient caring aspects. Many researches applied various approaches to detect sleep posture. Yousefi *et al.* developed an image-based algorithm to estimate sleep posture based on pressure mapping system [13]. However, it uses 2,048 sensors to cover whole bed, therefore high processing rate is unavoidable. Moreover, because the system should be set on the bed, it requires time and cost to setup the system when patients are moved to another place where the system is not installed. Shinar *et al.* introduced the algorithm which detects sleep posture characterized by morphological differences in QRS complex of the Lead I, II, and III electrocardiogram [14]. The limitation of this study is that this method is applicable only when ECG is clearly measured and QRS complex is accurately detected. Other study proposed an algorithm using 3-axis accelerometer signals to estimate sleep posture [16]. They developed a belt-type system equipped with ECG and accelerometer circuits which enables to measure patients' heartbeats and body movements. Based on the 3-axis accelerometer signals, they proposed the algorithm that detects four different sleep postures. However, the belt-type sensor could be shifted to inappropriate position with patients' movements.

In this study, we proposed a sleep posture estimation algorithm using accelerometer signal measured from a patch-type sensor. We used the device which was developed to analyze daytime autonomic nervous system based on heart

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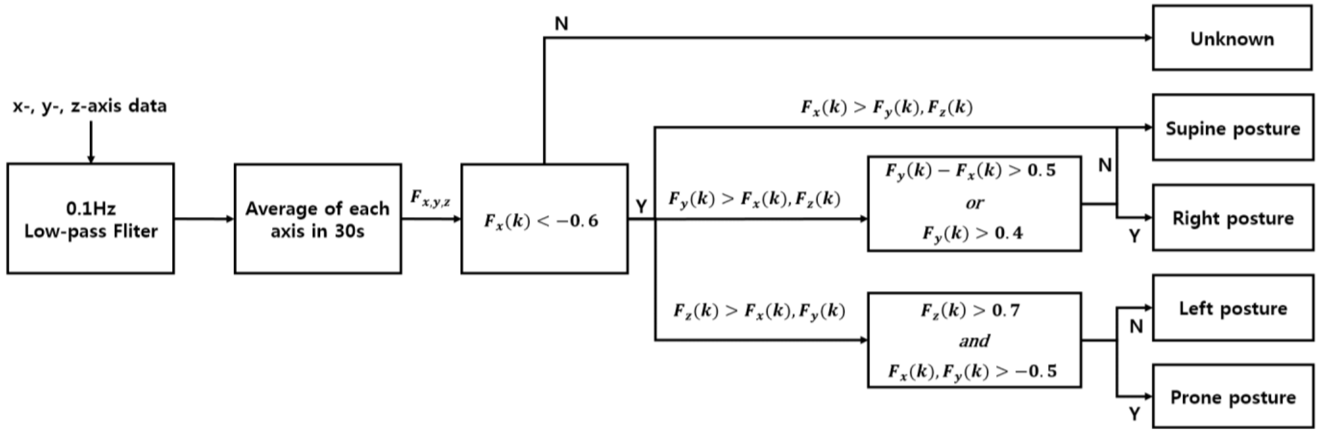

Fig. 1. Flowchart for estimating sleep posture epoch.

rate and activity based on accelerometer signal. It has embedded ECG measuring circuit and 3-axis accelerometer. The device continuously operates up to 2 days. Using the measured accelerometer signal, the algorithm discriminated five postures, supine, prone, left, and right lateral sleep postures, and unknown postures which are not classified to sleep postures such as sitting and standing.

II. Materials and Methods

A. Study Subjects

Thirteen subjects (4 males and 9 females) aged 46.4±9.6 years participated in this study. Table I presents the demographic and sleep data. All participants spent around 8 hours for the PSG recording and were shown 408.2 minutes of average total sleep time and 85.6% of sleep efficiency. For all sleep postures, the supine posture occupied the highest portion (68.5%) of all in our recordings, whereas there was no prone posture during the whole recordings for all subjects. Portion of unknown postures which are not classified to the four representative postures, such as sitting and standing was 0.12%.

The study was approved by the Institutional Review Board of Seoul National University Hospital (No. H-1405-124-582) and signed informed consent was obtained from each subjects prior to study participation.

TABLE I
Demographic and Sleep Data for the Subjects

	Statistical values (N=13, Male: 4)
Age (years)	46.4±9.6
BMI (kg/ m^2)	25.7±3.4
Total sleep time (min)	408.2±37.6
Sleep efficiency (%)	85.6±7.2
Supine posture (%)	68.5±24.3
Left lateral posture (%)	17.1±14.4
Right lateral posture (%)	14.2±14.0
Prone posture (%)	-
Unknown posture (%)	0.12±0.4

B. Data recording

All the subjects visited Center of Sleep and Chronobiology at Seoul National University Hospital, and underwent a full-night PSG recording. According to protocol of American Academy of Sleep Medicine (AASM), electroencephalogram, electrocardiogram, electrooculogram, abdominal and chest movement, nasal-oral airflow, oxygen saturation, anterior tibialis and submental electromyogram, and body position were acquired using Neuvo (Compumedics, Melbourne, Australia). The following morning, PSG data including sleep posture were manually scored by polysomnography technician who has more than 10-year experience. Sleep posture was firstly scored by output of body position sensor, and corrected based on video recording which was simultaneously acquired with PSG. Most frequent sleep posture in 30 s (1 epoch) was selected as a representative sleep posture for each epoch and scored as supine, right and left lateral, prone posture and unknown which is not classified in sleep posture such as sitting and standing.

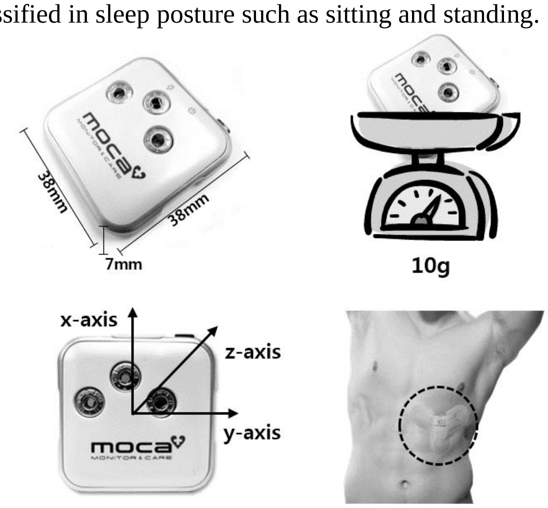

Fig. 2. A design specification of T-REX, and attached position of the device

Fig. 2 shows T-REX (Taewoong Medical, Gyeonggi do, Korea) which has embedded 3-axis accelerometer sensor. After the preparation of PSG recording, the subject attached the device on the left side of chest (see Fig. 2) to measure accelerometer signal during sleep, simultaneously with the PSG. After finishing the recording, the device was removed and the data recorded in the memory card were sent to the laboratory to evaluate our proposed sleep posture estimation algorithm described in the following section.

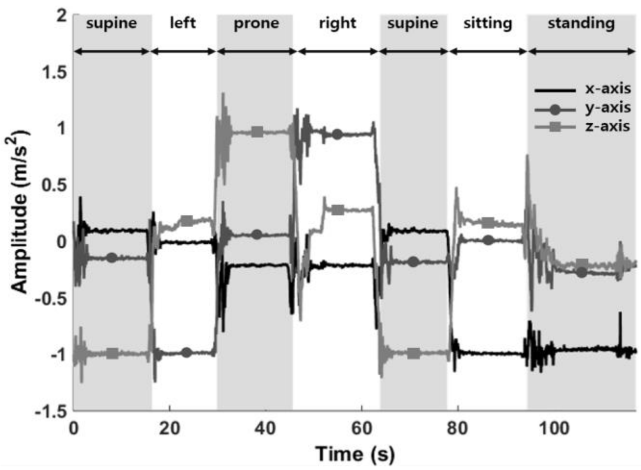

Fig. 3. Accelerometer signals during postural changes.

C. Sleep posture estimation

To develop an algorithm to estimate sleep posture, we firstly acquired the accelerometer signals from the device when people change their postures. Left side of patch-type electrode was located on the center of anticardium for all subjects to control the position of the device. Fig. 3 shows 3-axis accelerometer signals matched with the different sleep postures. Because postural change causes rotation of the device, each posture is corresponded with specific order of amplitude in each axis of the accelerometer. Based on the experimental results, we designed procedures to estimate sleep posture depicted in Fig. 1. Firstly, 0.1Hz low-pass filter was applied to eliminate undesired sources which were reflected on the recording of accelerometer signal such as respiration and snoring. Then, features, *Fx*, *Fy*, and *Fz* which are the average values of each axis data in non-overlapped 30 s sliding window were calculated. Finally, decision rules were applied to the extracted features to classify four sleep postures and non-sleep posture which was scored as unknown epoch. If the device receives the force in the downward direction, the value of *Fx(k)* is near "-1". Thus, we applied threshold "-0.6" to decide whether the epoch is sleep or non-sleep segment. If the value of *Fx(k)* is below "-0.6", the segment is classified as unknown epoch. Next, we compared the features to find the largest value in the segment. If *Fx(k)* is larger than *Fy(k)* and *Fz(k)*, the k-th epoch was classified as supine posture. Right posture was considered when *Fy(k)* is the largest compared to *Fx(k)* and *Fz(k)*. However, only the case when sub-condition 1 (see (1)) is simultaneously satisfied was classified as right posture, and the other case was regarded as supine posture. Similar as right posture detection, prone posture was found when *Fz(k)* is the larger than *Fx(k)* and *Fy(k)* at the same time satisfying sub-condition 2 (see (2)). Even when *Fz(k)* was the largest, the epoch was considered as left lateral posture, if sub-condition 2 was not satisfied.

The algorithm was established based on the data from the pilot study which people changed their postures on the bed set in the laboratory, and evaluated using the data recorded during PSG. Statistical analyses were performed between reference sleep posture from PSG and estimated sleep posture based on the proposed algorithm. The cohen's kappa and agreement were used for the evaluation of performance.

Sub-condition 1:

$$Fy(k) > 0.4 \ \ or \ \ Fy(k) - Fx(k) > 0.5 \tag{1}$$

Sub-condition 2:

$$Fz(k) > 0.7 \ \ and \ \ Fx(k),\, Fy(k) > -0.5 \tag{2}$$

III. Results

Table II presents 5-by-5 states matrix of sleep postures determined by reference epoch-by-epoch sleep posture and the proposed algorithm. Overall cohen's kappa and agreement of the automatic estimation of the five sleep postures were 0.98 (95% CI: 0.979-0.986) and 99.16±0.95%, respectively. For each sleep posture, supine posture showed the highest portion followed by left lateral, right lateral and the unknown state. There was no state of prone posture in our study. Fig. 4 depicts an example of epoch-by-epoch sleep postural estimation result. Pattern of the extracted features is highly correlated with the changes in sleep postures (Fig. 4 (a)). Fig. 4 (b) shows epoch-by-epoch reference sleep posture manually scored by PSG with simultaneous video recording and estimated sleep posture automatically scored by the proposed algorithm.

TABLE II
A CONFUSION MATRIX OF SLEEP POSTURES DETECTED BY REFERENCE AND THE PROPOSED ALGORITHM

Estimated	Reference				
	Unknown	Left	Supine	Right	Prone
Unknown	23	2	2	0	0
Left	0	2086	37	0	0
Supine	0	42	8436	18	0
Right	0	0	4	1751	0
Prone	0	0	0	0	0

IV. Discussion and Conclusion

We established the sleep posture estimation algorithm using the accelerometer signal from the patch-type device. Based on the features which were briefly extracted from the 3-axis accelerometer signals, several decision rules were applied to estimate 5-level sleep postures. As a result, overall kappa value and agreement of the proposed algorithm were 0.98 and 99.16%, respectively.

Table III shows a comparison between the sleep postural estimation results from the proposed method and those from previous studies. Yousefi *et al.* suggested the image-based processing algorithm to classify 5 sleep postures based on pressure mapping system and showed 97.7% of average agreement [13]. And another study based on the pressure sensor showed 83% of agreement for 6-level sleep postures

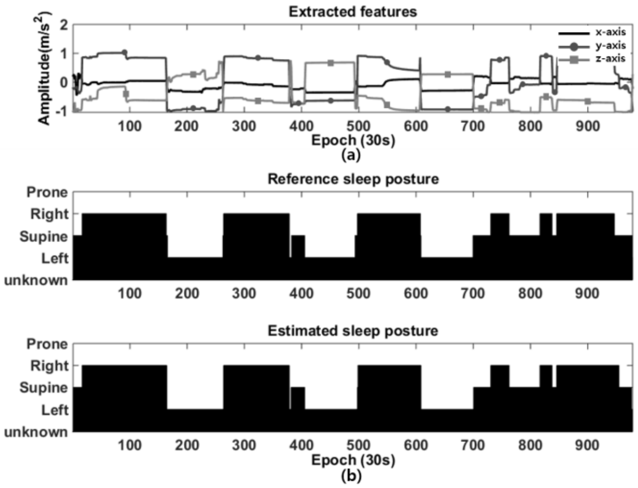

Fig. 4. Extracted features from 3-axis accelerometer signals (a), and reference and estimated sleep postures (b).

containing right and left yearner, left and right foetus, log, and supine. Shinar *et al.* proposed the ECG based sleep posture estimation algorithm. It focused on morphological differences in QRS complex with changes in sleep postures. As a result, this method achieved 91% of positive predictive value for detecting 4 level sleep postures [15]. Recently, Lee *et al.* estimated body posture when subjects were on bed with capacitively measured ECG, and provided 98.4% of agreement for supine, left and right lateral, and prone posture.

TABLE III
DETECTION PERFORMANCES OF RELATED WORKS

Method	# of postures	N	Agreement (%)
Pressure sensor [15]	6	8	83.0(PPV)
Pressure sensor [13]	5	6	97.7
ECG [14]	4	12	91.0(PPV)
Capacitive ECG [17]	4	13	98.4
This study (accelerometer)	5	13	99.2

Comparing with the previous methods, our algorithm showed higher performance for estimating sleep posture. Because the device was tightly attached on the left side of subject's chest, it was appropriate to acquire more accurate signals reflecting the changes of postures. Because the device does not detach by itself, once attached, it could be used to support in routine PSG study, since generally applied body positon sensor has possibility of being rotated with unexpected situations. Additionally, the device which operates up to 2 days has possibility to monitor not only sleep posture but also sleep related events including sleep/wake cycle, and even activities in daily life.

This study also has several limitations. First, there was no case of prone posture during sleep to evaluate the performance of the algorithm detecting prone posture. Second, the cohort size was not large enough, even though epoch-by-epoch based comparison was conducted for more than 10,000 samples. Thus, it is required to test the algorithm on large population.

Although there are several limitations, our suggested algorithm based on 3-axis accelerometer signals is capable of estimating sleep posture. It could be applied to PSG and other clinical purpose as a supportive use, and further to home-based healthcare environment.

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