J. Biomed. Eng. Res.
Vol. 25, No. 1, 5-10, 2004

Evaluation of Body Movement during Sleep with a Thermopile, Wavelets and Neuro-fuzzy Reasoning

Youngro Yoon[1], Jaewoo Shin[2], Hyunsook Lee[3], Jose C. Principe[4]

[1]Department of Biomedical Engineering, Yonsei University, [2]Home Healthcare Management System Research Center, Yonsei University, [3]Department of Computer & Electronic Physics, Sangji University, [4]Computational Neuro Engineering Laboratory, Department of Electrical Engineering, University of Florida

(Received November 13, 2003. Accepted February 14, 2004)

요 약 : 체동은 수면 분석에 있어서 중요한 변수중의 하나이다. 본 연구에서는 수면중에 발생하는 체동을 비접촉 방식으로 검출하기 위하여 4채널의 써모파일 검출기를 구현하였으며, 써모파일 센서를 이용한 방식의 체동 검출 가능성을 확인하기 위해 열적외선 카메라를 통해 획득한 영상을 써모파일의 수학적 모델에 적용하였다. 합성된 체동 신호는 Haar 웨이브렛을 이용하여 변환함으로써 체동이 발생한 시점과 움직임의 크기를 상체 및 하체로 나누어 순간체동을 검출하였다. 또한 뉴로-퍼지 알고리즘인 ANFIS를 이용하여 발생한 체동이 상체만 움직인 것인지 또는 하체만 움직인 것인지 또는 몸 전체가 움직인 것인지에 대한 부위별 체동을 검출하였고, 총 3명의 피험자에 대해 60분간의 데이터를 획득하여 실험한 결과 순간체동과 부위별 체동에 대해 각각 평균 96.3%와 89.2% 의 검출률을 나타냈다.

Abstract : Body movement is one of the important factors in sleep analysis. In this study, a thermopile detector with four channels was implemented as a non-contacting detector of body movement in sleep. Using a thermopile mathematical model and several frames of thermal images, the possibility of detecting body movement was evaluated. Instant body movement signals were evaluated for the upper, lower, and entire body using the Haar wavelet. This decomposition shows the points in time when the upper-body or lower-body movement occurred and the level of body movement. Additionally, partial body movement was decomposed in head-only, whole body, and leg-only movement using the ANFIS algorithm. Finally, three subject's data were evaluated for 60 minutes, and the detection rates of instant and partial body movement, on average, were 96.3% and 89.2%, respectively.

Key words : Body movement, sleep, thermopile detector, wavelet, neuro-fuzzy

INTRODUCTION

Body movement is one of the events occurring during human sleep and is considered an important parameter in evaluating quality of sleep[1]. Furthermore, body movement in sleep can be used for detecting sleep apnea[2] and myoclonic seizure in newborns[3]. Evaluating sleep characteristics has been accomplished through many kinds of signals such as ECG, EEG, EOG, and EMG. Although these physiological signals are commonly used, these methods are uncomfortable to the subjects due to the attachment of many electrodes. Body movements can be detected with numerous devices, and they can be defined in such a large variety of ways that each investigator can still design his own criteria[4].Devices to measure body movement are the accelerometer[5], the bed pressure sensor[6][7][8], the bed temperature sensor[9], and the sensor pillow system[1]. However, most devices require attaching sensors directly or indirectly to the body.

이 논문은 한국학술진흥재단의 연구지원(KRF-2001-013-F00042)에 의해 이루어졌습니다.

통신저자 : 윤영로, (220-710) 강원도 원주시 흥업면 매지리234 연세대학교 의공학과
Tel : 033)760-2440
E-mail : yoon@dragon.yonsei.ac.kr

Although detection of body movement using a CCD camera[2] does not require the use of electrodes, one of the major problems associated with video processing and analysis

THERMOPILE MODEL

A thermopile sensor is used for non-contact measurement of surfacetemperatures based on infrared radiation. It contains many thermoelements, each element being a thin wire made of two materials of different thermal characteristics. These thermoelements generate micro voltages when infrared radiation is emitted. The human body also emits infrared radiation, and a thermopile sensor can be used for detecting body movement.

First, in order to infer the possibility of using a thermopile sensor as a detector of body movement, a simulation based on a thermopile model was testedwith several thermal images by an infrared thermal imager. A total of 80 frames of thermal images were recorded while the subject moved his body from lying flat on his back to lying on his left side (Fig. 1). An infrared thermal imager comprises many pixels of thermal points, but a thermopile sensor has only one thermal point. In thermopile sensor detection, infrared radiation is received as an average of target points. Therefore a thermal image with 239 by 256 pixels can be converted to a single value by averaging the pixels of a captured image with a mathematical thermopile model:

$$V_{out} = M(T_t^4 - T_a^4)\ , \quad M = \frac{z}{\pi}\frac{A_t A_d}{D^2}R \qquad (1)$$

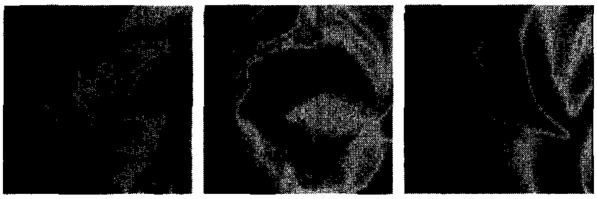

Fig. 1. Example of thermal imaging.
(a) Lying flat position
(b) left-side position
(c) right-side position

where Vout is output voltage of thermopile, Tt is temperature of target (K), Ta is temperature of ambient (K), z (5.688×10-12 W/㎠/K4) is Stefan-Bolzman constant, is experimental constant, At is the area of a target (㎠), Ad is the area of a thermopile element (㎠), R is responsivity of detector (V/W), and D is distance (㎝). Temperature of target was calculated from averaging 80 image frames. Temperature of ambient was 24.0?, and distance was 100㎝. The other parameters were decided from a datasheet of a thermopile sensor (TPS333, Heimann).

Each frame of the thermal image was calculated to mimic the output voltages of the thermopile sensor while the subject moved from straight lying flat on his back to lying on his left and right side (Fig. 2). The calculated output voltages of thermopile model by a thermal imager and was compared with the real output voltages of thermopile acquired by frames of thermal images from lying flat to left and right-side lying position. In the lying flat position at the image frame 1, 40, and 80, half of the subject's head and the upper part of his body were included in the view of the infrared thermal imager. As a result, lower output voltages were calculated. In the left-side lying position at the image frame 20, the output voltages increased since more parts of the body were included. In the right-side lying position at the image frame 60, the output voltages decreased since less parts of the body were included. This simulation of the thermopile model by a thermal imager has a similar trend with real output voltages of thermopile. Therefore, it shows that the proper implementation and installation of a thermopile detector can measure and detect body movement in sleep.

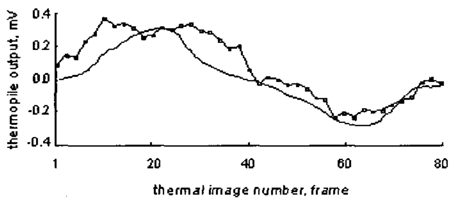

Fig. 2. Comparison with the calculated output voltages of thermopile model by a thermal imager ( ) and the real output voltages of thermopile ( ) acquired by frames of thermal images from lying flat to left and right-side lying position

EXPERIMENTAL METHODS

1. Hardware implementation

The detector of body movement consisted of three boards (Fig. 3). The analog board contained an infrared thermopile sensor, a digital-to-analog converter (DAC) with pulse width modulation (PWM), and several operation amplifiers.The body temperature of the subject was radiated to a thermopile detector. Only infrared wavelengths (1.2~15㎛) were passed to the sensor by the infrared filter. The infrared collecting mirror concentrated the infrared radiation to the sensor and restricted the viewing angle to about 30°. To drive the thermopile sensor, a chopper amplifier had to be used. Since the chopper amplifier (AD8551, Analog Device) had a very low offset drift (50㎁/C max), stable output voltage was available when the ambient temperature changed. The first amplification stage had three amplifiers which were the thermopile amplifier, the internal thermistor amplifier, and the summing amplifier to compensate for ambient temperature. At the second section of the amplifier, the offset voltage was controlled by PWM DAC with RC components. The initial temperature of the subject, the bed, and the ambient room were different. Therefore, when the measurement of body movement began, the initial voltage of amplified output had to be adjusted to half of analog-to-digital (ADC) scale. The PWM module with 16-bit resolution generated DAC signals and was converted to direct current (DC) offset signal by a capacitor. This signal controlled the offset voltage of an amplifier in the second section. Since a total of four thermopile detectors were used, each channel had an individual PWM DAC. An 8-bits RISC microcontroller (PIC16F876, Microchip) was chosen. All signals of body movement were converted by a 10-bit internal ADC with 100 samples per second, and the converted digital data was transmitted to a receiver module by 19200 bps using an RF module (TX2/RX2, Radiometrix). Finally, the received data was converted to a level of RS-232C and transmitted to a personal computer (PC) through a level converter (MAX232, Maxim).

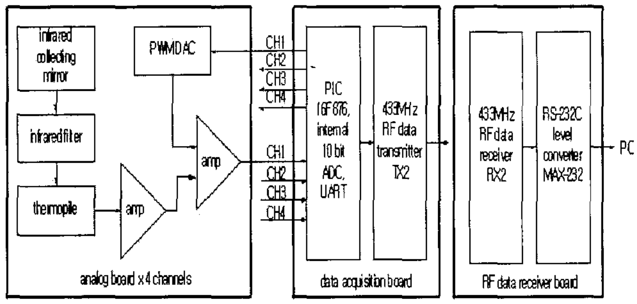

Fig. 3. Overall block diagram of body movement detector and data acquisition system

2. Thermopile detector installation

In this study, four thermopile detectors were installed (Fig. 4). Channel 1 (CH1) and Channel 2 (CH2) were placed on the upper-left and upper-right sections of the subject's head for detection of upper-body movement. Channel 3 (CH3) and Channel 4 (CH4) were placed on the lower-left and lower-right area of the subject's legs for detection of the lower- body movement. CH1 and CH3 were situated toward the left part of the body, and conversely, CH2 and CH4 to the right part of the body. The angle, height, and distance of each detector board with supporter were adjustable. Overall, 1 meter of distance from the subject's body was appropriate for detecting body movement.

After this system was started with the subject lying on the bed, a microcontroller read each amplified thermopile values by ADC. Then proper offset voltage was supplied to each channel through a PWM DAC controller until the initial value of ADC reached to Vcc/2 volts. After this process of offset adjustment was completed, a microcontroller started to transmit the ADC value of output voltages from each channel, and the RF data receiver board received the ADC values and transmitted them to the PC.

Each detector covered the range of half of the body, and therefore, they had the same voltages of the thermopile output when in the initial lying-flat position. However, when the position of the body changed, the output voltages of the thermopile detectors differed in value from each other. From this difference in the value of the signals, instant body movement, and the position of the body, and partial movement were able to be detected and evaluated.

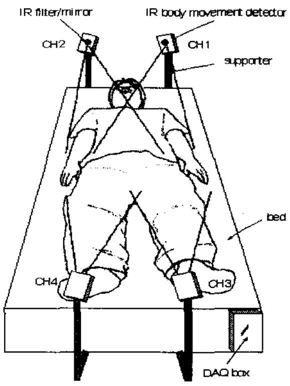

Fig. 4. Experimental system composed of four channels of infrared body movement detectors, a bed, and data acquisition box; All detectors had infrared filters and infrared collecting mirrors set at a 30° angle.

EVALUATION OF BODY MOVEMENT

1. Instant body movement

The first evaluating parameter proposed in this study is instant body movement. Even though body movements are not considered epochs of sleep, they are considered specific and discrete physiological events which occur during epochs[4]. The events of body movement occur when the body instantly moves and can be evaluated from derivatives of thermopile output signals. In this study, the detail signal calculated by a wavelet transform, which has a derivative property, was used for evaluating instant body movement. Since coefficients from using the Haar wavelet especially have smoothing and simplifying properties, transformed coefficients of body movement signals offer simple and visible readings.

Index C(j, k) called coefficients was calculated using the following equation:

$$C(j,k)=\int_R s_{CHi}(t)\frac{1}{\sqrt{2^j}}\psi\left(\frac{t-2^jk}{2^j}\right)dt \tag{2}$$

where SCHi(t) is thermopile output signal of channel i, j is detail level, k is discrete time, and Ψis the Haar wavelet.

Detail at level j was determinedusing the following equation:

$$D_j(t)=\sum_{k\in Z}C(j,k)\ \psi_{j,k}(t) \tag{3}$$

Detail level was selected with similar frequency to body movement. In general, most cases of body movement in sleep have a frequency range of 0.1~3.0Hz. In this study, detail at level eight D8(t) was chosenfor detecting normal and slow body movements, excluding abnormal and quick movements (e.g. myoclonic seizures). The detail signal at level eight had a frequency range of 0.19~0.39Hz at 100Hz sampling. After wavelet transform, the squares of the details of each channel were summed as follows:

$$b_{upper}(t)=\{D_{8,CH1}(t)\}^2+\{D_{8,CH2}(t)\}^2 \tag{4}$$

$$b_{lower}(t)=\{D_{8,CH3}(t)\}^2+\{D_{8,CH4}(t)\}^2 \tag{5}$$

$$b_{total}(t)=b_{upper}(t)+b_{lower}(t) \tag{6}$$

where bupper(t), blower(t), and btotal(t)are the instant upper-body movement, the instant lower-body movement, and the total instant body movement, respectively. Additionally, the points where bodymovement occurred were represented in the indication bars as follows:

$$b_{upper}(t)=1,\ b_{upper}(t)\geq B_{th,upper}$$
$$b_{upper}(t)=0,\ otherwise \tag{7}$$

$$b_{lower}(t)=1,\ b_{lower}(t)\geq B_{th,lower}$$
$$b_{lower}(t)=0,\ otherwise \tag{8}$$

where Bth,upper and Bth,lower are threshold values.

Since thermopile detectors of Channel 1 and 2 and Channel 3 and 4 were situated toward the upper- and the lower-part ofthe body, respectively, they were able to be evaluated for not only total body movement but also separate body movement with reference to the upper- and lower-part of the body.

2. Partial body movement

The other evaluating parameter proposed in this study is partial body movement. When the subject turned his body to the left or right side, all channels of the signal changed. However, when the subject turned only his head to either side, only CH1 and CH2 of the signal changed. In the same manner, when thesubject turned his legs to either side, only CH3 and CH4 of the signal changed. By using these properties, body movement signals could be decomposed into individual signals with partial body movement. They were head-only movement signal, whole body movement signals, and leg-only movement signals.

The neuro-fuzzy algorithm, adopted in this study for evaluating partial body movement, was the adaptive neuro-fuzzy inference system (ANFIS), one of the neuro-fuzzy algorithms, whichcombined fuzzy with a neural network[10]. To build a derived fuzzy knowledge model based on ANFIS for estimating partial body movement, two processing steps are required[11]. In this study, the fuzzy inference system had two inputs, x1 and x2, and three outputs of y1, y2, and y3. For the ANFIS training, the Gaussian bell type membership function was chosen. Then in the next step, for the first order Sugeno fuzzy model, the typical rule sets, which had four fuzzy if-then rules, were expressed as follows (Fig. 5)

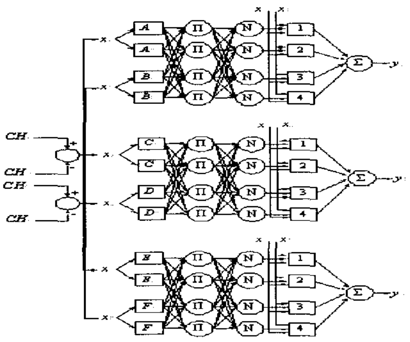

Fig. 5. The system diagram for evaluating partial body movement by integrating CH1, CH2, CH3, and CH4 signals using ANFIS

$$x_1(t) = s_{CH1}(t) - s_{CH2}(t)$$
$$x_2(t) = s_{CH3}(t) - s_{CH4}(t) \quad (9)$$

$$\textit{Rule 1}: \textit{if } x_1 \textit{ is } A_1 \textit{ and } x_2 \textit{ is } B_1$$
$$\textit{then } y_1 = p_1x_1 + q_1x_2 + r_1 \quad (10)$$

$$\textit{Rule 2}: \textit{if } x_1 \textit{ is } A_1 \textit{ and } x_2 \textit{ is } B_2$$
$$\textit{then } y_1 = p_2x_1 + q_2x_2 + r_2 \quad (11)$$

$$\textit{Rule 3}: \textit{if } x_1 \textit{ is } A_2 \textit{ and } x_2 \textit{ is } B_1$$
$$\textit{then } y_1 = p_3x_1 + q_3x_2 + r_3 \quad (12)$$

$$\textit{Rule 4}: \textit{if } x_1 \textit{ is } A_2 \textit{ and } x_2 \textit{ is } B_2$$
$$\textit{then } y_1 = p_4x_1 + q_4x_2 + r_4 \quad (13)$$

where y1 is the head-only movement signal. Additionally, the whole body movement signal y2 and leg-only movement signal y3were expressed as the same structure with different coefficients. One set of data from one subject was used as training data, and another subject's data was used for testing and verification.

RESULTS

Using the developed thermopile detectors with four channels, several types of body movement in sleep were evaluated (Fig. 6). Movement period of THL and THR showed that only CH1 and CH2 signals of the detectors placed at the upper area of the bed varied. Also, periods of FLL and FRL showed that only CH3 and CH4 signals of the detectors placed at the lower area of the bed varied. In the period of TBL and TBR, since the movements occurred in both the head and legs when the subject turned his body to either the left or right side, the body movement signals varied overall all channels. When the subject's body was oriented toward the direction of the thermopile detector, the output values increased from the initial baseline, and the detectors set in the opposite direction had negative outputs. Therefore, when TBL or TBR-type movements occurred, the output waves of CH1 and CH2 and CH3 and CH4 showed symmetrical characteristics.

From these movement signals, instant body movement was evaluated. The eighth scale detail signals were calculated with the Haar wavelet (Fig. 7), and instant body movement signals were evaluated (Fig. 8). They show points of time when the upper-body or lower-body movement occurred, and the level of body movement. In the case of TBL and TBR, the upper-body and lower-body movement occurred simultaneously, therefore, a higher signal level was shown in total instant body movement.

Although each raw signal of body movement (Fig. 6) has its own meaning, it is somewhat complicated to analyze raw signals. Using Formula (7), more intuitive signals were derived simply by subtracting each channel from each other using Formula (7) (Fig. 9). The subtracted signals x1 and x2 show the upper-body and lower-body movements including the direction of the body. Two sets of input data and one set of output data were trained by 30 epochs with converged and smallest root mean square error (RMSE). The training data was acquired with movements of THL, THR, TBL, TBR, LFP, FLL, and FRL for 100 seconds from one subject. After training the data by ANFIS algorithm, partial body movement was decomposed to head-only, whole body, and leg-only movements. The correlation coefficient between each decomposed signal and input signal showed values of 0.93, 0.99, and 0.95, respectively. This decomposing process using ANFIS included some basic inference rules. As shown in the input-output data signals, when only upper-body movement occurred without lower-body movement, the decomposing system inferred and evaluated head-only movement (y1). Similarly, the lower-body movement (y3) had the same inference rule for leg-only movement. Moreover, when both the upper-body and lower-body movement signals occurred simultaneously, the whole body movement (y2) was inferred alone.

After this training process, another subject's body movement signals in sleep were acquired for 60 minutes (Fig. 10). Instant body movement was shown by indication bars when this subject's body movement occurred and where movement occurred in the upper-body or lower-body. In this subject's case, a total 43 instant body movements occurred. Among these, one indication of movement was missed, therefore, the detection rate of the instant body movements was 97.7%. Partial body movement was decomposed to the head-only, whole body, and the leg-only movement signals, and they showed the direction which was to the left or right. The body movement output signal (f) was processed by the threshold value, and the signal values that were less than the threshold were calculated as zero. In this subject's case, the error period of detection was a total of 6.5 minutes; therefore, the detection rate of the partial body movements was 89.2%. Finally, an analysis of the results of all 3 subjects was shown in Table 1. The detection rate of instant and partial body movement, on average, were 96.3% and 89.2%, respectively.

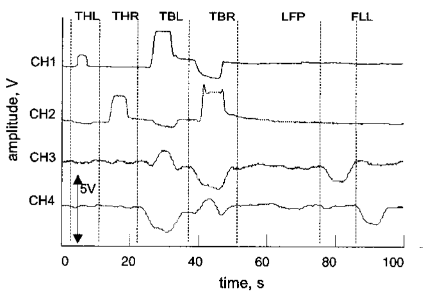

Fig. 6. Acquired raw signals of body movement by the four thermopile detectors; The periods of body movement were THL(turn head to left), THR(turn head to right), TBL(turn body to left), TBR(turn body to right), LFP(lying flat position), FLL(fold left leg), and FRL(fold right leg), respectively.

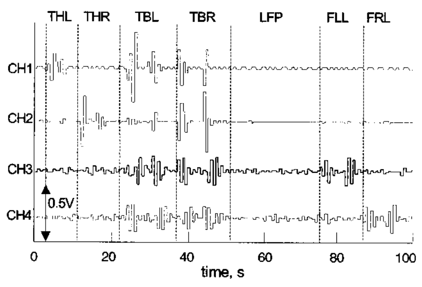

Fig. 7. he eighth scale detail signals (d8) of each of the four channels

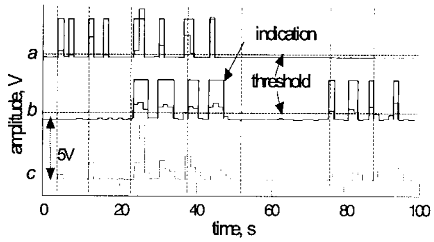

Fig. 8. valuation of instant body movement at (a) the upper part of the body, (b) the lower part of the body, and (c) the total body from the combination of the eighth scale detail signals (d8) for each channel by square and sum

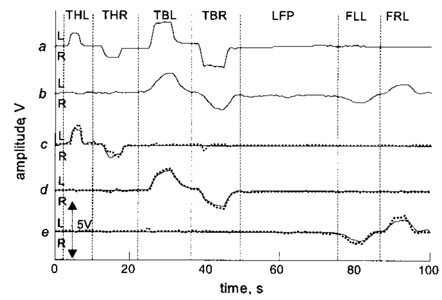

Fig. 9. Decomposition of partial body movement for training data sets from two input signals of (a) upper-body movement and (b) lower-body movement. After data training to the output data with solid lines from (c) to (e), (c) head-only movement signal, (d) whole body movement signal, and (e) leg- only movement signal with dotted lines were evaluated.

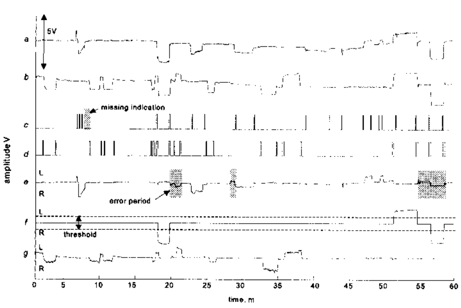

Fig. 10. Another subject's body movements were evaluated for 60 minutes in sleep. From two input signals of (a) x1 and (b) x2, the instant body movements, (c) the upper-body movement and (d) the lower-body movement, were evaluated by wavelet detail at eight. Partial body movements, (e) head-only, (f) whole body, and (g) leg-only, were evaluated by a neuro-fuzzy system.

DISCUSSION AND CONCLUSION

In this study, a thermopile detector with four channels was implemented as a non-contacting detector of body movement in sleep. The possibility of using a thermopile for detecting body movement was evaluated using the mathematical model of thermopile and several frames of thermal images. Instant body movement was evaluated at theupper, lower, and total part of the body from the combination of the eighth scale detail signals with the Harr wavelet. Additionally, partial body movement was decomposed to each part of the body comprising head-only, whole body, and leg-only movement using the ANFIS algorithm.

Although the partial body movement signals were calculated when the subject's movements occurred, the instant body movement signals showed the points of body movements more accurately, and these were able to be used for conventionalbody movement signals to add more detailed information comprising the lower- and the upper-parts of the body.

Detection error occurred mostly in the upper-body and the head-only movement. Due to this, the level of head movement signal was relatively smaller than the level of whole body or leg-only movement. The appropriate trade-off between the responsibility and the stability of CH1 and CH2 is needed for a more accurate system.

Since thermal infrared radiation from a human body is the source for detecting body movement, if blanket widely covers the subject's body, body movement will be hard to detect from infrared signals. Therefore, to acquire more reliable body movement signals, it is necessary to maintain appropriate room temperature for a comfortable sleep and to use a simple blanket as small as possible to cover the subject's abdomen.

Evaluated signals for partial body movement merely showed which part of body movement occurred and the direction of the movement. However, if other non-linear and artificial intelligent algorithms based on pattern recognition were used, each type of body movement (i.e., THL, THR, TBL, etc.) could be classified and recognized.

In this study, whole body movement including the head and legs was evaluated. If only a specific part of the body is focused on (e.g., abdomen, arm, or leg), it will be possible to detect sleep apnea, myoclonic seizures, and neonatal seizures.

REFERENCES

1. Tatsuya Harada, Akiko Sakata, Taketoshi Mori, and Tomomasa Sato, *"Sensor pillow system: monitoring respiration and body movement in sleep"*, Proc. of IEEE IRSO, Vol.1, pp. 351-356, 2000
2. Yoshifumi Nishida, Toshio Hori, Tomomasa Sato, and Sigeoki Hirai, *"The surrounding sensor approach application to sleep apnea syndrome diagnosis based on image processing"*, Proc. of IEEE SMC '99, Vol. 6 , pp. 382-388, 1999
3. Nicolaos B. Karayiannis, Seshadri Srinivasan, and Rishi Bhattacharya, *"Extraction of motion strength and motor activity signals from video recordings of neonatal seizures"*, IEEE Trans. Medical Imaging, Vol. 20, No. 9, pp. 965-980, 2001
4. Allan Rechtschaffen and Anthony Kales, *"A manual of standardized terminology, techniques and scoring system for sleep stages of human subjects"*, BIS/BRI, UCLA, Los Angeles, pp. 5-15, 1973
5. Avi Sadeh, Peter J Hauri, Daniel F. Kripke, and Peretz Lavie, *"The role of actigraphy in the evaluation of sleep disorders"*, Sleep, Vol. 18, pp. 288-302, 1995
6. Toshiyo Tamura, Chun-ichi Miyasako, Toshiro Fujimoto and Toshimitsu Nomura, *"Monitoring of body movement during sleep in bed"*, Proc. of IEEE EMBS, Vol.4, pp. 1483-1484, 1992
7. Yoshifumi Nishida, Toshio Hori, Takashi Suehiro, and Sigeoki Hirai, *"Sensorized Environment for self-communication based on observation of daily human behavior"*, Proc. of IEEE IROS2000, Vol. 2, pp. 1364-1372, 2000
8. Machiel Van der Loos, Hisato Kobayashi, Gregory Liu, Ying Yu Tai, Joel Ford, Joseph Norman, Tsuyoshi Tabata, and Tomoaki Osada, *"Unobtrusive vital signs monitoring from a multisensor bed sheet"*, RESNA Reno, NV, June, pp. 218-220, 2001
9. Toshiyo Tamura, Atsushi Nishigaichi, and Tatuso Togawa, *"Monitoring bed temperature in elderly in the home"*, Proc. of IEEE EMBS, Vol.1, pp. 57-58, 1996
10. Roger Jang and Chuen-Tsai Sun, *"Neuro-Fuzzy Modeling and Control"*, Proceeding of IEEE, Vol. 83, pp. 378-390, 1995
11. Xu-Sheng Zhang and Rob J. Roy, *"Derived fuzzy knowledge model for estimating the depth of anesthesia"*, IEEE Trans. Biomed. Eng., Vol. 48, No. 3, pp. 312-323, 2001