Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Estimation of thermal sensation using human peripheral skin temperature

Kanako Nakayama, Takuji Suzuki, Kenichi Kameyama
Humancentric Laboratory,Corporate Research and Development Center
Toshiba Co.
1 Komukai, Toshiba-cho, Saiwai-ku, Kawasaki, Japan
kanako.nakayama@toshiba.co.jp

Abstract—**Control of indoor thermal environments in accordance with people's preferences, makes an important contribution to comfort. To keep a suitably temperate environment, we tried to estimate a subject's thermal sensation using biologic signals. We focused on peripheral skin temperature to estimate individual thermal sensation. First we carried out an experiment involving an alteration of environmental temperatures to reveal the relationship between peripheral skin temperature and thermal sensation votes. Next we made an algorithm of estimating thermal sensation and assessed the algorithm. When thermal sensation indices estimated by our algorithm were compared with the subject's votes, error of mean squares was 1 or less in most cases. As a result, the possibility of thermal sensation measurement using peripheral skin temperatures is confirmed. Furthermore, we implemented the temperature control system using a household air conditioner and a thermal sensor.**

***Keywords*—thermal sensation, peripheral skin temperature, bio-signal**

I. Introduction

The climate is running our life, especially in a place like Japan in which there are four different seasons. But in resent years, the widespread use of air conditioners has improved indoor environment. Meanwhile, there are evils from controlling temperature using air conditioners. For example, because of overcooling, many people got air conditioner sickness, because of overheating, many people awakened during sleep. We believe that the control of indoor thermal environments should be individualized according to one's body condition. Thus we tried to estimate thermal sensation using biologic signals. We focused on peripheral skin temperature because it relates to vasomotion witch contribute to controlling one's body temperature. First, we had experiments to confirm the relationship between peripheral skin temperature and thermal sensation. Next we made an algorithm to estimate one's thermal sensation form peripheral skin temperature, and assessed our algorithm. Finally, we made household air conditioner system using our algorithm.

II. Existing Methods of Thermal Sensation Estimation

There are some thermal comfort models. For example, PMV (Predicted Mean Vote), ET (Effective Temperature), SET* (Standard Effective Temperature) and so on. Particularly, PMV is popularized model. PMV combines for physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity), and two personal variables (clothing insulation and activity level) into an index that can be used to predict the average thermal sensation of a large group of people and it adopted as an ISO standard (ISO 7730) [1][2]. In recent years some studies on thermal sensation have proposed systems which feed back the prediction of thermal sensation in daily life. Using Mori's model, Ishiguro studied about the system which control thermal indoor condition during sleep [3][4]. These systems can provide the majority to thermal comfortable conditions averagely, but they don't really adjust the conditions to suit individual.

Human body has some system to control body temperature in itself. So we have tried to estimate individual thermal sensation using a biologic signal. Especially we focused on peripheral skin temperature.

III. Thermal Control Mechanism of Humans

When we feel cold or hot, we put on or take off our clothes to maintain our body temperature. That is called "behavioral temperature regulation". At the same time, our body attempts to control its temperature using sweat secretion, chills, muscular activity and so on. This is called "autonomic temperature regulation". Peripheral blood vessels are part of this. Human peripheral blood vessels act as a radiator. Some cutaneous blood vessels which have smooth muscles can regulate blood flow. High and low temperature induces dilation and constriction of human cutaneous blood vessels, respectively. When we feel cold, cutaneous blood vessels constrict and blood flow through arteriovenous anastomoses (AVAs) to maintain body temperature. When we feel hot, cutaneous blood vessels dilate and it flows through them to release body temperature. At this time, our peripheral skin temperature becomes cool or hot depending on path of blood flow [5]. For this reason, we assume that vessel smooth muscles repeat dilation and constriction to control body temperature adequately when it is neither hot nor cold. And at that point, our peripheral skin temperature may fluctuate [6].

So we made a hypothesis that suggests peripheral skin temperature which reflects blood flow change relates to body

978-1-4244-2794-9/09/$25.00 ©2009 IEEE

temperature regulation, and thermal sensation can be estimated by measuring peripheral skin temperature.

Also peripheral cutaneous vessel's blood flow changes before the other autonomic temperature regulation like sweating. So we thought peripheral skin temperature is suitable for an estimation fine, thermal sensation.

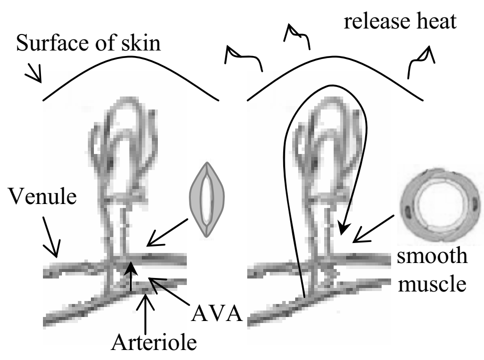


Figure 1. skin blood vessel

IV. FLUCTUATIONS OF PERIPHERAL SKIN TEMPERATURE AND THERMAL SENSATION

We planed experiments to confirm the above hypothesis and that relationship.

A. METHODS

Two healthy people (a man in late thirties and a woman in late twenties) served as the subjects. The experiment was carried out in August using a climate chamber.

Pattern1	T : 20℃ HR : 50%		T :25℃ HR:50%	T :30℃ HR:60%	T :35℃ HR:60%
	wear sensors (about 30[min])	40[min]	40[min]	40[min]	40[min]
		experiment			

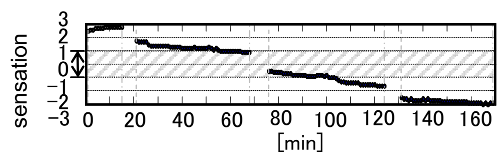
Pattern2	T : 35℃ HR : 60%		T :30℃ HR:60%	T :25℃ HR:50%	T :20℃ HR:50%
	wear sensors (about 30[min])	40[min]	40[min]	40[min]	40[min]
		experiment			

Figure 2. experiment protocol

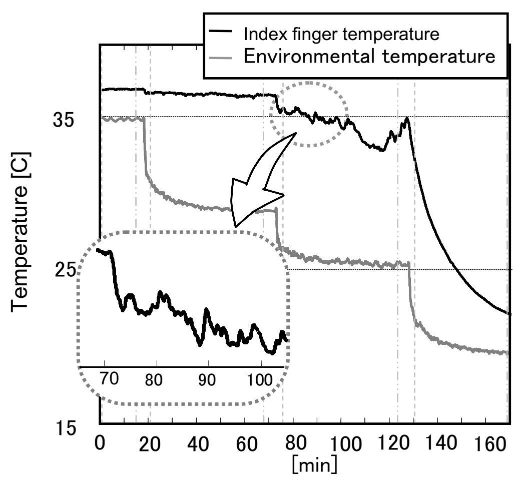
The subjects, wearing half sleeve shirts and shorts (0.3clo), sat down on a chair in the climate chamber and wore sensors under the first environmental condition (20C RH: 50% or 35C RH: 60%). After preparation, the measurement protocol was launched. We tested 2 temperature change patterns shown in Fig.2. In both pattern, each temperature was continued for 40 minutes except if a subject gave up. The subject alternated between 2 climate chambers, each of which was preset to the necessary temperature as required for our research (Fig. 2). Peripheral skin temperature, environment temperature and thermal sensation vote recordings were carried out continuously. Temperature signals were recorded at a sampling rate of 0.5Hz using thermistor thermometer, Logger Temperature 8 (Gram Co.) which has a temperature resolution of 0.01C. Peripheral skin temperature was recorded form the left index finger, because AVAs are located mainly in the skin of the hands, feet, lips, nose and ears. Every 1 minute, the subjects would rate their thermal sensation on a scale of ±3 comfort level (scale : -3 cold, -1 cool, 0 neutral, +1 warm, +3 hot (including decimal parts), This scale is based on the scale of PMV). This data was recorded into a laptop computer for later analysis. In this study, we decide an acceptable range of thermal sensation as "-1～+1".

B. RESULT

The male subject's results (Pattern2) is displayed in Fig. 3.



(a) thermal sensation vote



(b) peripheral skin temperature and environmental temperature

Figure 3. Temperatures and thermal sensation vote

Fig. 3 (a) shows the result of the thermal sensation vote and (b) shows the result of temperature dates. X axis is a time scale. As in Fig. 2, while the subject felt cold (the thermal sensation vote : -3～-2) or hot (the thermal sensation vote : +2～+3), his index finger temperature didn't fluctuate. And while he felt cold, his index finger temperature was kept at around the environmental temperature, while he felt hot, his index finger temperature was kept at around 36 ℃. On the other hand, while he felt neutral (the thermal sensation vote : -1 ～ +1), fluctuations were observed. We speculate that the fluctuations were the result of peripheral vessel's vasomotion to keep our body temperature constant. We can observe comparative results in other subjects and temperature patterns.

We analyzed the peripheral temperatures' frequency using FFT (First Fourier Transformation) (Fig.4). Before frequency analysis, the peripheral temperatures were preprocessed with smoothing and detrending. A 15-point moving average was used for smoothing and the first derivation was used for detranding. In Fig. 4 (b) and (c), the top-right numbers of (c) relate to the numbers of rectangles of (b), and each result of frequency analysis was calculated using the dates in a corresponding rectangle. When one feels cold or hot, no peaks are shown according to Fig. 4 (c) ① and ⑥. When one feels cool (the thermal sensation vote : -2~-1)or warm (the thermal sensation vote : +1~+2), the power is seen in the frequency range 0.007Hz to 0.01Hz, according to Fig. 3 (c) ② and ⑤. Furthermore, when one feels neutral (the thermal sensation vote : -1~+1), the power is seen in the frequency range 0.007Hz to 0.03Hz according to Fig. 4 (c) ③ and ④.

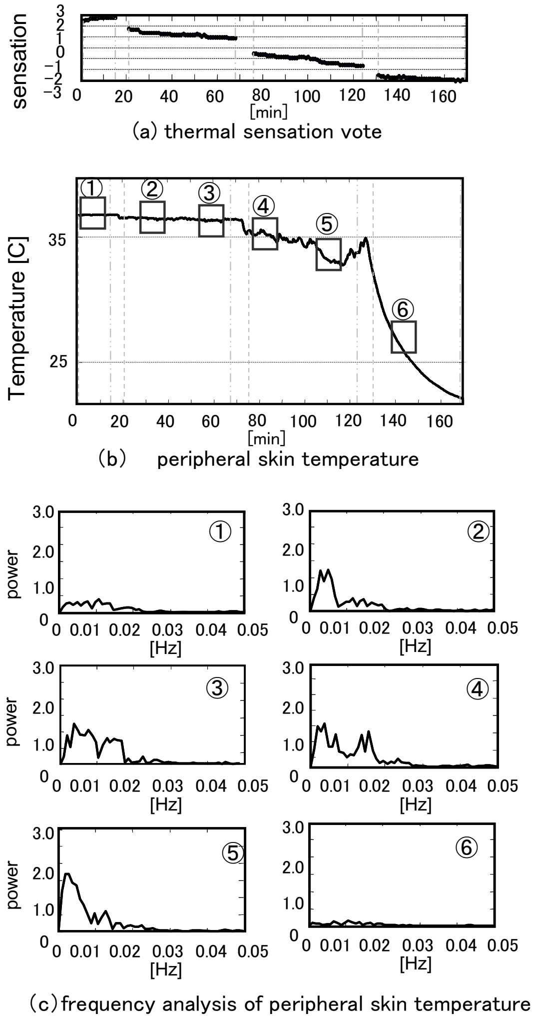


Figure 4. Results of frequency analysis

Within the limits of this experiment, one's peripheral skin temperature fluctuates in the frequency range 0.007Hz to 0.03Hz, while one's thermal sensation is in the -2 to +2.

C. REPRODUCIIBILITY OF PERIPHERAL SKIN TEMPERATURE FLUCTUATIONS

We assessed the reproducibility of peripheral skin temperature fluctuations. The experiment subjects were 4 healthy men and 4 healthy women. The experiment was carried out in March using an air conditioner. Each subject was in the experiment room under their suitable temperature for 20 minutes. Before measurement, each subject decided their suitable temperature by controlling the preset temperature of an air conditioner. The temperature of each subject's index finger was recorded continuously, and the subjects input their thermal sensations into a laptop computer system every 1minute as in the previous experiment.

As a result of this experiment, peripheral skin temperature fluctuations in the frequency range 0.007Hz to 0.03Hz were confirmed in all subjects.

V. ALGORITHM OF ESTIMATING THERMAL SENSATION

These results indicate that thermal sensations are expressed in the peripheral skin temperature. As mentioned above, our analysis shows

State1: When the subjects recorded feeling cold (-3~-2) or hot (+2~+3), there is no fluctuation. Furthermore if they recorded feeling cold, their peripheral skin temperature lowered, and if they recorded feeling hot, their peripheral skin temperature was stable at approximately 36C (Fig. 4 (c) ①⑥).

State2: When the subjects recorded feeling within the range of cool (-2) to warm (+2), their peripheral skin temperature fluctuated between 0.007Hz to 0.01Hz (Fig. 4 (c) ②⑤).

State3: When the subjects recorded feeling neutral (-1~+1), their peripheral skin temperature fluctuated between 0.007Hz and 0.03Hz (Fig. 4 (c) ③④).

Therefore, we made a rule of estimating one's thermal sensations using the peripheral skin temperature's fluctuation (State1~3) and gradient (positive gradient, negative gradient, no gradient). The predicted thermal sensation indices are renewed in accordance with the rule continuously.

First we give an explanation of State1. If the fluctuation condition is as per State1,

- The gradient is positive: the new index increases incrementally from the last index to +3.
- The gradient is negative: the new index decreases decrementally from the last index to -3.
- There is no gradient: the next index is decided depending on an average of the absolute peripheral skin temperature.
  - The average is higher than the threshold (e.g.35C): the new index increases incrementally from the last index to +3.

- ➢ The average is lower than the threshold: the new index decrements decrementally form the last index to -3.

Next we give an explanation of State2. If the fluctuation condition is State2,

- ■ The gradient is positive: the new index increases incrementally from the last index to ±0.
- ■ The gradient is negative: the new index decreases decrementally from the last index to -1.
- ■ There is no gradient: the next index is decided depending on an average of the absolute peripheral skin temperature also.
  - ➢ The average is higher than the threshold: the new index is a same as the last index.
  - ➢ The average is lower than the threshold: the new index is brought close to parity ±0 by a small increase/decrease from the last index.

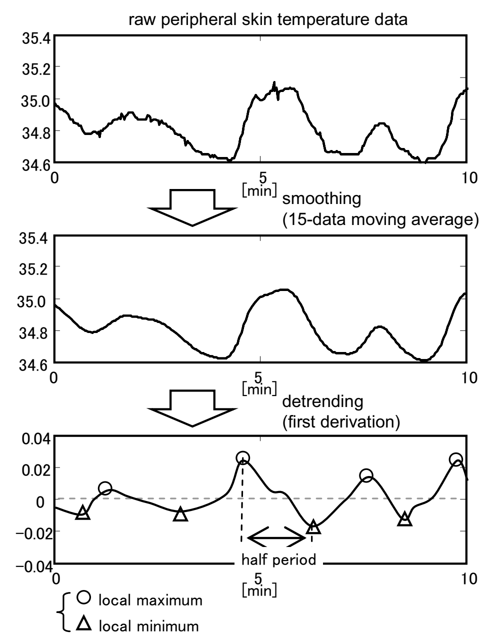
Finally we give an explanation of State3. If the fluctuation condition is State3,

- ■ The gradient is positive: the new index increases incrementally from the last index to +2.
- ■ The gradient is negative: the new index decreases decrementally from the last index to -2.
- ■ There is no gradient: the next index is decided depending on an average of the absolute peripheral skin temperature and the previous gradient.
  - ➢ The average is higher than the threshold: we seek the last gradient which is observed in the previous 10 minutes,
    - ✧ The previous gradient is positive: the new index increases incrementally from the last index to +2.5.
    - ✧ The previous gradient is negative: the new index decreases decrementally from the last index to +1.
    - ✧ No gradient is observed: the new index is brought close to parity ±0 by small step form the last index.
  - ➢ The average is lower than the threshold: the new index is bought close to parity ±0 by small step from the last index.
- ■ If the fluctuation and gradient conditions aren't above case, the next index is same as the last index.

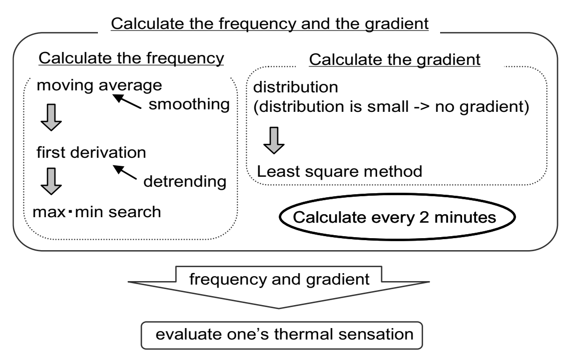
In this report, to calculate the frequency, we use a 15-data moving average and first a derivation instead of FFT (Fast Fourier Transformation), because for this research, real time estimation would have required too much data. The 15-data moving average was used for smoothing, and the first derivation was used for detrending. After determining the moving average and first derivation, a half period was calculated using local maximums and minimums (Fig5a). A time interval between a local maximum and the adjacent minimum corresponds to a half period, and the period is the reciprocal of the frequency. So, the frequency is approximated briefly by the period (Fig. 5 (a)).

At the same time as calculating the frequency, we also calculate the gradient. First, we calculate the variance of the raw peripheral skin temperature data to decide whether there is a gradient or not, and if the variance is lower than the threshold, we define that condition as no gradient. If the variance is higher than the threshold, a gradient is calculated using Lease Square Method to check the positivity or negativity of a gradient.

Both the fluctuation and the gradient are calculated every 2 minutes and a subject's thermal sensation is estimated according to these parameters (Fig.5 (b)).



(a) calculation of frequency



(b) process of estimating thermal sensation

Figure 5. process of estimationg thermal sensation

VI. ASSESSMENT OF ALGORITHM

We assessed our estimating algorithm. Firstly, we applied our algorithm to the data measured in the previous experiment.

Then we conducted another experiment and applied the algorithm to the new data.

A. Applingy our algorithm to the resulst of the previous experiment

Firstly, our algorithm was applied to the data measured in the above experiment. Fig .6 shows the result (subject: a man in late thirties). In Fig. 6, solid lines indicate the subject's thermal sensation votes and the dots represent the thermal sensation indices which were estimated from the peripheral skin temperature data using our algorithm. Fig. 6 (a) indicates the result of environmental temperature pattern 1and (b) indicates the result of environmental temperature pattern 2. It can be seen form Fig. 6 that the indices are roughly in accordance with subject's thermal sensation votes. σ 2 in each graphs stands for mean squared error. Both values of mean square errors are small (less than 1). We also applied the algorithm to the other data and all values of mean square errors are less than 1.

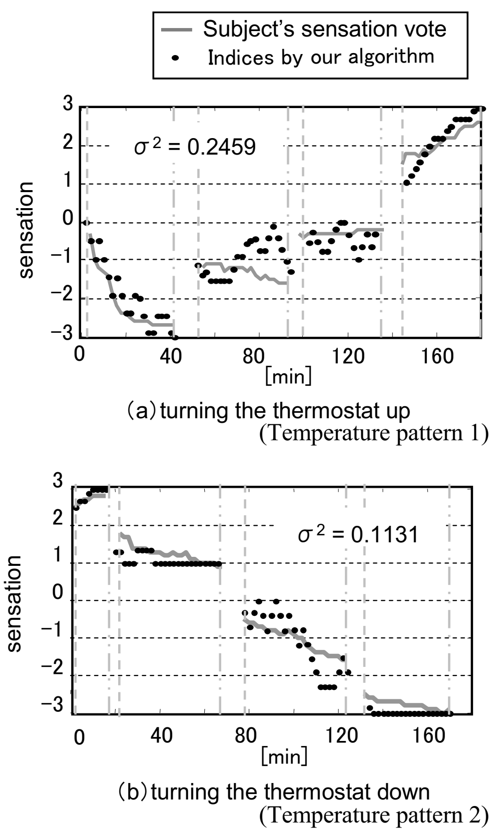


Figure 6. result of our evaluation algorithm

B. Applying our algorithm to the resulst of a new experiment

In addition, we conducted another experiment to assess our algorithm. In this new experiment, the environmental temperatures were kept 22C during the experiment, and each subjects tried 4 types of sartorial conditions.

- Sartorial Condition1: half sleeve shirt and shorts (0.3clo)
- Sartorial Condition2: long sleeve shirt and longs (0.5clo)
- Sartorial Condition3: half sleeve sweater and shorts (0.7clo)
- Sartorial Condition4: long sleeve sweater and longs (1.2clo)

The subjects are same as the previous experiment and, in addition to the peripheral skin temperature data and thermal sensation votes, local thermal sensation votes were measured .

As a result, the values of mean square errors were less than 1 in many cases. But we observed large errors in some cases. Fig. 7 shows subject's thermal sensation votes, thermal sensation indices which were estimated using our algorithm and peripheral skin temperature. Fig. 7(a) shows the results of the male subject experiment which was conducted under Sartorial Condition 4, and Fig. 7 (b) shows the results of the female subject experiment which was conducted under Sartorial Condition 2.

In Fig. 7 (a), the estimated indices are higher than the subject's votes. Magnifying the peripheral skin temperature, the fluctuation of small amplitude is observed and this fluctuation is sharper than Fig. 3's. So we assumed diaphoresis had an influence on this sharp fluctuations and because of this diaphoresis, the subject didn't feel so hot.

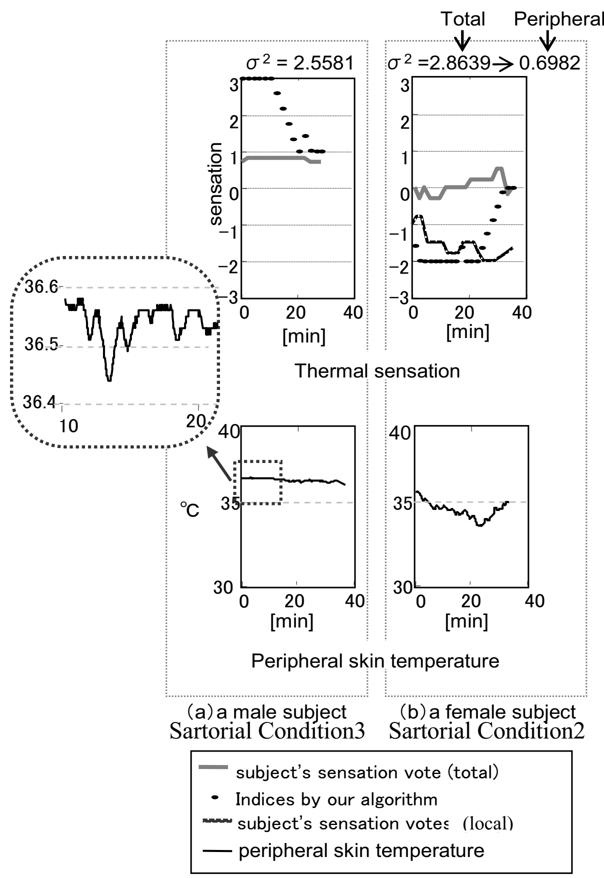


Figure 7, The results of apprication to new experiment's data

On the other hand, in Fig. 7 (b), the estimated indices are lower than the subject's votes. Here, taking notice of the local thermal sensation votes, the mean square error between the indices and the local thermal sensation votes become smaller. This indicates our algorithm may estimate local thermal sensation. The peripheral skin temperature change is depending on the activities of AVAs which maintain body temperature. Therefore, we assumed peripheral skin temperature doesn't contribute so much to the whole body thermal sensation, but local thermal sensation.

VII. AN APPRICATION OF THE PERIPHERAL SKIN TEMPERATURE'S FLUCTUATIONS

Finally, we applied the peripheral skin temperature fluctuations to control a household air conditioner. When someone sits down and keeps still in a room, they can sometimes feel cold even though they felt comfortable at first. Fig.8 (a) shows the peripheral skin temperature and thermal sensation votes when the subject sat through 90 minutes in 22 C. At first, the subject felt neutral, but after 10 minutes, he began to feel cold. At the same time, his peripheral skin temperature fluctuations finally disappeared.

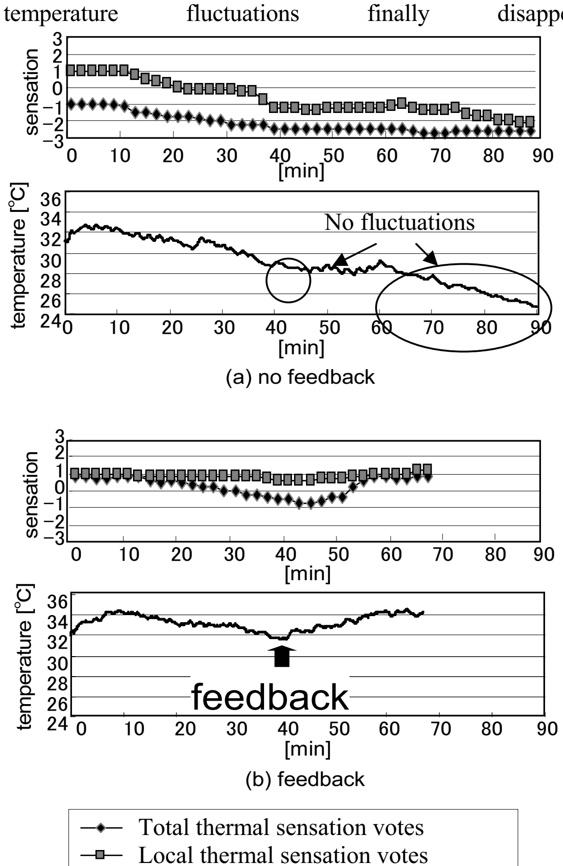


Figure 8. result of feedback

This indicates that the preset temperature of air conditioners witch one set well-intended at first can ultimately become too cold. So, we made an air conditioner controlling system using peripheral skin temperature fluctuations to avoid chill.

The system consists of a thermometer, a PC and an air conditioner. In this system, the thermometer can communicate wirelessly by Bluetooth to a PC, which analyzes the temperature data. If the PC doesn't find out the peripheral skin temperature fluctuations, it sends a command to the air conditioner to change the preset temperature to 30C. In this experiment, the initial preset temperature is 22 C. The subjects are 4 healthy adults (2 males and 2 females). This experiment starts under 22 C and maintains the preset temperature until PC change it.

Fig 8 (b) shows the results of a male subject (Fig .8 (a) and (b) use the same subject). His total and peripheral thermal sensation votes remained above -1 and his peripheral skin temperature continued to fluctuate. This must be caused by feedback. Now we defined keeping thermal sensation votes above -1 as success. In total thermal sensation votes, 4 trials were successes, and in local thermal sensation votes, 5 trials were successes. This indicates peripheral skin temperature fluctuations are again suitable for estimating local thermal sensation. In one trial in which both total and peripheral votes weren't successes, the subject's peripheral skin temperature didn't fluctuate throughout the experiment. In this case, our system couldn't find out why this occurred but we assume that peripheral skin temperature fluctuated at first.

These results indicate the feedback has a beneficial effect on chill.

VIII. CONCLUTION

This series of experiments indicate that we can estimate one's thermal sensation by the peripheral skin temperature's fluctuations and gradient, and that this method using the peripheral skin temperature is suitable for estimating local thermal sensation. In the experiment of household air conditioner system, the subject didn't feel chill by our algorithm. So, we believe that our algorithm can provide thermal comfortable indoor air condition to individual. We will continue to study for individual thermal comfort.

[1] Fanger,P.O., "Thermal Comfort-Analysis and Applications in Environmental Engineering", Danish Technical Press, Copenhagen, 1970

[2] ISO 7730 "Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort", 1994

[3] I. Mori, S. Hokoi, S. Takada, H. Tanaka, "Experimental study on thermal sensation index in thermal transients", Archit. Plann. Environ. Eng., AIJ, No563, pp.9-15, Jan, 2003

[4] A. Ishiburo, S. Hokoi, S. Tanaka, N. Komoto, M. Abuku, K. Ishizu, "Indoor climate for comfortable sleep, considering heat and moisture transfer between a bedroom, bedding and a human body : Air control system using a predictive model for thermal comfort", The Third International Conference on Human-Environment System ICHES'05. Tokyo, pp.139-144, September 2005.

[5] Eduardo H, Rubinstein, "Skin-surface Temperature Gradients Correlate with Fingertip Blood Flow in Human", Anesthesiology, Vol.73, No.3, pp.541-545, September 1990.

[6] Burch,G.E., Cohn,A.E., Neumann,C., "A study quantitative methods of the spontaneous variations in volume of the finger tip,toe tip and posterio-superior portion of the pinna of resting normal white adultes", American Journal of physiology, Vol.136, pp.433-447,1942.