Computers in Biology and Medicine 40 (2010) 650–656

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Dynamic infrared imaging for analysis of fingertip temperature after cold water stimulation and neurothermal modeling study

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ARTICLE INFO

Article history:
Received 20 July 2009
Accepted 14 May 2010

Keywords:
ANS (autonomic nervous system)
Microcirculation
Mathematical modeling
Thermography
Image processing

ABSTRACT

The human hand is considered to be the terminus of the nervous system. It contains numerous capillary vessels, and it plays an important role in the regulation of the autonomic nervous system.

We have used infrared thermography and ultrasound Doppler flowmetry to investigate characteristics of the temperature variation of the hand and the blood flow after cold stimuli. We have also developed an image processing algorithm to measure temperature of various parts of the hand via sequential thermal images. Measured results show that local cold stimuli will induce oscillation of temperature, which may be due to neuroregulation during rewarming. Finally, in order to explain the mechanism of autonomic nervous system (ANS) regulation we have developed an ANS regulation model on the basis of the knowledge of the physiology and bioheat transfer. The results computed using our model are in good agreement with the experimental results.

1. Introduction

The human fingertip is sensitive to outside stimulation due to the presence of numerous blood vessels and neural structures in the fingertip. Research of the patterns of thermoregulation and blood flow in the human hand is of great importance in the diagnosis of peripheral diseases and rehabilitation of functions of the hand and brain.

Thermal and hemodynamic responses of human extremities to different stimuli have been investigated in several studies. Shitzer et al. [1] simultaneously measured the temperature and blood perfusion in the fingertips that had been exposed to cold air. Bornmyr and Svensson [2] monitored the changes in finger skin blood flow and temperature after cigarette smoking. Zontak et al. [3] investigated the response of skin temperature to exercise using dynamic thermography and wanted to detect hemodynamic changes through variations of thermal images. Ducharme et al. [4] monitored finger blood flow and finger temperatures during cold air exposure in order to identify the critical factor for maintenance of finger dexterity during cold exposure. Sakashita [5] measured the skin temperature of the hands and the blood pressure before and after eating, mental activity, and exercising in order to investigate the relationship between autonomic nervous system (ANS) regulation and human physiological parameters. Hara and Nagaya [6] measured the temperature changes of a hand and a glove that was filled with a soft gelatin phantom during radiation heating using an electric stove. They observed that the temperature of the human hand increased and gradually approached a constant temperature, whereas that of the glove containing the soft gelatin phantom increased continuously.

Kistler et al. [7] investigated the changes in the fingertip temperature to determine if these changes are representative of sympathetically mediated reflex vasoconstrictor responses. They compared the changes in fingertip temperature and cutaneous blood flow caused by various sympathetic stimuli using infrared thermography, laser Doppler flowmetry, and photoplethysmography. From the results of these experiments, they easily observed the vasoconstrictions through fingertip temperatures.

Blank and Kargel [8] developed digital image processing techniques for dynamic thermal images, and they analyzed temperature variations in the finger and palm over time for different subjects who had been chewing nicotine gum or smoking cigarettes. They observed a significant decrease in palm and finger temperatures due to vasoconstrictors in habitual smokers when smoking cigarettes, whereas the temperature increases and decreases were found in about half of the smokers when chewing nicotine gums. In the group of nonsmokers, both smoking cigarettes and chewing nicotine gums showed temperature increases. They concluded that although the effects of nicotine on vasomotor control and temperature were difficult to assess, it is clear that nicotine has the strong and immediate impact on the human body. The image processing techniques

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doi:10.1016/j.compbiomed.2010.05.003

developed by them are useful for most dynamic image processing applications.

The above mentioned studies were mainly focused on the investigation of the effect of vasoconstriction and vasodilation on finger skin temperature; however, only local blood perfusion and finger skin temperature were measured in most studies. Hence, only qualitative explanations of the relationships between blood flow, the ANS, and thermal regulation could be obtained from these studies.

On the other hand, many researchers have attempted to develop quantitative models to measure the effect of the ANS and blood flow on peripheral temperature. Xu et al. [9] developed a model of nociceptor transduction for thermally induced skin pain and established a direct relationship between thermal stimuli and neural response. Their model includes three sub-models: (1) biothermomechanical model to calculate skin temperature, damage, and thermal stress; (2) current generation model to quantify the heat and for chemical and mechanical stimulation; (3) frequency modulation model to investigate the relationship between stimulation and spike rate. This model first established the relationship between skin temperature and neuroregulation.

He et al. [10] developed a one-dimensional thermofluid model of blood circulation in a human limb, which can simulate blood pressure, blood flow, and blood temperature in different vessels. Their model was further coupled with a finite element thermal model of a real-geometric middle finger to investigate blood perfusion and finger temperature [11]. They observed that contribution of blood flow in large arteries to tissue temperature was as important as that of blood perfusion. Their model first established the relationship between blood circulation and peripheral temperature.

Ley et al. [12] developed a lumped thermal model to study alternations in fingertip temperature during arterial occlusion and subsequent reperfusion. This lumped model provided an effective method to study vascular reactivity in the fingertip.

The purpose of our current study is to investigate the mechanism of regulation of blood flow and peripheral temperature by the ANS. In our modeling study, we present an integrative model that includes an ANS and a thermal model. In the experimental study, we performed infrared imaging to investigate fingertip temperature variation after cold water stimulation.

2. Experimental method

Five participants between 20 and 40 years of age volunteered as subjects for this study. They were all in good health. All experiments were carried out in a room with temperature and relative humidity 17 °C and 62%, respectively. Each experiment consisted of an 11-min protocol. During the first 100 s, the subject sat comfortably and the thermal images of the subject's hand were acquired. Subsequently, the index finger of the hand was immersed into cold water at 20 °C for 1 min. After immersion, the hand was taken out of the cold water and carefully dried, and thermal images of the palmar surface were obtained for 500 s by infrared thermography (TH5100, NEC). Time resolution was 1 frame every 5 s. After the imaging experiments were completed, the subjects sat still for about 1 h until the finger temperatures of the subjects restored to their initial values. Subsequently, the cold water stimulation experiment was repeated in order to measure the blood flow in the index fingertip before and after cold water stimulation. The wave form of blood in the fingertip was determined by ultrasound Doppler flowmetry (Hadeco, Smartdop 50EX-F) involving the use of a photoplethysmography (PPG) probe. It should be noted that all the volunteers were told if they felt uncomfortable during the experiment, they could stop in the midway. In addition, we tried different protocols before performing the experiment and found that immersing the finger in the cold water for 1 min might be feasible to avoid significant pain in the fingertip.

3. Data processing

The thermal images were 256×256 in size, and grey levels ranged from 0 to 255. In order to obtain temperature variations in different parts of the hand, automatic analysis techniques were performed on the acquired infrared images using a MATLAB-based platform. Procedures for image processing were as follows:

Step 1. Segmentation of target (hand) from images.
Step 2. Extraction of fingertips and palm.
Step 3. Computation of temperature variation in palm and fingertips.

3.1. Step 1. Segmentation of hand

The Otsu algorithm [13] is conventionally used for automatic detection of a threshold. The optimum threshold should be the value that helps to optimize the difference between the target and its background. Generally, maximum between-class variance is employed as criterion.

Suppose u_0 is the average grey level of background pixels; w_0, the area ratio of background pixels to total image pixels; u_1, the average grey level of the target pixels; w_1, the area ratio of target pixels to total image pixels. The global average grey level of the image may be then expressed as follows:

$$u = w_0 u_0 + w_1 u_1 \tag{1}$$

For a given image, global average grey level is constant, and the between-class variance is expressed as follows:

$$g = w_0(u_0 - u)^2 + w_1(u_1 - u)^2 \tag{2}$$

In order to improve efficiency of program computation, we used the following equation, which was developed from Eq. (2):

$$\begin{aligned} g &= w_0 u_0^2 + w_1 u_1^2 + (w_0 + w_1)u^2 - 2(w_0 + w_1)u \\ &= w_0 u_0^2 + w_1 u_1^2 + (u^2 - 2u) \\ &= w_0 u_0^2 + w_1 u_1^2 + u_0 u_1 - u_0 u_1 + \text{const} \\ &= -u_0 u_1 + u(u_0 + u_1) + \text{const} \end{aligned} \tag{3}$$

The between-class variance for every grey level from 0 to 255 in a given image was computed using Eq. (3) in order to obtain its maximum value; the threshold of the target was obtained using the maximum between-class variance.

The temperature of the index finger was observed to be lower than the temperatures of other target areas from the sequential images obtained after cold water stimulation; this implies that the index finger may be incorrectly detected as the background by the Otsu method. Hence, we developed an improved Otsu algorithm to detect the threshold of the target for the images obtained after cold water stimulation. The specific processing procedures for this improved Otsu algorithm are as follows:

(1) Divide a thermal image into $p \times q$ subimages (Fig. 1(a)).
(2) Compute threshold in subareas of the image and global threshold of the image, $T(p,q)$ and T_global, respectively (Fig. 1(b)).

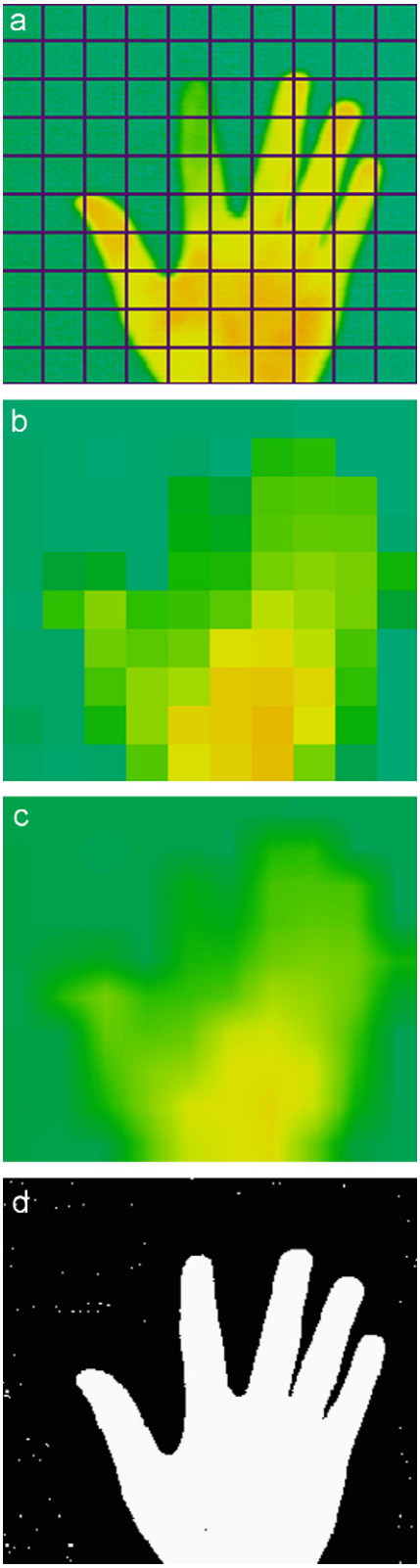

Fig. 1. Process for segmentation of hand: (a) subareas in an original image, (b) threshold corresponding to the subareas, (c) threshold area, and (d) binary image of the original image.

(3) Compute threshold area on the basis of the global threshold and the thresholds in the subareas, using the following expression:

$$T\_final = (1-k)T\_global + kT(p,q) \quad (4)$$

Here, k is assigned different values in different images. In our study, the values of k were in the range of 0.5–0.9. (Fig. 1(c)).

(4) Convert the original image into binary image according to the threshold map. If the grey level in the original image was less than the threshold in the corresponding area, then pixel would be set to 0; otherwise, pixel would be set to 1 (Fig.1 (d)).

3.2. Step 2. Extraction of fingertips and palm

In this step, we performed mathematical morphological image processing using three characteristic values, as follows:

Length of noise l_n 1–3 pixels
Width of finger w_f 15–20 pixels
Width of palm w_p 50–150 pixels

Using a disk-shaped structure element whose diameter was greater than l_n and less than w_f (In this step, the diameter was set to be 5, which is greater than 3 and less than 15.), a morphological opening was introduced in the binary image, so that noise in the background and heaved points at the edge could be deleted. Subsequently, a morphological closing was introduced using the same structure element to delete the noise in the palm and concave points at the edge. The binary image obtained after deleting the noise is shown in Fig. 2(a). The image of the palm was extracted by an opening operation using a disk-shaped structure element whose diameter is less than w_p and greater than w_f. Fig. 2(b) shows the image of the palm obtained after extraction.

The fingertip region was extracted by a thinning operation, which can be considered as an erosion operation with additional conditions. While performing the thinning operation, a pixel will be retained only if it is at the end point (i.e., there is only one pixel with the same grey level in its 8 neighborhood) or if the connectivity of the image is changed by the deletion of the pixel. After performing several iterations of thinning the binary image, an image with the thin lines of fingers was obtained (Fig. 2c). We considered the end point of the line to be the positions of the fingertips, and the fingertips could be extracted by a dilation operation (Fig. 2(d)).

3.3. Step 3. Computation of temperature variation for palm and fingertips

On the basis of the correlation between the grey level and temperature, we used the processed images to determine the average temperature variation with time in the palm and fingertips.

4. Modeling study

We developed our ANS model on the basis of earlier studies by Liang [14] and Xu et al. [9]. The peripheral thermoregulation pathway comprises the sensory nerves, receptors, central nervous system (CNS), efferent nerves, and effectors. Receptors are located in the hypothalamus; efferent nerves are sympathetic vasoconstrictors, and effectors adhere to arteriole smooth muscle. The flow chart of signal transport is shown in Fig. 3. The thermoregulation signal is considered to start from the current by the opening of ion channels in the sensory nerves, and the intensity of the current is related to the environmental temperature and the threshold of comfort. The receptors receive the frequency of impulse from external stimulation, and this frequency is a function of current. Therefore, the frequency in the

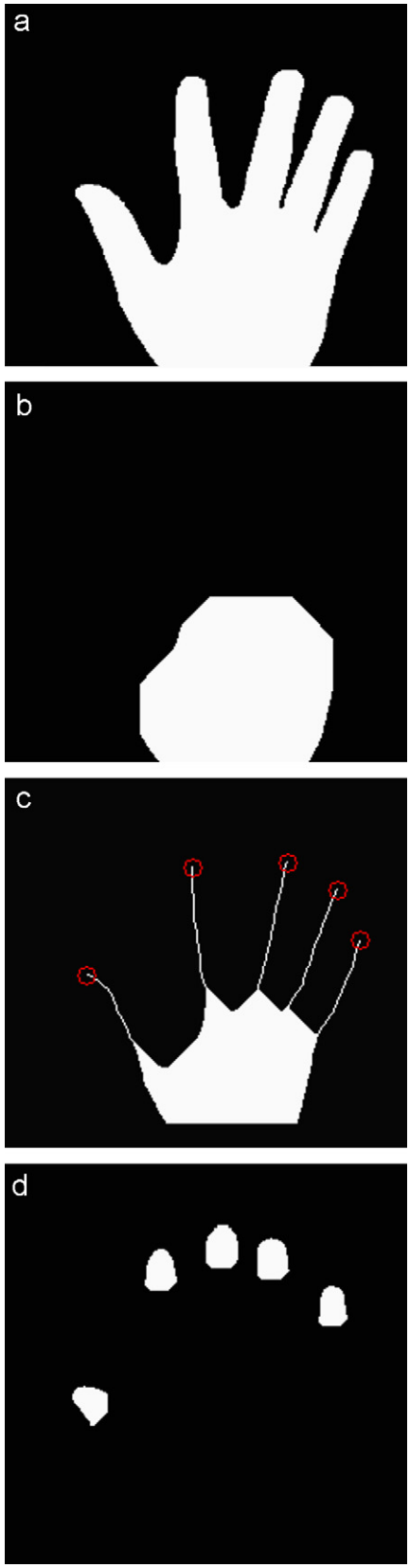

Fig. 2. (a) Binary image obtained after filtering the noise from Fig. 1(d), (b) palm region extracted from Fig. 2(a), (c) image obtained after thinning operation, and (d) image of fingertips extracted from Fig. 2(a).

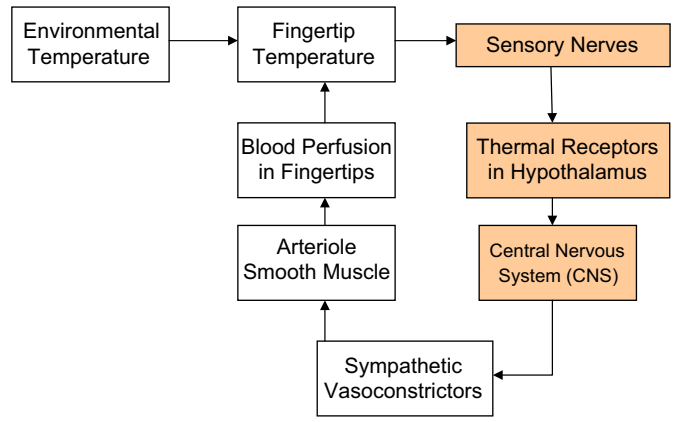

Fig. 3. Flow chart of peripheral thermoregulation of sympathetic nervous system.

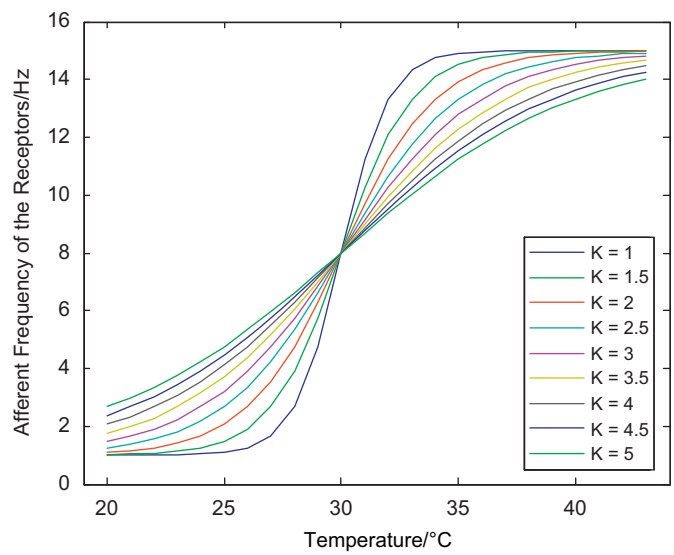

Fig. 4. The relationship between temperature and afferent frequency for different K (plotted according to Eq. (5)).

afferent fibers can be expressed as a function of temperatures, as follows:

$$f_{af} = \frac{f_{af,min} + f_{af,max}\exp[(T_{ftip,t} - T_{cri})/K]}{1 + \exp[(T_{ftip,t} - T_{cri})/K]} \tag{5}$$

Here, f_{af} is the frequency of spikes in the afferent fibers and $f_{af,min}$ and $f_{af,max}$ are the minimum and maximum values, respectively, of the frequency. K is the parameter that controls the slope of ($T_{ftip,t}$, f_{af}). Fig. 4 shows the relationship between the afferent frequency and temperature for different values of K. If K is equal to 3, f_{af} will reach its maximum value (15 Hz) when the fingertip temperature is 43 °C. It is considered that 43 °C is the threshold value of the tissue [9]. Thus, it is reasonable to choose K as 3. T_{cri} was considered as 30 °C.

After the thermal receptor receives the frequency in the hypothalamus, it delivers these signals to the central nervous system (CNS). It is considered that the CNS is instrumental in gathering the input information from the receptors and sending the modulatory signals, which it judges as the minimum one, to the effectors. The expression for this process is as follows:

$$f_{ef,in} = \min(f_{ef,in,max}, T_{af}) \tag{6}$$

Here, $f_{ef,in,max}$ is the maximum constant frequency discharged from the sympathetic nerves. Control signals from the CNS are

subsequently transferred to the effectors. In thermoregulation during cold water stimulation, a cutaneous vasoconstrictor nerve may be activated as the effector to allow arteriole smooth muscle to constrict; this causes changes in the blood perfusion. This variation is expressed as follows:

$$\sigma(t) = G_A \log[f_{ef,in}(t-D_A) - f_{efin,min} + 1] \tag{7}$$

Here, $f_{ef,in,min}$ is the threshold of the sympathetic nerve; D_A, latency time of nerves. Therefore, the blood perfusion after cold water stimulation can be expressed as follows:

$$\frac{d\Delta\omega(t)}{dt} = \frac{1}{\tau_A}\left[-\Delta\omega(t) + \sigma(t)\right]$$

$$\omega(t) = \omega_0 + \Delta\omega(t) \tag{8}$$

Here, $\omega(t)$ is the blood perfusion at time t; ω_0, the initial blood perfusion before stimulation; $\Delta\omega(t)$, the variation of blood perfusion at time t. The equation for skin temperature variation in the fingertip is adopted from Ley et al. [12], as follows:

$$\rho V C_p \frac{dT}{dt} = h_{air} A (T_{air} - T_{ftip,t}) + \rho_b C_{pb} \omega(t)(T_A - T_{ftip,t}) \tag{9}$$

Here, ρ is tissue density in fingertip; C_p, specific heat of tissue; ρ_b, density of blood; C_{pb}, specific heat of blood; T_A, temperature of arterial blood (assumed to be 34 °C) in the fingertip; T_{air}, environmental temperature; $T_{ftip,t}$, the fingertip temperature at time t; h_{air}, heat transfer coefficient. V is defined as volume of fingertip, which is assumed to be a hemisphere, and it is expressed as follows:

$$V = \pi D^3/12 \tag{10}$$

Here, D is average diameter of the fingertip. A is the skin area of the fingertip and is defined as follows:

$$A = \pi D^2/2 \tag{11}$$

Eqs. (5)–(9) were solved numerically by the fourth-order Runge–Kutta method.

5. Results and discussion

Some important parameters related to the autonomic nervous system model are listed in Table 1. Thermophysical properties used in Eq. (9) are listed in Table 2.

Fig. 5(a) shows the experimental results of the average temperature variations in the fingertips and palm at a state of rest. Fig. 5(b) shows the average temperature variations after cold water stimulation, and Fig.5(c) shows the temperature recovery profiles of one subject after cold water stimulation. We can see that temperatures in the palm and fingertips at the rest state are similar; moreover, there are almost no oscillations in the

Table 1
Some important parameters used in the model.

Minimum frequency	$f_{ef,min}$, $f_{af,min}$	1 Hz
Maximum frequency	$f_{ef,max}$, $f_{af,max}$	15 Hz
Sensitivity of receptor	K	3
Time constant for vessels	τ_A	6 s
Latency time of nerves	D_A	3 s

Table 2
Values of thermophysical parameters used in Eq. (9).

Properties	Tissue	Blood
Density ρ (kg/m^3)	1012	1060
Heat capacity C_p (J/kg K)	2865	3770
Initial blood perfusion ω_0 (m^3/s)		2.3×10^{-10}
Heat transfer coefficient at skin level h_{air}	6	

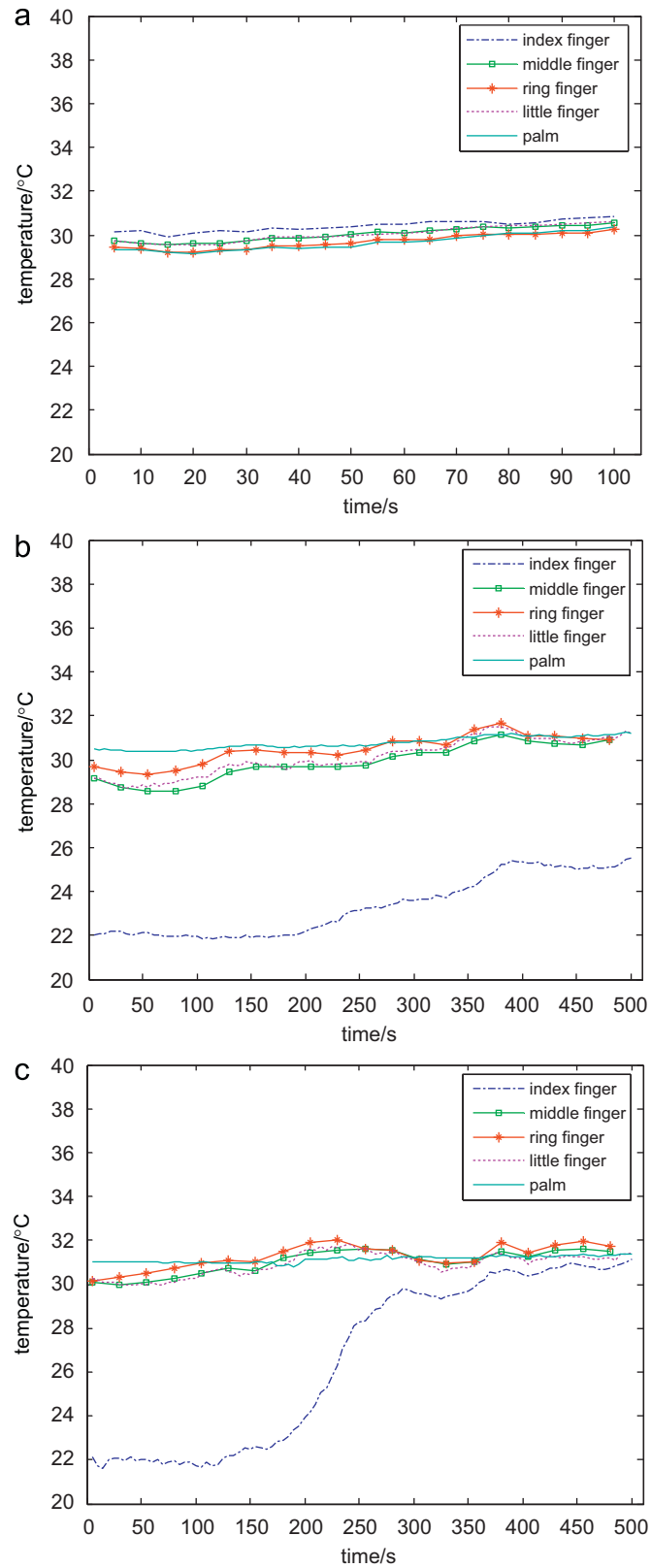

Fig. 5. Temperature variations in fingertips and palm: (a) average temperature variations for five subjects at rest state, (b) average temperature recovery profiles for five subjects after cold water stimulation, and (c) temperature recovery profiles of one subject after cold water stimulation.

temperature profiles. After cold water stimulation in the index finger, all temperature profiles show oscillations; however, the temperature profile of the palm shows the minimum oscillation.

Fig. 6 shows the blood flow wave forms in the fingertip at the rest state and after cold water stimulation measured by ultrasound Doppler flowmetry. The vertical coordinate denotes the parameter related to volume blood flow. We can see that blood flow in the index finger decreased considerably, and the wave form changed after cold water stimulation.

Fig. 7(a, b) shows the simulated results with different nervous control signals. Fig. 7(a) shows the temperature recovery profiles when the nervous control signal is periodic and can be expressed as follows:

$$f_{ef} = \left[1 + \frac{1}{2}\sin(\pi t)\right] f_{af,pre} \tag{12}$$

Here, $f_{af,pre}$ is the afferent frequency in the previous time step. We can see that the simulated variation profiles follow the same trend as those obtained from measurements. If the nervous control signal is constant, temperature recovery profiles will be smooth and oscillation-free, similar to those plotted in Fig. 7(b). From these results, it is speculated that temperature oscillation in the measurements may be due to periodic variation of the nervous control signal.

Fig. 8(a) shows the results of the simulation when the blood perfusion rate is zero. We can see that temperature of the index finger increases slowly, while the temperatures of the other fingertips decrease. This implies that blood perfusion plays an important role in recovery of temperature in the index finger. If there is no blood perfusion, temperature in the index finger cannot be restored to its original value at the rest state. Fig. 8(b) shows temperature variations when the control of the ANS is not activated. We can see that in this case, temperatures of the fingertips will increase beyond a comfortable skin temperature and be close to the arterial temperature. This implies that the ANS is instrumental in regulating blood perfusion, so that skin temperature is maintained at a comfortable level.

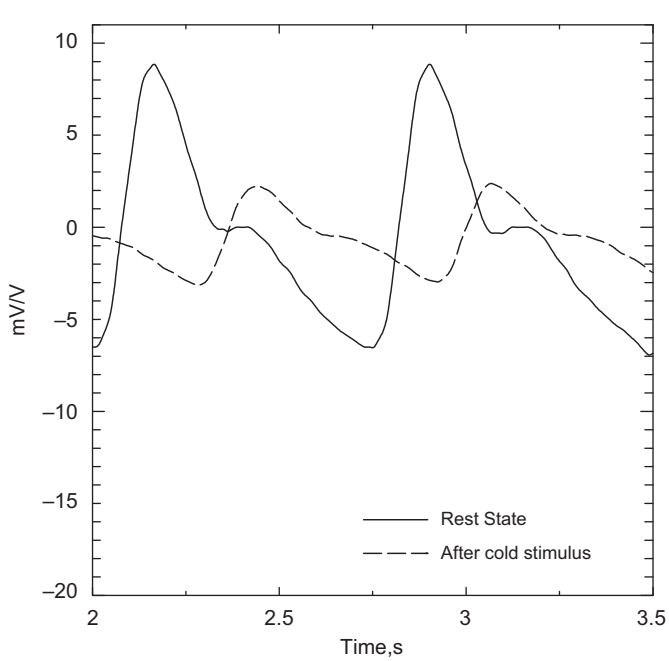

Fig. 6. Blood-flow wave form in the index fingertip.

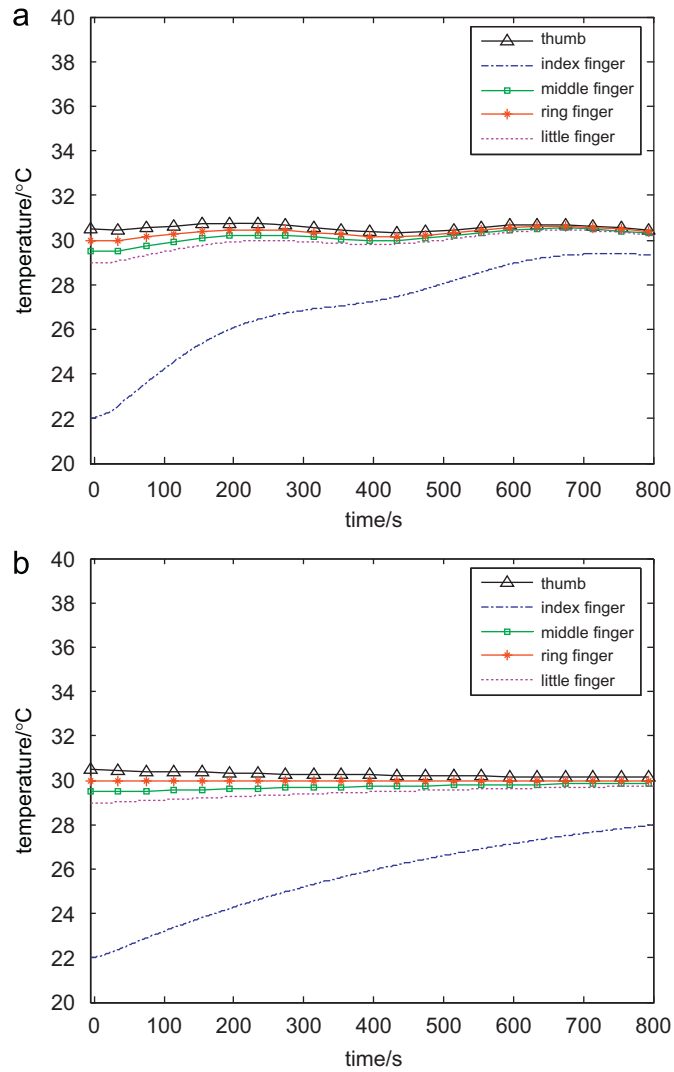

Fig. 7. Simulated temperature variations in fingertips and palm: (a) under periodic control of the ANS and (b) under constant control of the ANS.

6. Conclusions

In this study, we developed integrative neural and thermal models to study thermoregulation in peripheral extremities, and we conducted an experimental study involving thermographic monitoring of cold water stimulation. In the course of our experiments, we developed an automatic image processing method that can be used to study the temperature variation in a specific part of the hand. Our conclusions are as follows:

1. After cold water stimulation, periodic variations are observed in all fingertip temperature profiles, even if the finger was not stimulated by cold water.
2. The blood flow plays an important role in the recovery of fingertip temperature. If the blood perfusion in the fingertip is zero, the simulated temperature in the index finger will increase more slowly than the measurements and the temperature in other fingers will decrease, which is in disagreement with the experiments.
3. Our modeling study shows that the periodic variations may be due to the periodicity of the nervous control signal. In the absence of nervous control signals, fingertip temperature will increase rapidly to a point beyond a comfortable temperature.

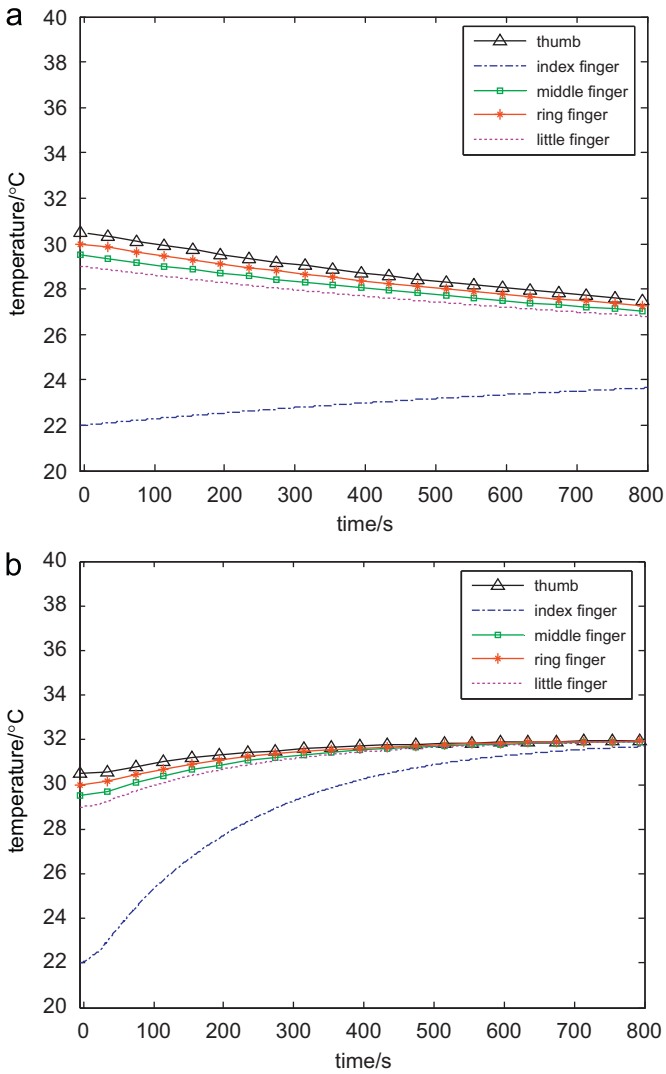

Fig. 8. Temperature recovery profiles for different fingertips in different regulation conditions: (a) without blood perfusion and (b) without nervous control.

Further development of this model is required to investigate the CNS pathway and achieve better pattern recognition. Moreover, blood flow variation in the fingertip during periods of cold water stimulation should be simulated, so that the relationship between blood flow and nervous control can be monitored continuously.

Conflict of interest statement

There is no conflict of interest for this paper.

Acknowledgments

This work is supported by NSFC Grant no. 10772176 and the National Innovative Program for Undergraduate Students (2008). We thank Dr. Fu-You Liang for his helpful suggestions.

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