Analysis, Design and Modeling Skin Thermal Pain Sensation in Robot

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Abstract: In human and robot coexistence, human sensory feelings are aroused in the case of interaction. This causes such an unpleasant feeling called pain, which is an important feeling in avoiding danger. For more safe interaction, it becomes important for robots to sense pain. Thus in this paper the focus is on design a controller based on the thermal pain that is subjective of human. When the temperature is out of the normal physiological range, skin fails to protect, and the pain sensation is evoked. The first goal of this paper is to present the computer-aided analysis of the heat transfer in skin tissue using the clinical data. Afterward, we aim to cast the biological behavior of skin in an engineering system. Then we attempt to establish a modeling of skin thermal pain through ion channel to pain sensation. Finally, to emulate the thermal pain, we design a controller based on the thermal pain model.
[Farshid Tabatabaie S, Haghipour S, Soltani A. **Analysis, Design and Modeling Skin Thermal Pain Sensation in Robot**. *Life Sci J* 2013;10(3s):515-520] (ISSN:1097-8135). http://www.lifesciencesite.com. 81

Keywords: Nociceptor; Neural response; Pain modeling; Bioheat transfer; Safety system

1. Introduction

Recently, as robots have started to share the daily life with human and they are working in ever-closer physical proximity to each other, an interaction between human and robot is being one of the main problems because of these share and proximity. Thus in order to keep this interaction safe among them, the pain sensing will be an important ability for robots. In this study "thermal pain system" has been focused, which is a typical unpleasant feeling when one contacts extreme hot/cold objects. One of the important aims of the presented study is that robots, in their assigned duties, not only to confront least damage, but also to harm-minimally the environment, especially human. Thus by applying a pain system in robots, they would have a capability to do this safety duty in the best way. In order to design an optimized pain sensation system, this study focused on the issues of analyse and modeling human skin thermal pain sensation. The ability to feel pain is one of the great importances for our survival. It can be described as the perceptual counterpart of the body's response to stimuli that threatens the integrity of body's tissues [1]. Therefore the pain system functions such a warning system of threats to the organism.

The idea of sensing and extracting temperature data is not new, but tends to be ignored, even though thermal properties help in the identification of an unknown object or environment. There are early theories about pain and transmission of pain signals in the body, which one of the oldest presented by Aristotle 300 years BC [2]. The ancient Greek philosopher Aristotle described pain as a feeling, situated in the heart. Several hundred years later a physician in Alexandria, Galen, described the brain as the basis for feelings and concluded that pain was a sensation of the brain [2]. In 1644 Descartes published his text *De l'homme* (*About man*), representing his famous image of pain transmission from the periphery to the brain. In 2005, Matsunaga et al. presented a mechanical pain model using ANNs, focused on realization of safety robot embedded the pain model but did not investigate the physiology of pain and skin tissue [3]. In 2008, Matsunaga et al. developed a novel pain sensor with laminated structure of skin and the output of the dynamical pain model that uses the signal of developed pain sensor as an input was evaluated in experiments. But the developed pain sensor could not simulate the construction and characteristics of skin precisely [4]. In 2010, Xu et al. presented a mathematical model to characterize the non-Fourier thermal behavior effect in skin tissue upon the thermal-neural response of thermally sensitive nociceptors [5].

The paper is outlined as follows: the physiology of pain is first introduced, followed by currently available mathematical pain models and computerized analysis of the heat transfer. Afterward, the development of the model and the design of pain sensation system based on the biological system are presented. The major problems, issues and topics for further studies are also outlined.

2. Physiology of pain

All creatures live in a thermal environment, where skin is the interface with protecting function. Skin plays a variety of roles which enable it to be one of important parts of body and acts as a barrier to various outside conditions [1]. However, when the temperature range exceeds the thermal threshold, the skin will be failed to protect the body in the best way, which caused pain [1].

Pain, as one of the main sensations of creatures, has been investigated vastly for a long period of time. The International Association for the Study of Pain has defined it as: "Pain is an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" [7-8]. Pain motivates the individual to withdraw from damaging situations, to protect a damaged body part while it heals, and to avoid similar experiences in the future. According to aetiology, pain can be classified as three different classes: nociceptive pain; inflammatory pain, and pathological pain. Painful stimuli to the skin tissue is received by special receptors called nociceptors which respond to painful stimuli by sending nerve signals in the form of electrical pulse to the spinal cord and brain via Aδ and C fibers. The pain pathway is shown in Figure 1 and can be classified as the following steps: transduction: the moment a pain is evoked, some action potentials are generated by nociceptors; transmission: the signals are transmitted in the form of chains of action potentials to the spinal cord; perception and modulation: the perception of signals arriving in higher structures as pain [1].

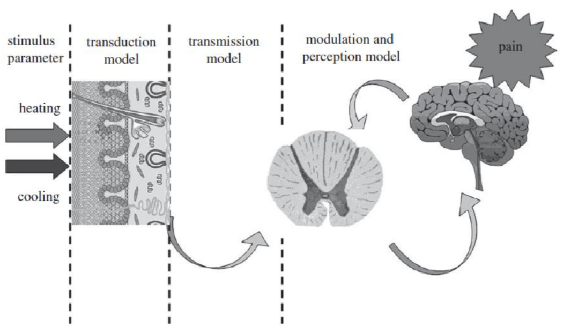


Fig. 1. Thermal-pain pathway [1].

materials and methods

A. Skin thermal pain modeling

Mathematical modeling can help us to solve complex theories as well as predict skin thermal pain behavior that had perhaps previously gone unnoticed [10]. The proposed model of pain transduction is divided into three sub-models: bioheat model of skin tissue, current generation model and frequency modulation model.

A.1 Bioheat model of skin tissue.

Mathematical modeling has proved that bioheat transfer is one of best selections for analyzing temperature distribution and heat transfer in skin tissue [12]. In this section bioheat simulation has done by using Pennes classical bioheat equation. With involving physical parameters, heat transfer in the layers of skin tissue has modeled. Pennes' model is considered the original bioheat transfer model, and was the first model which attempt to quantify the contribution of perfusion to the heat transfer within skin, which is given as:

$$\rho C\frac{\partial T}{\partial t}=k\frac{\partial^2 T}{\partial t^2}+\rho_b \dot{w}_b C_b (T_a - T)+q_{met}+q_{ext}$$

Where ρ is the density of tissue; C is the volumetric specific heat of the tissue; T is the temperature; t is the time; k is the thermal conductivity of the tissue; ρ_b is the density of blood;ω_b is the blood perfusion rate; c_b is the volumetric specific heat of the blood; and T_a is the blood temperature entering the thermally-treated area (core body temperature); q_{met} is the metabolic heat generation; and q_{ext} is the heat source owing to other heating. It is assumed in the current study that a more advanced model of bioheat transfer with greater mathematical complications, does not warrant higher accuracy and also seems to be unnecessary in the current study.

All physical and geometrical properties of the model are presented in Table 1. With having these parameters and also solving bioheat transfer equation we can model the heat transfer distribution in skin tissue.The radius and temperature of the hot plate are 3mm and 70°C. The ambient temperature was considered as being 37^0C. When the skin temperature be exceeded a critical value, which is approximately 43°C, thermal pain will be induced.

The human skin can be modeled as a three layered region: epidermis, dermis and subcutaneous fat. Axis oz is the symmetry axis. In Figure 2 the 2-D model of the human skin is shown in the plane orz. The Pennes bioheat equation in the case of cylindrical coordinates will be changed to Eq.2 [15]:

$$\rho C\frac{\partial T}{\partial t}=k(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2})+\rho_b \dot{w}_b c_b (T_a - T)+q_{met}$$

TABLE I. Physical and geometrical properties of the model [1].

Parameters	**Epidermis**	**Dermis**	**Fat**
Thickness (mm)	***0.075***	***1.5***	***3.42***
Density (Kg/m^3)	***1190***	***1116***	***971***
Specific heat (J/Kg.K)	***3600***	***3300***	***2700***
K	***0.21***	***0.37***	***0.16***
q_{met} (W/m^3)	***368.1***	***368.1***	***368.3***

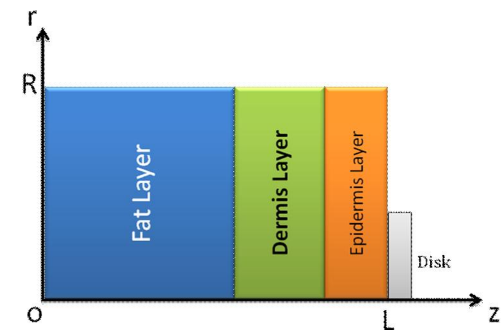


Fig. 2. An axisymmetric model.

A.2 Current generation model.

After determining the degree of temperature surrounding receptors, the next step is to determine the amount of stimulated current due to opening ion channels in nociceptors which are gated by three different types of stimuli. These types of stimuli include thermal, mechanical and chemical. Thus the stimulated current will be related to three different currents [17], and can be simply given as:

$$I_{st} = I_{heat} + I_{chem} + I_{mech}$$

Since in this paper, only thermal pain is considered, the mechanical and chemical currents can be omitted. Thus the total stimulated current can be calculated as:

$$I_{st} = I_{heat} = \left[C_{h1} \exp\left(\frac{(T_n - T_t)/T_t}{C_{h2}} \right) + C_{h3} \right] \times H(T_n - T_t)$$

where C_{h1}, C_{h2} and C_{h3} are constants; and $H(x)$ is the Heaviside function.

A.3 Frequency modulation model.

The moment stimulated current be above of the critical degree of temperature, an impulse is generated, and by calculating the frequencies of such this impulse, the intensity of stimulation can be extract [17]. Some experimental observations of nociceptors are presented in Figure 3 [13], which refers the stimulus intensity-impulses frequency relationship. It can be inferred by the figure that the low stimulus causes low frequency of output impulses and by increasing stimulus intensity, the frequency as well as increases nonlinearly.

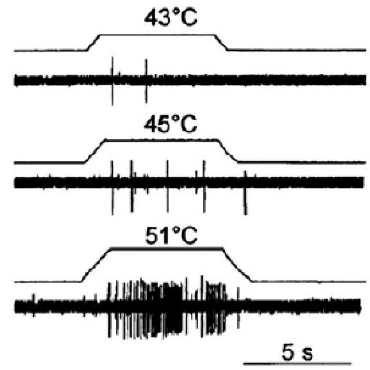


Fig. 3. Experimental observations of the nociceptors in skin tissue evoked by heat stimuli (response threshold to heat was 43°C) [13].

Several factors like ionic and leak channels contribute to the electronic features of the cell membrane. Since scientists prove neurons behavior is qualitatively similar to that described by the Hodgkin–Huxley (H–H) model, we have used the H-H model to simulate biological neuron behavior [16]. The H–H model was originally developed for an unmyelinated nerve fiber. It is used here for skin nociceptors that are found to be both unmyelinated (C-fiber) and myelinated (A-fiber), in view that the H–H model has already been extended to myelinated axons and muscle fibers.

In the electronic skin model of Hodgkin and Huxley (Figure 4), the voltage-gated channels are represented as variable resistors since their amounts depend on the membrane potential, while the leak channel is represented by a constant resistor. Since the cell membrane acts as a dielectric, it is shown as a capacitor in this model.

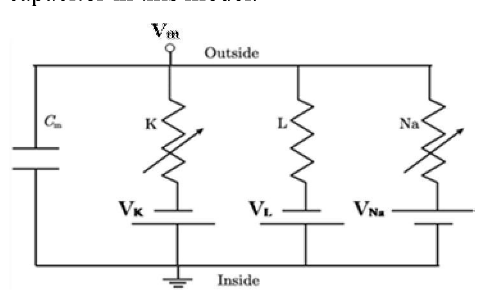


Fig. 4. Hodgkin and Huxley model [16].

By solving this model, the ionic and leak currents can be calculated.

$$C_m \frac{dV_m}{dt} = I_{st} + \bar{g}_{Na} m^3 h (E_{Na} - V_m) + \bar{g}_K n^4 (E_K - V_m) + g_L (E_L - V_m)$$

B. thermal pain system designing

Despite a large base of research on tactile transduction and feedback, a few researches have been conducted on thermal and pain sensation. This section describes the development of the thermal pain system to cover the aim and objectives.

In industrial applications, the safety of human-robot interaction is affected by isolating robots from the human. As robots move from isolated industrial environments to interactive ones, this approach is no longer tenable. Three main approaches can be used to mitigate the risk during human-robot interaction: (i) redesign the system to eliminate the hazard, (ii) control the hazard through electronic or physical safeguards, and (iii) warn the operator/robot, either during operation or by training. While the warn/train option has been used in industry, it had not been deemed effective in that setting, and is even less suitable for robot interaction with untrained users. An example of redesign includes using a whole body robot covering.

In unstructured environments, mechanical design alone is not adequate to ensure safe and human friendly interaction. Additional safety measures, utilizing system control and planning, are necessary. Several approaches have been proposed for ensuring safety through control. They focus on either slowing down or stopping when a hazardous situation is identified, moving to evade contact, or trying to minimize the impact force if contact occurs. A key problem for all of these control methods is to identify when safety is threatened. One approach is to use thermal sensors and tactile sensors to identify a hazard when unplanned contact occurs.

In this section, the multi-sensor model has been designed by the biological model and the modeling results that explained below. Thus some temperature sensors are used to detect the temperature of the environment, which send relevant information to microcontroller 1 that plays the role of cell body in nerve.

Here some impulses with different frequencies according to the temperature sensed by the sensors are sent to the microcontroller 2 which plays the role of brain. By passing this process, the necessity commands are submitted to the related actuators of the robot to protect it from risks.

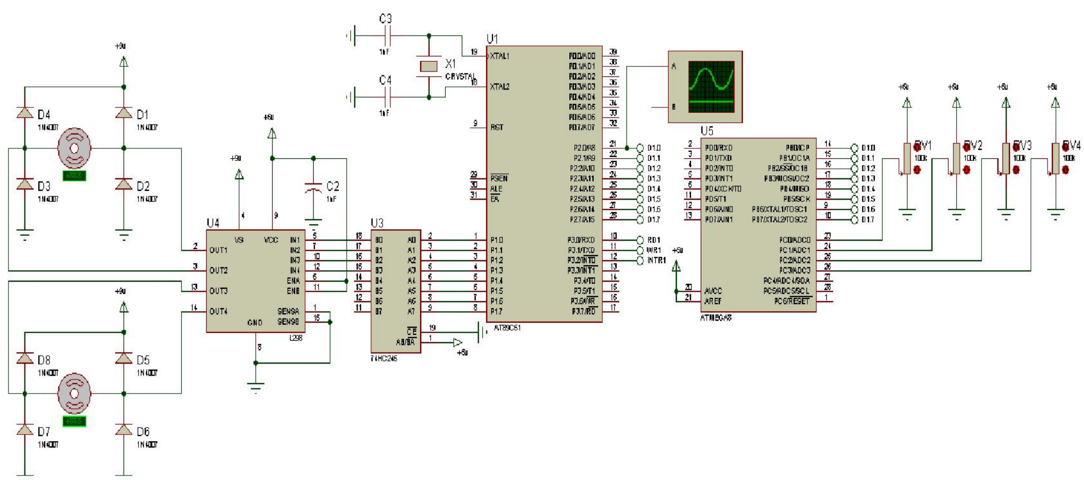


Fig. 5. Schematic of a multi-sensor thermal pain system.

3. Results

In Fig.6 and Fig.7 the results of the numerical simulation are shown using the PDE Toolbox of the software Matlab.

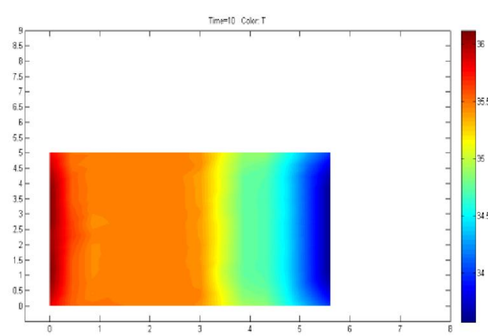


Fig. 6. Map of initial temperature.

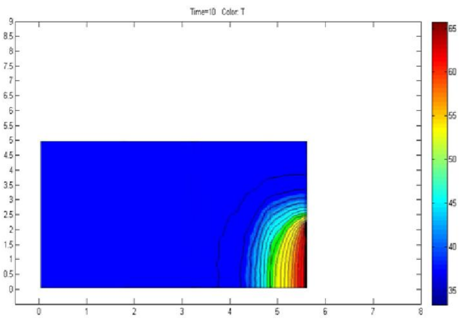


Fig. 7. Simulation of heat transfer in the stimulated zone of the skin tissue at 70ºC.

In the model of current generation section, the current-temperature relation predicted from Eq. (4) is plotted in Fig.8. At current understanding, it is not sure of the highly nonlinear neural impulse initiation component in the response characteristics of nociceptors.

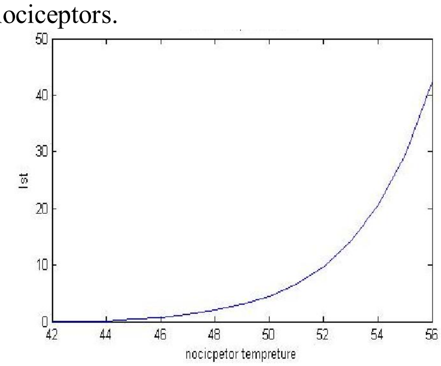


Fig. 8. Current-temperature relationship.

In the model of frequency modulation section, as shown in Figure 9, four neurons in different distances of the stimulated part were used and the input stimulus has been considered as a ramped pulse. It can be inferred from the results, whatever the neurons keep distance from the stimulated point, they cannot follow the input in a best way and also it can be seen that the low stimulus causes low frequency of output impulses and by increasing stimulus intensity, the frequency as well as increases nonlinearly.

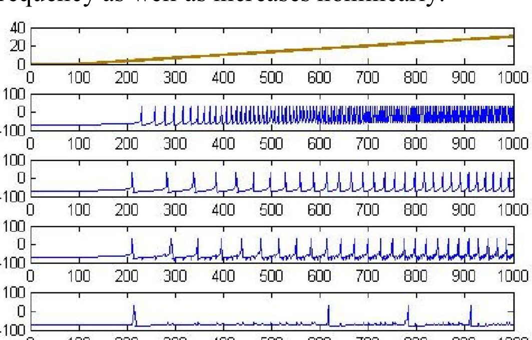
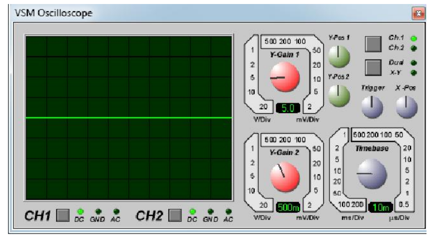
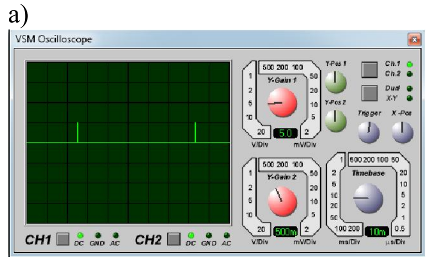


Fig. 9. Four connected networks follow the input oscillations.

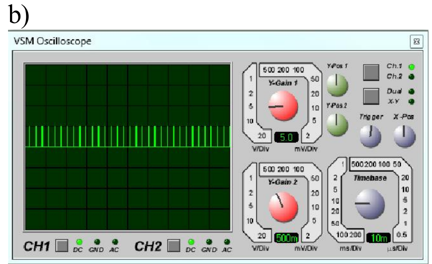
The results of the design are shown in Figure 10. As seen in the Figure 10, whenever the ambient temperature of sensors exceeds the pain threshold, the frequency of impulses which indicates the pain intensity, will increase.



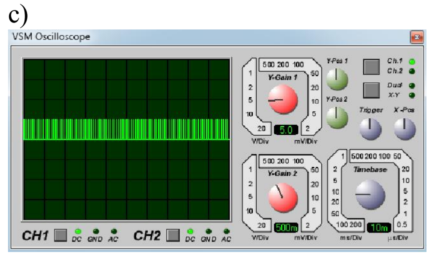
a)



b)



c)



d)

Fig. 10. Microcontroller output at the temperature a) below the threshold, b) equal to the threshold, c) relatively higher than the thresholds, d) beyond the threshold.

4. conclusion

In this study, to prepare a safe interaction between human and robot, the focus has been on modeling thermal pain sensation which is as sophisticated as other physiological phenomena. In this paper, according to the mechanism of nociceptor transduction, the proposed model of transduction is further divided into three sub-models: a bio-thermal model of skin tissue, a model of current generation and a model of frequency modulation.

The mathematical model enriches the understanding of the transduction of temperature to action potentials. This model has been developed to characterize the effect of thermal behavior in skin tissue upon the thermal-neural response of thermally sensitive nociceptors. The model is used to calculate the temperature, membrane voltage variation and frequency response of nociceptors under surface heating. It has been demonstrated that the model is capable of capturing the essential properties of experimentally measured frequency responses. With the presented model, the intensity of thermal pain can be predicted directly by a robot to safe itself from probable dangers. In this paper, the pain model was evaluated by experiments comparing the subjective pain. This pain model, which can simulate the construction and characteristics of skin precisely, provides the good signal with the subjective pain.

References

[1] Xu, F., Lu, T. J., 2011. Textbook of “Introduction to Skin Biothermomechanics and Thermal Pain”. Science Press Beijing and Springer-Verlag Berlin Heidelberg.

[2] Perl, E., 2007. “Idea about pain, a historical view”. Nature Rev Neuroscience , pp. 71-80.

[3] Matsunaga, N., Kuroki, A., and Kawaji, S., 2005. “superficial pain model using ANNs and its application to robot control”. *IEEE/ASME Int. Conf. Advanced Intelligent Mechatronics*. Monterey, California, pp. 664-669.

[4] Matsunaga, N., Kawaji, S., 2008. “Development of the Pain Sensor Simulated the Laminated Structure of Skin”. Asia International Symposium on Mechatronics, pp. 419-424.

[5] Xu, F., Lu, T. J., and Lin, M., 2010. “Modeling skin thermal pain sensation”. Computers in Biology and Medicine 40, pp. 478–486.

[6] Marasco, P. D., 2011. “Robotic touch shifts perception of embodiment to a prosthesis in targeted reinnervation amputees”. A Journal of Neurology, Brain Advance Access published January 20, 2011, pp 2-12.

[7] Loeser, J., Treede, R., 2008. “The Kyoto protocol of IASP basic pain terminology”. Pain 137, pp. 473–477.

[8] Merskey, H., Bogduk, N., 1994. “Classification of Chronic Pain”. IASP Press, Seattle, Second edition, pp. 209-214.

[9] Brooks, J., Tracey, I., 2005. “From nociception to pain perception: Imaging the spinal and supraspinal pathways”. Journal of Anatomy, 207(1), pp. 19–33.

[10] Britton, N. F., Skevington, S. M., 1996. “On the mathematical modeling of pain. Neurochem”. Res. 21, pp. 1133–1140.

[11] Tillman, D. B., Treede, R. D., Mayer, R. A., and Campbell, J. N., 1995b. “Response of C fibre nociceptors in the anaesthetized monkey to heat stimuli: estimates of receptor depth and threshold”. Journal of Physiology 485 (Pt 3) , pp. 753-765.

[12] Pennes, H. H., 1948. “Analysis of tissue and arterial blood temperatures in the resting human forearm”. Journal of Appl. Physiology 1, pp. 93–122.

[13] Cain, D. M., Khasabov, S. and Simone, D., 2001. “Response properties of mechanoreceptors and nociceptors in mouse glabrous skin: an in vivo study”. Journal of Neurophysiology 85, 1561–1574.

[14] Ping Huan, Hsueth-Erh Liu, Chih-Wei Chen, Hong-Sen Kou, 2008. “Temperature response in biological tissue by alternating heating and cooling modalities with sinusoidal temperature oscillation on the skin”. International Communications in Heat and Mass Transfer 35, 1091-1096.

[15] Dominique Van de Sompel, Tze Yean Kong, Yiannis Ventikos, 2009. “Modelling of experimentally created partial-thickness human skin burns and subsequent therapeutic cooling: A new measure for cooling effectiveness”. In: Medical Engineering & Physics 31, Elsevier Ltd.

[16] Hodgkin, A. L., Huxley, A. F. 1952. “A quantitative description of membrane current and its application to conduction and excitation in nerve”. Journal of Physiology 117, 500–544.

[17] Zhu, Y. J., Lu, T. J., 2010. “A multi-scale view of skin thermal pain: from nociception to pain sensation”. Phil. Trans. R. Soc. A 368 , 521-559.

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