35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Thermophysiological Responses Induced by a Body Heat Removal System with Peltier Devices in a Hot Environment *

Jun Suzurikawa, Sho Fujimoto, Kousei Mikami, Hiroshi Jonai, and Takenobu Inoue

Abstract— **Individuals with spinal cord injuries often experience thermoregulation disorders as well as sensory and motor disabilities. In order to prevent such individuals from becoming hyperthermic, we developed a body heat removal system (BHRS) with thermoelectric devices. Our BHRS comprises four Peltier devices mounted on a wheelchair backrest and continuously transfers body heat through the contacting interface to the external environment. Here, we characterized thermophysiological responses induced by this novel contact-type cooling system. A cooling experiment in a hot environment with five able-bodied subjects demonstrated that sweating and systolic blood pressure in the back-cooling (BC) trial were significantly suppressed compared with those in no-cooling (NC) trial, while no difference was found in oral and skin temperatures. A correlation was observed between chest skin temperature and blood flow in the NC trial; this was not observed in the BC trial. These results suggest that BHRS modulates normal thermoregulatory responses, including sweating and vascular dilation and has the capability to partly replace these functions.**

I. Introduction

Human body temperature is maintained by the thermoregulatory system, which monitors and adjusts heat balance between the body and external environment [1],[2]. Individuals with physical disabilities, however, are known to lose this thermoregulatory function. Most individuals with spinal cord injuries (SCI), for example, have lost not only their sensory and motor functions but also their autonomic functions [3]-[5]. Individuals with SCI, therefore, often cannot sweat even in a hot environment. Consequently, they face the risk of heat stress in everyday life, especially in situations where atmospheric temperature control devices such as air conditioning systems are not available. Because hyperthermia, also known as abnormal increase in body temperature, can sometimes leads to serious adverse events, including death, the heat risk critically limits the daily activities of individuals with disabilities.

Some trials utilized contact-type cooling apparatuses focused on increased suppression of body temperature in individuals with physical disabilities [6]-[8]. However, most of these trials reported on acute symptomatic treatments under limited circumstances, such as wheelchair sports, and dealt with the problem of how to lower already increased body temperature. Moreover, during the cooling phase in these trials, the subjects were constrained by the cooling apparatus and restricted from moving freely. No solution has been proposed from the viewpoint of preventing hyperthermia onset during the activities of daily living.

To address this issue, we developed a body heat removal system (BHRS) that is mountable on a wheelchair and prevents individuals with physical disabilities and thermoregulaory disorders from becoming hyperthermic [9]. The main component of this system is a Peltier thermoelectric device that is attached on the backrest of the wheelchair. Peltier devices continuously transfer body heat through the contacting interface to the external environment, and this continuous heat transfer is expected to prevent hyperthermia in hot environments, even when thermoregulatory responses are compromised. Because the wheelchair backrest is the component on which individuals with physical disabilities normally make contact with, body temperature control by BHRS is an automatic event that occurs during everyday activities.

This study aimed to comprehensively determine the type of thermophysiological responses induced and/or altered by this novel contact-type continuous cooling system in a hot environment. In order to achieve this aim, we performed a body-cooling experiment in a hot environment with five able-bodied subjects. Temporal changes in various physiological parameters with and without cooling by BHRS were systematically monitored and compared. Statistical analyses were then performed to ascertain the feasibility of body temperature control and characterize relationships among the physiological parameters measured.

II. Materials and Methods

A. System description

Fig. 1(a) shows a schematic diagram of BHRS proposed. This system comprises four Peltier devices (Ampere Inc., UT40U100F) clamped on a backrest of a power wheelchair (Permobil, C300TS) as shown in Fig. 1(b; i, ii). The backrest is constructed from two duralumin plates, and two Peltier devices are attached with a pressing load of 200 N to both plates. The Peltier devices are driven by external controllers (Ampere Inc., UCT200A). The total heat absorption rate of the present BHRS is 144 W when the temperature difference between the hot and cold sides of the Peltier device is zero.

* This work was supported in part by NEDO.

J. Suzurikawa is with Research Institute, National Rehabilitation Center for Persons with Disabilities, Saitama 359-8555, Japan (Corresponding author, e-mail address: suzurikawa-jun@rehab.go.jp).

S. Fujimoto is with Graduate School of Science and Technology, Nihon University, Tokyo 101-8308, Japan.

K. Mikami is with College of Industrial Technology, Nihon University, Chiba 275-8575, Japan.

H. Jonai is with Graduate School of Science and Technology, Nihon University, Tokyo 101-8308, Japan.

T. Inoue is with Research Institute, National Rehabilitation Center for Persons with Disabilities, Saitama 359-8555, Japan.

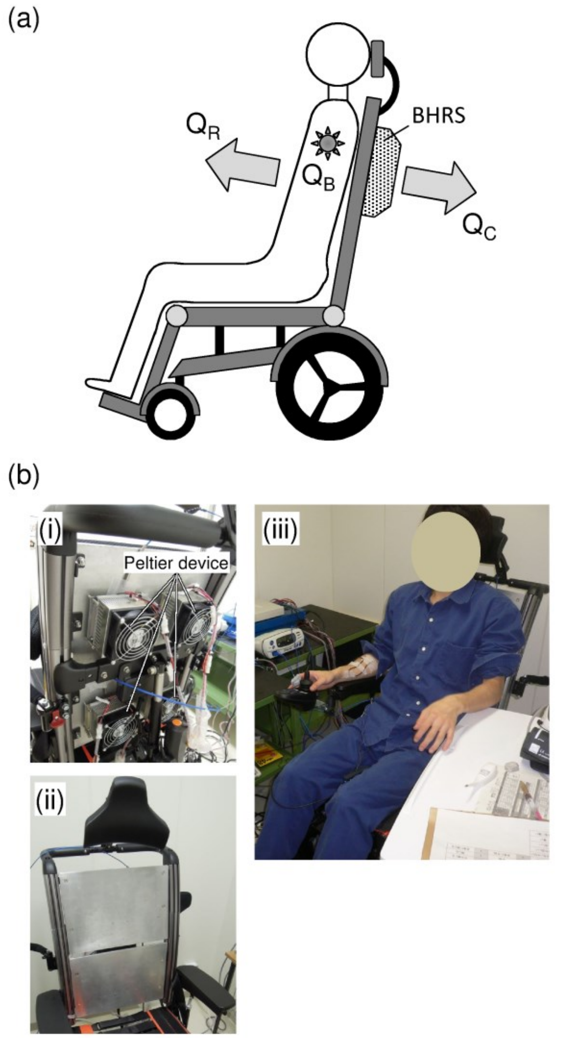

Figure 1. Experimental scheme. (a) Conceptual diagram of BHRS. Artificial heat removal (Q_C) assists in balancing heat production by the body (Q_B) with heat dissipation by thermoregulation (Q_N). (b) The test BHRS setup. Four Peltier devices (i) are attached to the duralumin backrest of a wheelchair (ii) on which the subject is seated (iii).

B. Subject

Five healthy and able-bodied subjects participated in the experiment. The age, height and weight of the subjects ranged from 21 to 23 years, 172 to174 cm, and 50 to 70 kg, respectively. Before the experiment, informed consent was obtained from all subjects. The experimental procedure was approved by the Institutional Review Board of the National Rehabilitation Center for Persons with Disabilities.

C. Experimental procedure

As shown Fig. 1(b)(iii), subjects were seated on the power wheelchair with BHRS during trials. The physiological parameters measured included oral and skin (dorsal, abdominal, chest) temperature (T_{OR}, T_{Back}, T_{AB}, T_{CH}), forearm and chest blood flow (BF_{FA}, BF_{BF}), blood pressure, and level of sweating. Oral and skin temperatures were measured using a precision thermometer (Omron Corp., MC-612) and thermistors (Tateyama Kagaku Industry Co. Ltd., SZL-64), respectively. Blood flow rates were measured using laser Doppler flowmetry (Advance Co. Ltd., ALF21D). In order to measure the level of sweating during the trials, body weight was measured before and after the experiment. Skin temperatures and blood flow were recorded using a data logger (Keyence, NR600) at 1 Hz. Oral temperature and blood pressure were measured once every 15 min.

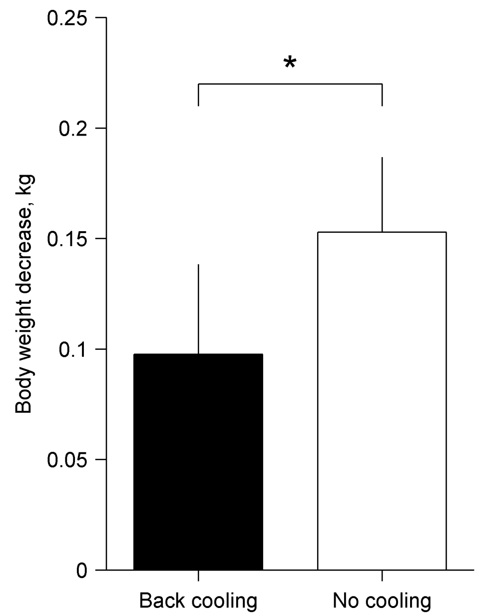

Figure 2. Body weight decrease due to sweating. Values are expressed as means ± standard deviations ($N = 5$). The decrease was significantly reduced by cooling with BHRS. *$P < 0.05$ (t-test).

The subjects were first placed in an anterior chamber at 24 °C. After a 60-min rest period, they were moved to an artificial climate chamber simulating a hot environment (33 °C; relative humidity, 40 %) and seated on the test wheelchair. After 10 min, monitoring probes were attached to the subjects and recording was initiated. In the back-cooling trials, the Peltier devices were set in constant-temperature mode where power was controlled to maintain the cold side of the Peltier devices at 10 °C.

III. Results and Discussion

In order to ascertain the feasibility of body temperature control by BHRS, sweating levels during the trials were compared. Fig. 2 shows decreases in body weight after the trials with back-cooling (BC) and no cooling (NC); the decreases were 0.098 ± 0.041 kg and 0.153 ± 0.034 kg [mean ± standard deviation (SD)], respectively, and a significant difference ($P < 0.05$, t-test) was found between the two trials. The greater part of these weight decreases was attributed to sweating during the trials, showing direct evidence of sweat suppression by BHRS.

Fig. 3 shows the time course of T_{OR} and systolic and diastolic blood pressure. Mean changes from pre-trial values are shown with SDs. As shown in Fig. 3(a), there was no significant difference in ΔT_{OR} between the BC and NC trials,

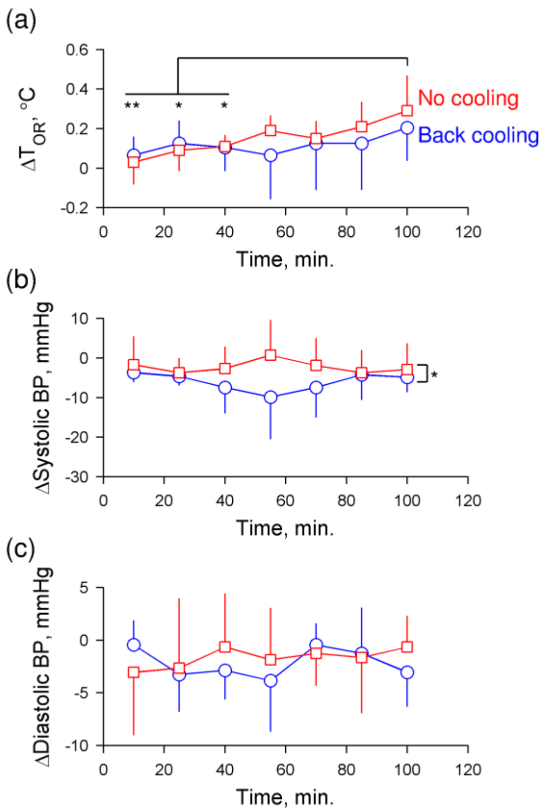

Figure 3. Time course of oral temperature and blood pressure. (a) Oral temperature. (b) Systolic blood pressure. (c) Diastolic blood pressure. Mean changes from the pre-trial values are shown with SDs ($N = 5$). Blue lines with circles and red lines with squares represent the results from the BC and NC trials, respectively. *: $P < 0.05$, **: $P < 0.01$ (ANOVA).

whereas there were significant temporal differences suggesting a slight increase in body temperature during the trials ($P < 0.01$, t = 10 min vs 100 min; $P < 0.05$, t = 25, 40 min vs 100 min, ANOVA). Even with lower levels of sweating, ΔT_{OR} in the BC trial did not exceed that in the NC trial. This result infers that back-cooling by BHRS partly replaced thermoregulation by inducing sweating. The difference in systolic blood pressure shown in Fig. 3(b) is difficult to explain rationally at present.

In the following analyses, we will explore whether BHRS modulated other thermophysiological responses. Fig. 4 shows the time course of skin temperature and blood flow rate. There was no significant difference in any parameters excep T_{Back} between the BC and NC trials. This finding suggests that thermoregulation by vascular dilation at the skin surface was not significantly altered by BHRS. This lack of response could potentially be clarified if a larger number of subjects had been studied because the difference in BF_{FA} was quite close to statistical significance ($P = 0.054$, ANOVA). The lower BF in the BC trial also suggests that BHRS partly replaced thermoregulatory responses. It is noteworthy that variance in T_{AB} in the NC trial was significantly greater than that in the BC trial ($P < 0.01$, Bartlett's test). The higher level of sweating in the NC trial may have increased temperature variability among subjects.

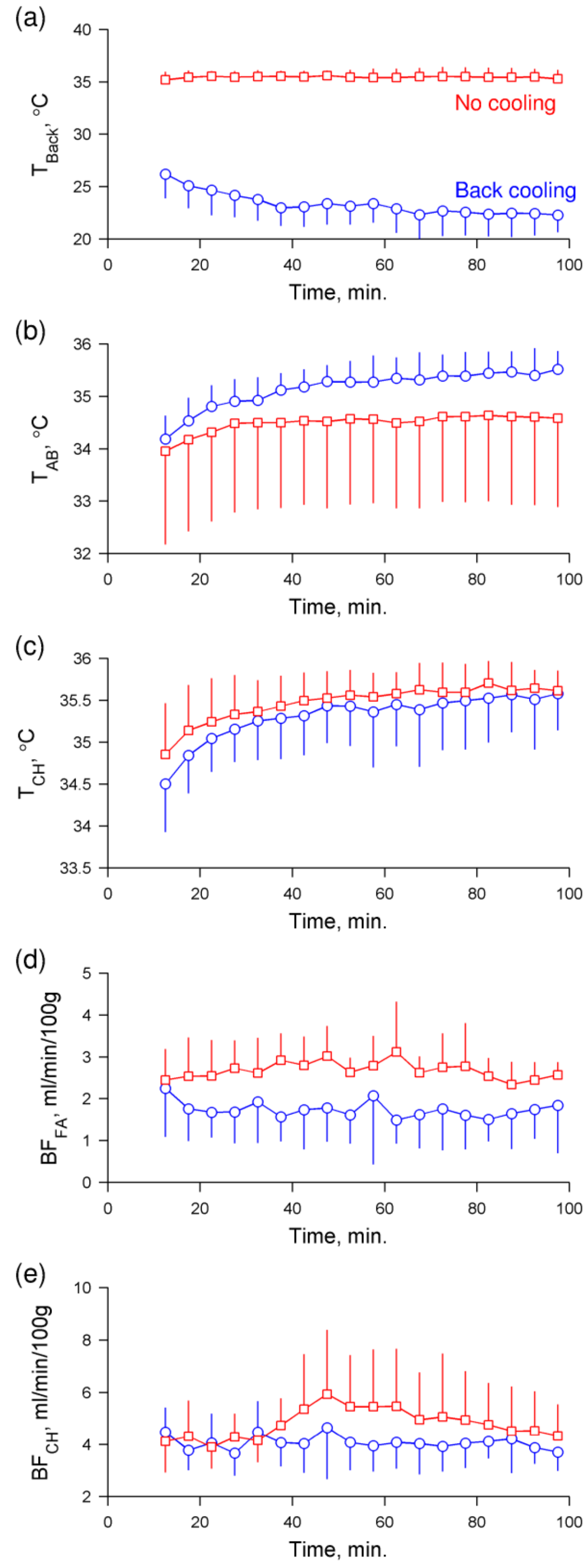

Figure 4. Time course of skin temperature and blood flow. (a) Dorsal skin temperature. (b) Abdominal skin temperature. (c) Chest skin temperature. (d) Forearm blood flow. (e) Chest blood flow. A significant difference was found only in the dorsal skin temperature between the BC and NC trials ($P < 0.01$, ANOVA). Values are means ± SDs ($N = 5$). Blue lines with circles and red lines with squares represent the results from the BC and NC trials, respectively.

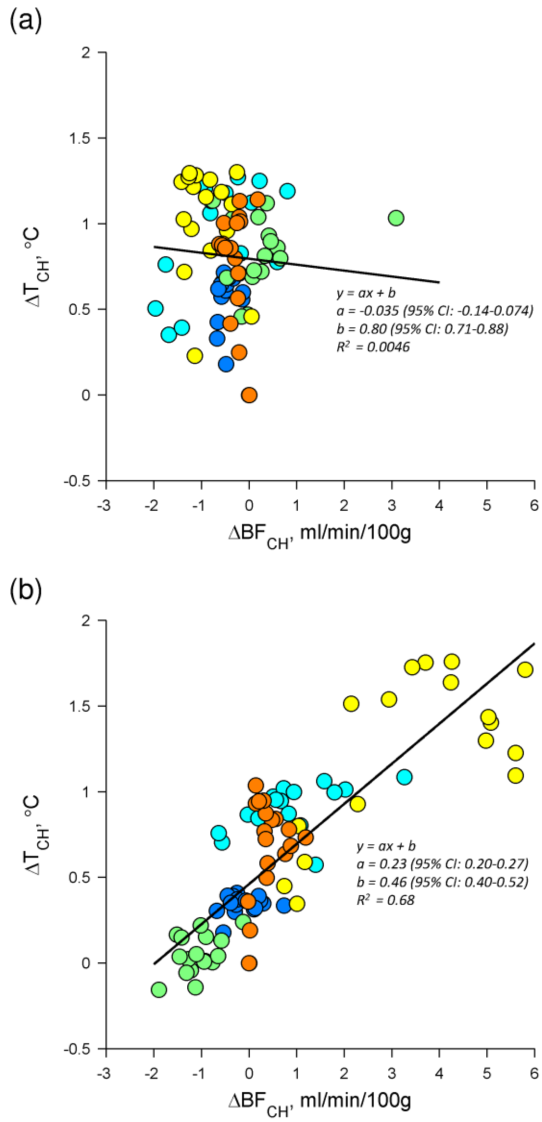

Figure 5. Correlation between changes in chest blood flow and skin temperature. Scatter plots of variations in chest skin temperature from initial values (t = 10 min in Fig. 4) with variations in chest blood flow are shown for the BC (a) and NC (b) trials. A clear correlation was found for the NC trial ($P < 0.01$), but not for the BC trial. The colors of the dots correspond to the five subjects, and regression results are shown by the solid lines.

Fig. 5 shows scatter plots of changes in T_{CH} and BF_{CH} from the initial values (t = 10 min in Fig. 4). As shown in Fig. 5(b), a significant correlation was found between ΔT_{CH} and ΔBF_{CH} in the NC trial ($R^2 = 0.68$, $P < 0.01$). In the BC trial, however, no correlation was found. The correlation between skin temperature and blood flow in the NC trial can be attributed to one particular thermoregulatory response, namely, vascular dilation for heat dissipation [2]. The fact that this relationship was eliminated implies the existence of BHRS-induced modulation of thermoregulation. The advantages and disadvantages of this modulation with regard to normal thermoregulatory responses should be addressed in a future study.

The results shown above are from the experiment with able-bodied subjects, who have normal thermoregulatory functions. It should be further investigated, therefore, whether the thermophysiological responses observed here are also the case with individuals with thermoregulatory disorders.

IV. Conclusion

In this study, we characterized thermophysiological responses induced by a body heat removal system (BHRS) incorporating Peltier devices. This system, which is mounted on a wheelchair backrest, can prevent hyperthermia in individuals with physical disabilities, particularly those with SCI with disorders of thermoregulatory capacity. Following a cooling experiment in a hot environment with five able-bodied subjects, the proof-of-principle of BHRS was obtained, i.e. the comparison of sweating levels between the back-cooling (BC) and no-cooling (NC) conditions showed that sweating was significantly suppressed by heat removal attributed to the test system. Forearm blood flow also showed a difference that was close to statistical significance between the BC and NC trials. In addition, the correlation observed between chest skin temperature and blood flow in the NC trial was absent in the BC trial. These results strongly suggest that artificial heat removal by the backrest modulated and partly replaced thermoregulatory functions including sweating and vascular dilation.

References

[1] C. Jessen, *Temperature regulation in humans and other mammal.* Springer, 2001.

[2] K. C. Parsons, *Human-thermal-environments: the effects of hot, moderate, and cold environments on human health, comfort and performance – 2nd ed.* Taylor & Francis, 2003.

[3] A. V. Krassioukov, A. K. Karin, J. M. Wecht, L. A Wuermser, “Assessment of autonomic dysfunction following spinal cord injury: Rationale for additions to International Standards for Neurological Assessment,” *J. Rehabil. Res. Dev.*, vol. 44, pp. 103-112, 2007.

[4] S. Muraki, M. Yamasaki, K. Ishii, K. Kikuchi, K. Seki, “Relationship between core temperature and skin blood flux in lower limbs during prolonged arm exercise in persons with spinal cord injury,” *Eur. J. Appl. Physiol.*, vol. 72, pp. 330-334, 1996.

[5] K. Mikami, K. Aoki, H. Hachisu, H. Takeda, “Features of physiological responses to thermal stimuli in patients with cervical spinal cord injuries,” *Journal of Human and Living Environment*, vol. 14, pp. 47-57, 2007.

[6] T. A. Hagobian, K. A. Jacobs, B. J. Kiratli, A. L. Friedlander, “Foot cooling reduces exercise-induced hyperthermia in men with spinal cord injury,” *Med. Sci. Sports Exerc.*, vol. 36, pp. 411–417, 2004.

[7] V. Goosey-Tolfrey, M. Swainson, C. Boyd, G. Atkinson, and K. Tolfrey, “The effectiveness of hand cooling at reducing exercise-induced hyperthermia and improving distance-race performance in wheelchair and able-bodied athletes,” *J. Appl. Physiol.*, vol. 105, pp. 37-43, 2008.

[8] N. Webborn, M. J. Price, P. C. Castle, V. L. Goosey-Tolfrey, “Effects of two cooling strategies on thermoregulatory response of tetraplegic athletes during repeated intermittent exercise in the heat,” *J. Appl. Physiol.*, vol. 98, pp. 2101-2107, 2005.

[9] S. Fujimoto, J. Suzurikawa, H. Jonai, K. Mikami, T. Inoue, "Prevention of Hyperthermia by a Body Heat Removal System with Peltier Devices on a Wheelchair", *Proceedings of 2012 IEEE/SICE International Symposium on System Integration*, pp. 170-175, 2012.