생활과학 석사 학위논문

Analysis of Non-invasive Parameters to Augment Validity in Predicting Core Temperature for Firefighters

- 주기적으로 변하는 기온에서의 피부온과 반복 작업 시 심박수 특성 -

소방관의 심부온 예측 타당도 향상을 위한 비침습적 지표 분석

2015 년 2 월

서울대학교 대학원

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이 논문을 생활과학 석사 학위논문으로 제출함
2015 년 2 월

서울대학교 대학원
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2015 년 2 월

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Abstract

Analysis of Non-invasive Parameters to Augment Validity in Predicting Core Temperature for Firefighters

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Real-time monitoring of firefighters' core temperature could be an important strategy used to prevent firefighters' heat-related illness. The current study included three sub-studies as a series of processes to develop the predictive methods of core temperature with non-invasive parameters.

At first, we examined skin temperatures which could firmly predict rectal temperature under fluctuating ambient temperatures. Eight firefighters participated in an experimental protocol consisting of 20 min rest on a chair and 60 min exercise on a treadmill followed by a 10 min recovery on a chair while wearing firefighting protective equipment, excluding only a self-breathing apparatus. The air temperature was changed periodically, which approximately followed a sine wave pattern, showing a phase of 19 min and amplitude of 5°C. The results showed that skin temperatures were influenced by fluctuating ambient temperature even while fully equipped with personal firefighting gear and the stable sites for indirectly measuring core temperature were identified as the forehead, chest, upper arm and toe. Thus, it was identified that influences of ambient temperature could act as exogenous variables in predicting core temperature with skin temperatures.

Secondly, we investigated physiological changes during intermittent exercises and rests. Thirteen firefighters participated in two experimental trials. One of them included 30 min exercise, while the other included two 15-min exercises with a 10 min intermission. Participants were fully equipped with firefighters' gear and the ambient temperature was maintained at 32^{o}C. The results showed that skin temperature and rectal temperature did not show any significant differences at the end of exercise and during recovery excepted for forehead temperature, which inferred that the 10-min intermission while wearing firefighting gear was insufficient for alleviating thermal strain. These results imply that thermal strain would be accumulative in cases of firefighters who did not fully remove their clothing or equipment during the rests between intermittent works.

Finally, a predictive equation of rectal temperature was developed by measuring heart rate at pre-exercise rest periods instead of skin temperature, which is influenced by changes of ambient temperature and rests between exercises. As a result, a significant predictive equation of rectal temperature was developed by measuring heart rate at pre-exercise rest periods (R^2=0.680) and relative heart rate by maximal heart rate (R^2=0.722). In addition, a heart rate limit index to prevent firefighters' heat-related illness was suggested where heart rate limit to return to work during 30-min at 32^{o}C in the 60%$\dot{V}O_{2max}$ work intensity was 111bpm or 57%HR_{max}.

Keywords: Firefighter, heat stress, repetitive work, core body temperature, heat strain, heart rate, occupational health and safety
Student Number: 2013-21515

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List of Abbreviations

HR	Heart rate
$HR_{absolute}$	Heart rate (bpm)
$HR_{relative}$	Relative heart rate in repect to maximal heart rate ($\%HR_{max}$)
S_1	First ambient temperature-reduced section which was analyzed
S_2	Second ambient temperature-reduced section which was analyzed
t	Time for which exercise lasted (min)
t_1	Time for which skin temperature decreased induced by decrease in ambient temperature at first
t_2	Time for which skin temperature decreased induced by decrease in ambient temperature secondly
T_{re}	Rectal temperature
$T_{re.rest}$	Rectal temperature at rests
$T_{re.exe}$	Rectal temperature at the end of exercise
ΔT_{re}	Change of rectal temperature per minute during exercise
ΔT_1	Magnitude of decrease in skin temperature induced by decrease in ambient temperature at first
ΔT_2	Magnitude of decrease in skin temperature induced by decrease in ambient temperature secondly

Chapter 1. Introduction

Heat-related injuries remain a very dangerous and potentially fatal threat to the health and operational effectiveness of workers operating in hot environments. Recently, the US Department of Defense reported that there were 324 cases of heat stroke and 1,701 incidents of other heat related injuries among military members in 2013 (Medical Surveillance Monthly Report, 2014). In particular, firefighters, special forces such as chemical, biological or bomb disposal squads, and athletes are at risk because they are frequently exposed to hot environments, have to perform strenuous physical work and/or must wear protective clothing which disturbs heat dissipation (Gunga et al., 2008; Wenger, 2001). Under these conditions, core body temperature may increase rapidly and reach deleterious levels. In order to estimate the level of thermal strain and to initiate appropriate actions at an early stage, numerous heat strain indexes have been developed, one of which is the Physiological Strain Index (PSI) introduced by Moran et al. (1998). PSI, which is based on rectal temperature and heart rate recordings in humans, describes heat strain in quantitative terms. However, core temperatures cannot be easily recorded non-invasively in the work place compared to heart rate. Accordingly, several non-invasive measurements for core temperature through skin temperatures have been suggested (e.g. Zero-heat flux, Double sensor). However, they still have problems related to practicality, such as supply of electric power, and size of probes. Furthermore, they have not solved the underlying problem, changeability with the measurement location, clothing, and environmental conditions (Xu et al., 2013), which is caused by the dual role of skin temperature, effector and thermo receptor in the thermoregulatory system in the human body. It implies that changes in ambient temperature or exercise state could influence skin temperatures, which will impact the validity in predicting core temperature for firefighters.

We focused our study on analyzing non-invasive parameters under fluctuating ambient temperatures and during intermittent exercise so that we could develop an alternative method to estimate rectal temperature. This study was comprised of three parts. We first examined the influences of fluctuating ambient temperature. Second, we investigated the relationship between rectal temperature and non-invasive parameters during intermittent exercise. Finally, we developed prediction equations of rectal temperature using heart rate measured in the pre-exercise rest periods and suggested an allowable heart rate limit enough to go back in the operation using heart rate during pre-exercise rest periods (Figure 1.1). This study should offer assistance to develop standards related to occupational health, which could be used practically as a heat-related illness precaution for firefighters and utilized along with smart/next generation firefighter gear.

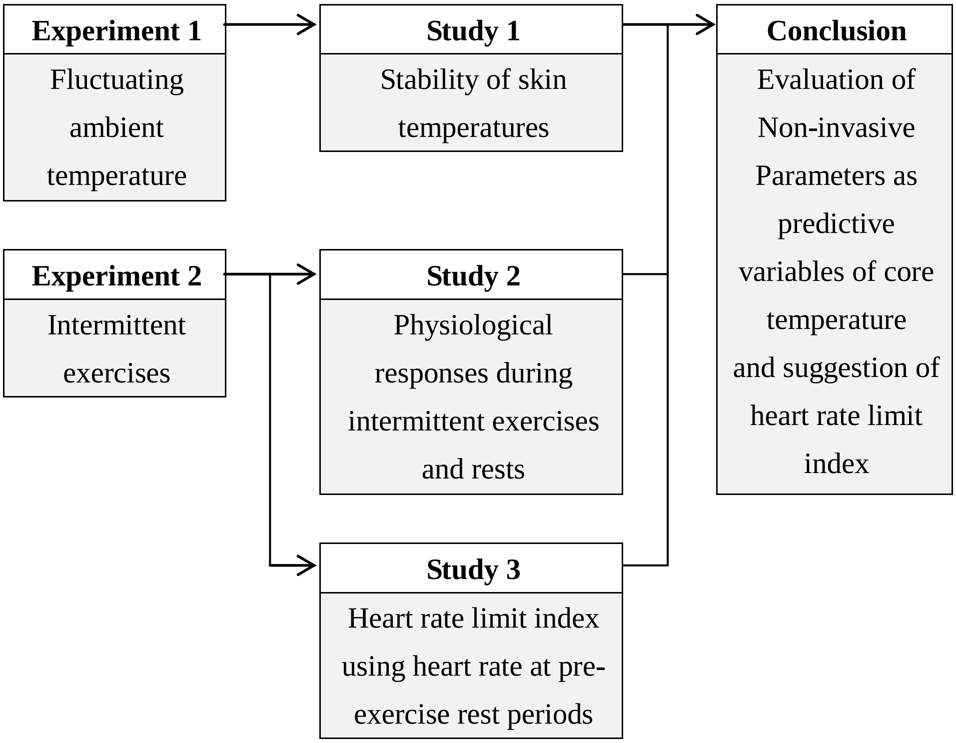


Figure 1.1 Schematic construction of the study

Chapter 2. Theoretical Background

2.1 Firefighting and heat stress

2.1.1 Occupational environmental conditions

Firefighting is a very strenuous operation, which is often performed under hazardous environmental conditions. In addition to extremely high environmental temperatures and radiant heat flux, heavy and impermeable turnout gear and physical activity add to thermal strain upon firefighters.

At first, a combination of high ambient temperature and radiant heat flux impose heat strain. According to Abeles et al.(1973), typical ambient temperatures at which firefighters had been routinely exposed ranged from 38℃ to 66℃. However, they are exposed to much higher air temperature occasionally. Foster and Roberts (1994) proposed a time limit of 25 min when operating at 100℃ with thermal radiation limits of 1 kWm^2, and ~1 min at 160℃ with thermal radiation of 4kWm^2.

The total firefighting ensemble is made up of boots, gloves, bunker coat and pants, flash hood, and self-contained breathing apparatus (SCBA). A typical firefighting ensemble weighs approximately 26kg (Barr et al., 2010) with an insulation value of 2.44clo (Holmer et al., 2006). Firefighters' turnout gear consists of an outer shell, moisture barrier, and a thermal liner to protect firefighters from heat, flames, and other hazardous environments. The weight and insulating properties of firefighting protective clothing and equipment impose additional stress on firefighters. Duncan et al. (1979)

reported that the energy cost of work had been greatly increased by wearing protective clothing and SCBA.

Finally, the tasks associated with firefighting such as carrying equipment, dragging hoses, rescuing victims and climbing stairs demand high physical capacity. The energy cost of selected firefighting tasks ranged from $11.0 kg \cdot min^{-1}$ to $12.7 kcal \cdot min^{-1}$ (Lemon & Hermiston, 1977), which is equated with 55~82%$\dot{V}O_{2max}$ provided averaged VO2max of firefighters are $45 ml \cdot kg^{-1} \cdot min^{-1}$. Oxygen uptake during stair climbing with protective equipment reached 80%VO_{2max}. Firefighting elicits an almost maximal heart rate response for prolonged periods (Barnard & Duncan, 1975).

2.1.2 Work patterns of firefighting

Firefighting operations in Korea could be broadly subdivided into three classes: fire suppression, rescuing, and emergency medical. Firefighters involved in fire suppression and rescuing directly face and enter into the scene of the fire. Rescuing generally precedes fire suppression. Fire suppression lasts until the fire is completely extinguished. Therefore, the operating time to suppress a fire ranges from several minutes to several hours over multiple days depending on the magnitude of the fire.

Firefighters perform fire suppression intermittently due to the limited volume of stored air in the SCBA, yet previous studies have rarely reported the intermittent work patterns of firefighters. However, when considering the capacity of SCBA, the duration of time for an individual suppressing a fire is estimated at 20~30 min with short breaks lasting 5~10 min. During short breaks, firefighters may recharge the air in SCBA. Further investigation in regard to firefighers' working patterns need to be studied.

2.1.3 Physiological responses during firefighting

Muscular work during operating tasks causes an increase in the body's core temperature, the magnitude of which is determined by the relative intensity of the activity performed (Saltin & Hermansen, 1966). Increases in core body temperature caused by changes in metabolic heat production result in an increase in the activation of the heat-dissipating mechanisms of skin vasodilation and sweating (Hammel, 1968; Hardy, 1961). On the other hand, increases in skin blood flow resulting from cutaneous vasodilation are associated with a marked increase in cutaneous venous volume, which can cause a fall in blood pressure subsequent to decreases in thoracic blood volume, central venous pressure, stroke volume, and cardiac output (Rowell, 1977). Accordingly, heart rate increases to restrain the fall in blood pressure and to maintain constant cardiac output (Costrini et al., 1979).

Elevations of skin blood flow and sweating increase the rate of heat dissipation from the body, but heat dissipation is suppressed if the microclimate temperature is maintained above or approximately equated with skin temperature and humidity inside turnout gear reaching saturation. For this reason, core body temperature increases rapidly in response to carrying out heavy tasks while wearing personal protective equipment in a hot environment. Smith et al. (1996) have documented that core temperature approached approximately 38.6℃ after firefighting activity in a structure that contained live fires for 18 minutes, and one of the interior experiments reported that an increase in rectal temperature of 1.86℃ was caused from 30min of treadmill walking while fully wearing firefighting gear (Lee et al., 2014). The magnitude of heat strain would be enhanced with longer working time, repeated operations with few breaks, and when high levels of psychological stress in the real scene of a fire are integrated with environmental factors.

2.1.4 Firefighters' heat-related illness

A worker who wears heavy and impermeable protective clothing in hot environments has the potential to be exposed to heat-related illnesses. In the case of firefighters, heavy and impermeable clothing (~26kg), prolonged work and successive bouts of moderate to high intensity efforts aggravate their thermal strain. In the United States, 255 cases of firefighters' heat-related illness were reported in the USA from 2000 to 2011 (NIOSH, 2011), and seven heatstroke deaths were identified from 1979 to 2011 (Fahy, 2011). Last year, a Korean firefighter died from heat stroke due to extensive firefighting, which lasted for five hours (National Fire Service Academy [NFSA], 2013). Unfortunately, local firefighters working in rural areas are facing much higher risks and dangers of heat related injuries than firefighters working in Seoul, since the number of firefighters and superior firefighting equipment are insufficient. Presumably, the damages and casualties have been underestimated, since not only are firefighters' injuries reported passively, especially in Korea, but secondary injuries during firefighting resulting from overexertion and thermal strain have not been documented well either.

2.2 Measuring or estimating heat strain

2.2.1 Direct measurement of core temperature

Core body temperature measurement is fundamental to the study of human thermoregulation, since it is supposed to be maintained within a specific range for homeostasis. Core temperature is implicated in heat-related illnesses and mainly used to diagnosis heat stroke with accompanied symptoms. Heat exhaustion is a mild to moderate illness due to water or salt depletion that results from exposure to high environmental heat or strenuous physical exercise, whereas heat stroke is defined clinically as a core body temperature that rises above 40°C and that is accompanied by hot, dry skin and central nervous system abnormalities (Bouchama & Knochel, 2002).

Yet, the term 'core' does not describe a specific anatomical location, and no single regional internal temperature provides an index of the average internal body temperature (Byrne & Lim, 2006). Measuring the temperature of the pulmonary artery is considered the best representation of the average internal temperature of the body, however, it is not accessible, so core temperature is often measured at the rectum, oesophagus, mouth or tympanic membrane. Furthermore, the process involved with installing those sensors takes time and causes discomfort. As an alternative, ingestible telemetric core body temperature sensors, particularly suited for field based ambulatory applications, were developed. But, limitations due to the high price and weak transmission distance of telemetric pills have been raised.

2.2.2 Heat stain index

Numerous attempts and efforts to develop heat strain indexes to evaluate the risk of heat-related illness have been made. However, the indexes based on only meteorological parameters still lack the capability to adjust for different levels of metabolic rate and different clothing, such as protective clothing (Kenney, 1987; Paull & Rosental, 1987), while the indexes based on physiological parameters still face the complexity of calculating the indexes and the inability to rate the strain online, which is regarded as the main reasons for it not being universally accepted (Moran et al., 1998). In 1998, Moran and colleagues suggested a physiological strain index (PSI) as following:

$$PSI=5(T_{ret}-T_{re0})\cdot(39.5-T_{re0})^{-1}+5(HR_t-HR_0)\cdot(180-HR_0)^{-1} \quad \text{[Eq. 1.1]}$$

In this equation T_{ret} and HR_t are simultaneous measurements taken at any time, while T_{re0} and HR_0 are the initial values of rectal temperature and heart rate, respectively. PSI represents the combined load of the cardiovascular and the thermoregulatory systems. PSI has been widely accepted since it had been developed, because it is quite simple and easy to apply or interpret than other indexes. However, rectal temperature, the critical dependent variable in PSI, is hardly collected in the real work place, because its direct measurement is often expensive or impractical.

2.2.3 Non-invasive measurement of core temperature

Continuous attempts and efforts to develop a non-invasive measurement method of core temperature have been made since first attempted by Fox and Solman (Bernard & Kenny, 1994; Fox & Solman, 1971; Gunga et al., 2008; Taylor et al., 1998; Xu et al., 2013). The zero-heat flow principal developed by Fox and Solman consists of a heat flux sensor, a heating disc, and a servo control system. Zero-heat flow systems have been widely used in cardiac surgery in Japan (Yamakage & Namiki, 2003), but they are not suitable for sustained field applications due to the power requirement (Xu et al., 2013). Recently, Gunga et al. (2008) developed “Double sensor”, a combination of a skin temperature sensor and heat flux sensor attached to the inside of the helmet of firefighters. However, the use of this sensor could be limited, since “Double sensor” attached to the helmet was evaluated without the hood, which is one of the main components of firefighter’s gear and worn under the helmet to protect the face and neck. There also have been attempts at alternative core temperature measurement using insulated skin (Bernard & Kenney, 1994; Taylor et al., 1998) or multiple linear regression models using skin temperature and heat flow (Xu et al., 2013), and at making criteria for heat strain using skin temperature or skin temperature with heart rate (Buller et al., 2008; Lee et al., 2010; Yokota et al., 2005).

Even with these efforts, accurate and reliable non-invasive measurement methods for core temperature are still challenging. The changeability with the measurement location (Taylor & Amos, 1997; Tamakage & Namiki, 2003; Xu et al., 2013), clothing (Bernard & Kenney, 1994; Taylor et al., 1998), and environmental conditions (Taylor et al., 1998; Gunga et al., 2008; Teunissen et al., 2011) were suggested as factors influencing the accuracy and reliability of the methods (Xu et al., 2013). Although, skin temperatures, the most frequently used variables in the non-invasive measurement method of core temperature, increases linearly with an increase in core temperature beyond a core temperature onset threshold (Flouris & Cheung, 2009; Kenny & Johnson, 1992; Wissler, 2008). It also tends to be susceptible to changes in environmental temperatures, and the changes are varied with measurement sites, which are also influenced by the clothing. In addition, skin temperature reflects metabolic rates. Therefore, in order to raise the accuracy of non-invasive measurement methods for core temperature, reliability of skin temperatures on the various measurement sites against environmental temperature changes and during intermittent exercises will need to be investigated.

Chapter 3. Methods

3.1 Experiment 1: Fluctuating ambient temperatures

3.1.1 Subjects

Eight professional male firefighters participated in the study [38.9±7.2 years in age, 173.6±4.5 cm in height, 77.9±10.9 kg in body weight, 21.7±4.2% body fat (%BF), 41.8±4.4 $ml \cdot kg^{-1} \cdot min^{-1}$ in maximal oxygen consumption (VO_{2max}), and 12.3±7.1 years of employment]. Each firefighter was free of known cardiovascular and respiratory dysfunction. Before participating in experiments, all subjects had been informed of the content, purpose, and potential risks of the experiment. Then, written informed consent was obtained. This study was approved by the Institutional Review Board of Seoul National University (IRB#1406/001-026).

3.1.2 Experimental setup and procedures

Participants visited two separate times for the VO_{2max} and one experimental trial. They were encouraged to refrain from alcohol use, and strenuous exercise for the previous 24 h, along with any food and caffeine for 3 h prior to their scheduled tests. Each visit was separated by at least 48 h while all trials were completed over a four week span. Participants were required to consume 300 ml of water before each experiment’s commencement. Measurement of body mass was then obtained while wearing only underwear and short pants. The experimental ensemble consisted of shorts (0.07±0.014kg), long shirts (0.20±0.022kg), long pants (0.37±0.061kg), socks (0.05±0.001kg), bunker jackets (1.79±0.081kg) and pants (1.43±0.145kg), hood (0.09±0.001kg), helmet (1.18±0.001kg), gloves (0.20±0.001kg) and boots (2.37±0.128kg). In the present study, self-contained breathing apparatus (SCBA) was excluded because of the exercise intensity. Environmental temperature and relative humidity were maintained at 32.4±2.24^{o}C and 46.0±5.50%RH, respectively. The air temperature was changed periodically, which approximately followed a sine wave pattern, with a phase of 19 min and amplitude of 5 ^{o}C (Figure 3.1). The subjects began each trial with a 20 min rest sitting down for stabilization and walked on a treadmill at 4.5 km·hr-1 (with 1% slope) for 60 min, which was followed by a 10 min recovery period while seated after the cessation of exercise. The test was terminated if their rectal temperature reached 39.2^{o}C, their heart rate (HR) reached 95% of their maximal HR, or if any volunteer felt they were unable to continue the exercise.

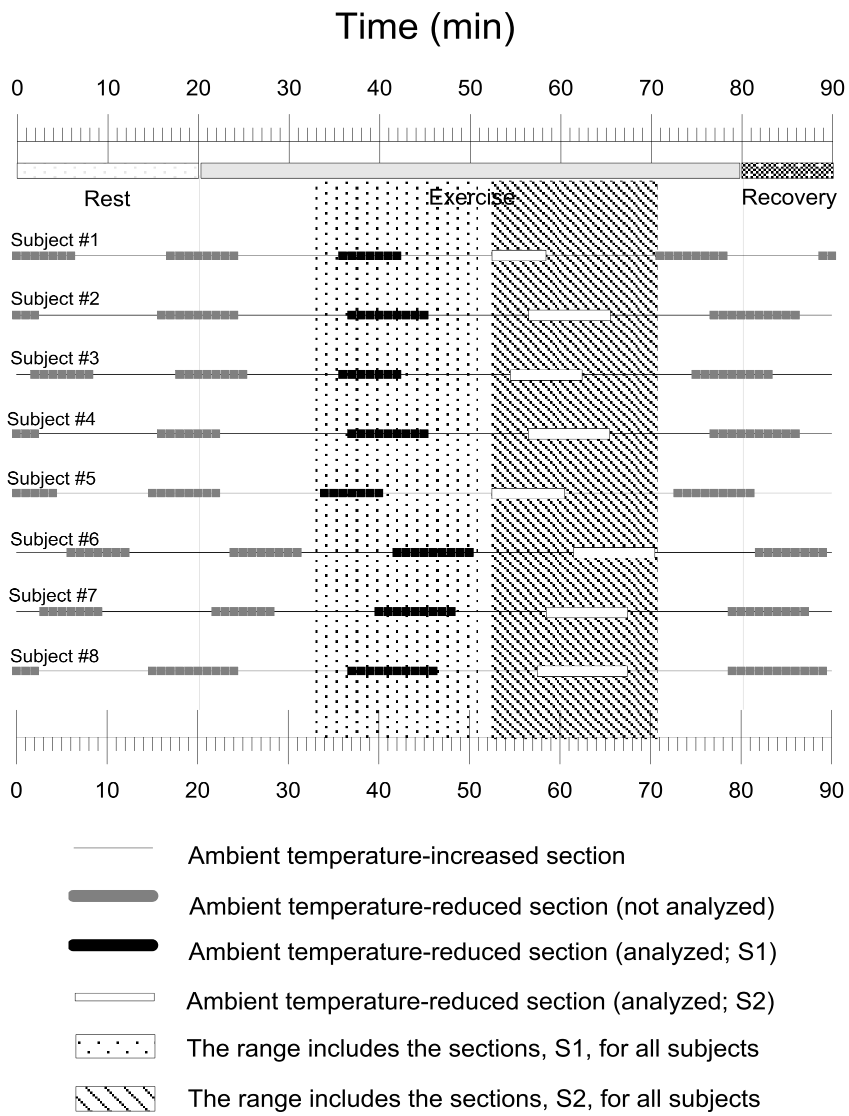


Figure 3.1 Change of ambient temperature and analyzed ranges

3.2 Experiment 2: Intermittent exercises

3.2.1 Subjects

Twelve professional male firefighters participated in the study [37±7.0 years in age, 175±4.8 cm in height, 75.0±8.23 kg in body weight, 12.4±5.10 % body fat (%BF), 45.6±7.6 $ml \cdot kg^{-1} \cdot min^{-1}$ in maximal oxygen consumption ($VO2_{max}$), 189±7.3 bpm in maximal heart rate (HR_{max}), and 8±8.1 years of employment]. Each firefighter was free of known cardiovascular and respiratory dysfunction. Before participating in experiments, all subjects had been informed of the content, purpose, and potential risks of the experiment. Then, written informed consent was obtained. This study was approved by the Institutional Review Board of Seoul National University (IRB# 1501/001-009).

3.2.2 Experimental setup and procedures

All participants volunteered for three separate testing days. On the first testing day, anthropometric data, VO_{2max}, and HR_{max} were measured. VO_{2max} was measured during a progressive incremental protocol performed on a treadmill. Subjects were asked to walk or run at a starting work rate of $4 km \cdot h^{-1}$ for 1 min. The work rate was then incremented every 1 min thereafter until the subject could not maintain the running speed. On the second and third testing day, the 30 min exercise protocol (NoBreak) or the intermittent exercises protocol (Break) was performed (Figure 3.2). In order to avoid the effect of familiarization during the two trials, the experiments were scheduled across all subjects. To control for seasonal acclimatization,

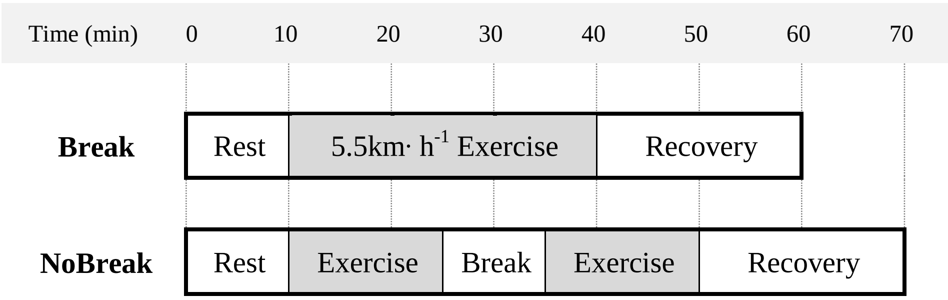


Figure 3.2 Experimental protocol for Break and NoBreak

all experimental trials were performed in October. Testing days were separated by a minimum of 48 h from the first testing day. Participants' circadian rhythm was not controlled for generalization. Experimental trials commenced at 09:00h for three, 11:30h for four, and 14:00h for five of them. Participants were instructed to refrain from alcohol use for 24 h, along with any food and caffeine for 3 h prior to their scheduled tests.

After participants arrived, they were required to consume 300 ml of water. Then, body mass was measured while wearing only underwear and short pants. The experimental ensemble consisted of shorts, long shirts, long pants, socks, bunker jackets and pants, hood, helmet, gloves and boots, and self-contained breathing apparatus (SCBA), and the total mass was 15.02±3.269kg. We used SCBA without air, and the face-piece of the SCBA was replaced by a respiratory mask connected with the gas exchange analyzer to collect respiratory gases. Materials and mass of each item are shown in <Table 3.1> (Figure 3.3). Environmental temperature and relative humidity were maintained at 32.1±0.19^{o}C and 43±7.2%RH, respectively. In

NoBreak, participants began each trial with a 10-min rest sitting down for stabilization. Thereafter, the participant performed 30-min exercise at 5.5km·hr^{-1} (with 1% slope), which approximately equated to a relative work intensity of 60% of their predetermined VO_{2max}, followed by 20-min final recovery. Whereas participants in Break performed two 15-min bouts of exercises separated by 10 min of stationary rest, but their rests for stabilization and the final recovery corresponded with NoBreak. The test was terminated if their rectal temperature reached 39.2^{o}C, their heart rate (HR) reached 95% of their maximal HR, or if any volunteer felt they were unable to continue the exercise.

Figure 3.3 Experimental ensemble

Table 3.1. Physical characteristics of experimental garments

Item	Mass (g)	Materials
Shorts	72±10.2	Cotton 100%
Long-sleeved shirts	229±75.5	Cotton 100%
Long pants	379±72.2	Cotton 100%
Socks	53±1.2	Cotton 80%, Spandex 16%, Polyester 4%
Turnout coat	1,816±33.4	Outer shell: Polybenzimidazole 40%, Para-Aramid 60%, Moisture barrier: Aramides, Thermal liners: Aramides
Turnout trousers	1,496±48.9	
Hood	92±2.8	Aramid 100%
Helmet	1,184±2.3	Ultem PEI Polyetherimide
Gloves	198±12.8	Outer shell; Para-Aramid with carbon coating, Moisture barrier; Gore-tex X-trafit^{TM} Membrane
Boots	2,448±93.6	Rubber with steel toe insert
SCBA	7,050	-
Total mass	**15,018±3,268.6**	-

3.3 Measurements

Before each trial, subjects' semi-nude body weight was measured on a calibrated scale (ID2, Mettler-Toledo, Germany; resolution of 1 gram). Rectal temperature was measured every 5 s using a data logger (LT-8A; Gram Corporation, Japan) which was inserted 16 cm beyond the anal sphincter. Heart rate was measured continuously every 5 s using a Polar coded transmitter, recorded, and stored with a Polar Advantage interface and Polar Precision Performance software (RS400, Polar Electro Oy, Kempele, Finland). Oxygen consumption, carbon dioxide production and ventilation were continuously measured during all trials (Quark b^2, COSMED, Italy). Prior to each measurement, the respirometer was calibrated using room air, a standard gas mixture (4%CO_2, 16%O_2, balance nitrogen) and a volume calibration using a 3-litre syringe. Skin thickness was determined using a caliper (Eiyoken-group; Meikosha Co. Ltd., Japan) on the chest, abdomen and thigh, while the participants were standing.

3.4 Data analyses

3.4.1 [Experiment 1] Analysis of stability of skin temperatures

To analyze the stability of skin temperatures against changes in ambient temperature, data from experiment 1 were utilized. We selected two sections of ambient temperature decrease during exercise and analyzed the magnitude of the decrease in skin temperature (ΔT) and duration of time decrease in skin temperature (t) (Figure 3.4). Rate of ΔT against t was calculated as a slope.

The presented data of ΔT, t, and slope were a mean value of two and all data were expressed as the mean and standard deviation. ΔT was recorded from when the skin temperature decreased at least 0.01°C and t was described by units of 5 s.

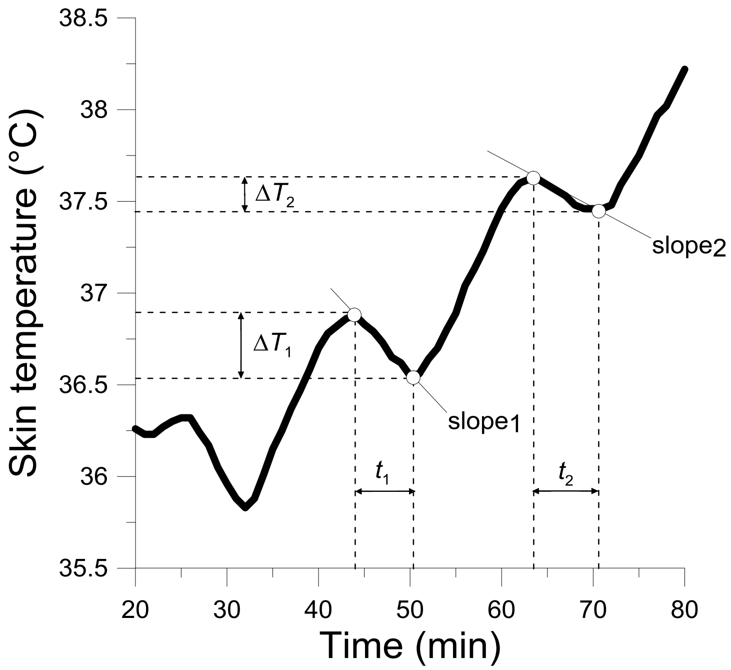


Figure 3.4 An example of fluctuating skin temperatures affected by ambient temperature and its analytical variables

The observed data shows that rectal temperature did not increase until skin temperature approached the rectal temperature (Figure 3.5). To eliminate the range where core temperature was presented as a flat plateau while skin temperature increased and to extract the section showing the linear relationship between skin temperature and core temperature, the point where the rapid increase of core temperature by skin temperature needed to be determined. Although observed data implied the existence of an inflection point, it contains considerable fluctuation due to changes in environmental temperature. Hence, slope was calculated in order to smoothen this out according to the following equation where the inflection point was determined as the minimum value of time, where slope (t) exceeds 1/10.

$$Slope(t) = \frac{\Delta T_{re}(t)}{\Delta T_{sk}(t)} = \frac{\overline{T}_{re}(t+60s) - \overline{T}_{re}(t)}{\overline{T}_{sk}(t+60s) - \overline{T}_{sk}(t)} \qquad \text{[Eq. 3.1]}$$

Minimum of t, which fulfills Slope (t) $\geq \frac{1}{10}$

- $\overline{T}_{sk}(t)$: Averaged local skin temperature for 1 min after t
- $\overline{T}_{re}(t)$: Averaged rectal temperature for 1 min after t

Observed data of forehead temperature of a participant presented discontinuous changes with great fluctuation. It was assumed that the sensor which had come unstuck from the forehead resulted in the unstable data. Some heart rate data also failed to be recorded. Missed data and unreliable data were not included in the analysis and this was disclosed, where applicable, when describing the results presented in tables and figures.

With precedence of analysis, the Kolmogorov-Smirnov test was used to test for normality of the distribution. As a nonparametric test, the Kruskal-

Wallis test was used to analyze the difference between groups in regard to ΔT and t. The Mann Whitney U-tests were conducted with each paired groups as a *post hoc* test. Regression analysis was used to identify the relationship between skin temperatures and rectal temperature. Prior to regression analysis, normality, linearity, independence, and homoscedasticity of the distribution were investigated. Residual plot analysis was used to test normality, linearity and homoscedasticity of the distribution, and the Durbin-Watson statistic was used to test independence of the values separated from each other by a given time lag. Simple regression analysis and multiple regression analysis were used to develop linear regression equations along with data during the third phase. To compare the predictive power of all predictive equations, goodness-of-fit was measured for each by adapting the R^2 statistic from linear regression. All statistical analyses were performed with IBM SPSS statistics v. 21. Significance was accepted at $p<0.05$. Values were represented as mean ± SD.

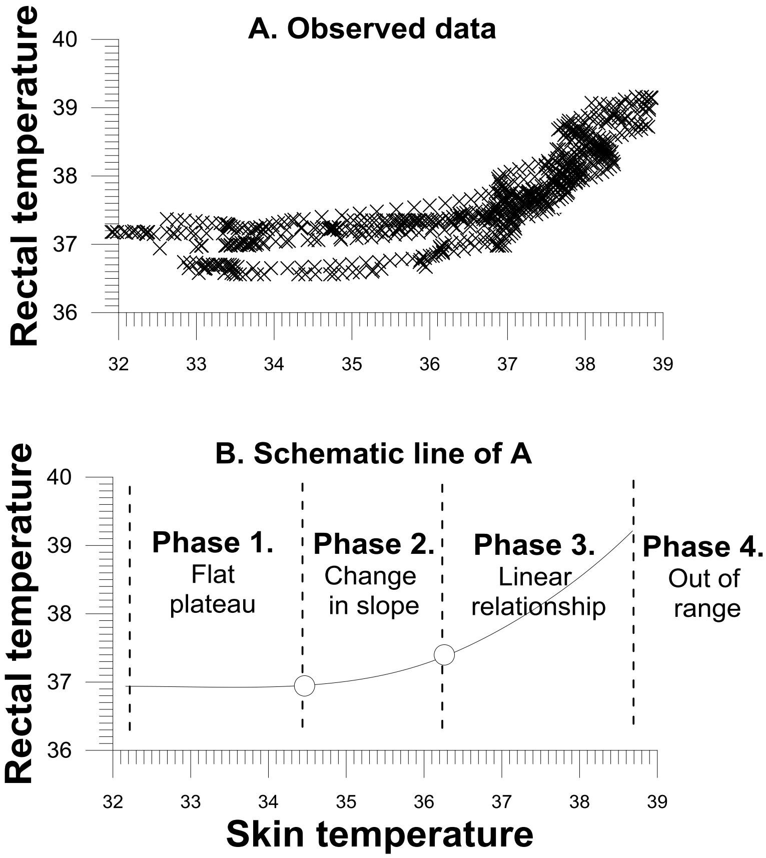


Figure 3.5 Scatter plot of observed data (A) and Schematic line (B) of rectal temperature and skin temperature.

3.4.2 [Experiment 2] Comparison between Break and NoBreak

To identify physiological influences of rest between exercises, we compared rectal temperature, skin temperatures (forehead, forearm, and toe), and heart rate at rest, at the end of exercise and during recovery with data from the second experiment. Values at rest were averaged from 1 min to 4 min before the commencement of each exercise. Data for 1 min before exercise were excluded to avoid unstable and increased data resulting from preparation action following exercise. Likewise, values at the end of exercise and during recovery were averaged for the last 3 min of exercise periods and of recovery periods, respectively. The Wilcoxon signed rank test was performed to compare two groups, whose samples did not show normal distributions. Significance was accepted at $p<0.05$. To identify the cumulative body temperature in Break, a one-way ANOVA with a Tukey HSD *post hoc* test was performed.

3.4.3 [Experiment 2] Development of predictive equations for rectal temperature by heart rate and of heart rate limit index

Data from the Break condition, one of the groups in the second experiment, were used to develop predictive equations of rectal temperature using heart rate. Data of twelve among thirteen participants were used, since those of a participant whose heart rate had not been recorded were excluded. To calculate mean heart rate ($HR_{absolute}$) during pre-exercise rest periods, the most important variable, heart rate data was averaged from 1 min to 4 min before the commencement of each exercise. Relative heart rate ($HR_{relative}$) was calculated as a rate of predetermined maximal heart rate. Values for 1 min before exercise were excluded to avoid unstable and increased data resulting from preparation action following exercise. Change in rectal temperature during exercise was calculated by subtracting mean rectal temperature for 1 min before the end of exercise ($T_{r.exe}$) from mean rectal temperature for 1 min before the commencement of exercise ($T_{r.rest}$). Change rate in rectal temperature per minute (ΔT_{re}) was calculated on the assumption that rectal temperature increased linearly with time as the following equation :

$$T_r(t) = T_{r.rest} + \Delta T_{re} \times t \qquad \text{[Eq. 3.2]}$$

In this equation, t (min) is time in duration of exercise and $T_r(t)$ is the value of rectal temperature at t. 24 samples were collected from 12 participants since each experimental trial contained two bouts of exercise.

Simple regression analysis was used to develop linear regression equations between HR and $T_{r.rest}$, between HR and $T_{r.exe}$, and predicted rectal temperature (T_{re}) and observed T_{re}. To compare the predictive power of all predictive equations, goodness-of-fit was measured for each by adapting the R^2 statistic from linear regression. The Bland-Altman scatter-plots were used to verify the absolute agreement between predicted T_{re} and observed T_{re} (Bland & Altman, 1986). Simple regression analysis was used to confirm the insignificant tendency of the difference between predicted T_{re} and observed

T_{re}. A one-way analyses of variance (ANOVA) was used to identify differences in the changes of mean heart rate during post-exercise rest periods for every minute, with LSD *post hoc* test. All statistical analyses were performed with IBM SPSS statistics v. 21. All data were represented in mean±SD. Significance was accepted at $p<0.05$.

Chapter 4. Results

4.1 [Experiment 1] Stability of skin temperature against fluctuation of ambient temperatures

4.1.1 Magnitude and the time duration of decrease in skin temperatures

The time duration of decrease in skin temperature was significantly lower on the forehead (35±70.5s), whereas those of forearm temperature and temperature inside the boots were significantly greater than the other sites (404±163.0s, 373±139.3s) (Figure 4.1A). The magnitudes of decrease in skin temperature induced by decreases in ambient temperature was significantly lowest on the forehead (-0.08±0.173^{o}C) (p<0.05), whereas, those in the abdomen, thigh (-0.38±0.633^{o}C), back (-0.54±0.710^{o}C) and inside the boots (-0.43±0.232^{o}C) were significantly greater than those in the other sites. Skin temperature on the chest (-0.11±0.097^{o}C), upper arm (-0.11±0.117^{o}C) and toe (-0.15±0.137^{o}C) were lower than those in the forearm, hand, abdomen, thigh, boots, and back, while they did not show any significant difference with those in the foot, calf, and lateral foot.

Slope was significantly greater on the back (0.0032±0.00441) than the other sites, except for the forehead (0.0021±0.00063), lateral foot (0.0015±0.00158) and thigh (0.0015± 0.00142) (p<0.05). Mean value of slopes were 0.0010±0.00126 (the unit of slope was ˚C/s) which was significantly lower than the back, forehead, lateral foot and thigh. Accordingly, the forehead, chest, upper arm, and toe were selected as the stable measurement sites, among 13 measurement sites.

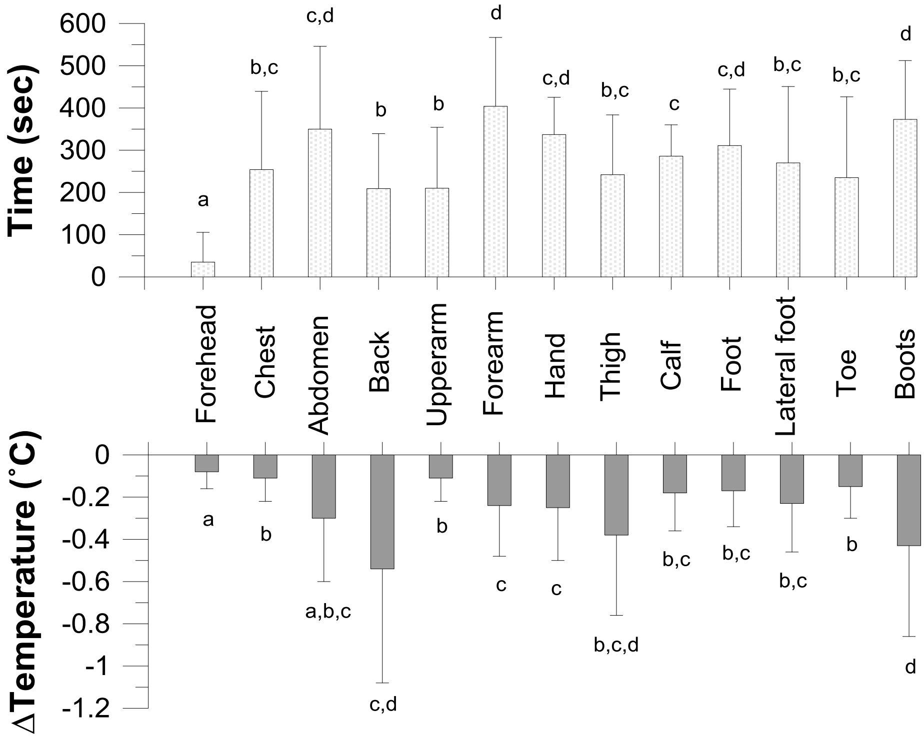


Figure 4.1 Time duration of decrease and the magnitude of change in each site. The letters (a, b, c, d) above or below error bars represent significant differences among 13 measured sites during the decrease in the environmental temperature as a result of the Mann Whitney U-test (*p*<0.05)

4.1.2 Valid range to analyze

The point where skin temperature and rectal temperature started to show a linear relationship was determined as 36.18±0.29˚C at the forehead, 35.32±0.46˚C at the chest, 36.04±0.52˚C at the upper arm and 36.70±0.35˚C at the toe, and the effective range of prediction was selected when skin temperature exceeded those temperatures at each site (Table 4.1). Rectal temperature was ~37˚C when the relationship between skin temperature and rectal temperature started to be linear (Phase 3 of the Figure 3.5).

Table 4.1 Points where skin temperature and rectal temperature showed a linear relationship

	N	**Skin temperature (˚C)**	**Rectal temperature (˚C)**
Forehead	7	36.18±0.29	37.01±0.27
Chest	8	35.32±0.46	37.05±0.29
Upper arm	8	36.04±0.52	37.05±0.31
Toe	7*	36.70±0.35	37.05±0.31

*The outlier, which showed 33.48˚C in the toe skin temperature was excluded in the mean value.

4.1.3 Predictive equation of rectal temperature

Within the valid range to analyze, a regression equation, whose independent variables were forehead temperature and heart rate, was found to be the most valid predictive equation of rectal temperature (R^2=0.836, p< 0.001), followed by a regression equation with chest temperature and heart rate as independent variables (R^2=0.831, p<0.001, Table 4.2). Among simple regression equations, the equation whose independent variable was forehead temperature was presented as the most valid one (R^2=0.827, p<0.001), followed by the equation using chest temperature (R^2=0.816, p<0.001).

Table 4.2 Regression equations of rectal temperature

Type	**Region**	**Regression equations**	$\mathbf{R^2}$
Single	Forehead	$y=0.830x_1+6.943$	0.827
	Chest	$y=0.863x_1+6.238$	0.816
	Upper arm	$y=0.935x_1+3.217$	0.782
	Toe	$y=0.652x_1+14.087$	0.539
Multiple	Forehead	$y=0.742x_1+0.003x_2+9.823$	0.836
	Chest	$y=0.769x_1+0.004x_2+9.199$	0.831
	Upper arm	$y=0.841x_1+0.003x_2+6.308$	0.776
	Toe	$y=0.443x_1+0.007x_2+20.067$	0.519

4.2 [Experiment 2] Physiological responses during intermittent exercises and rests

4.2.1 Effects of the rests between exercises

In regard to rectal temperature, skin temperatures (forehead, forearm, and toe), and heart rate, there was no significant difference between Break and NoBreak except for forehead temperature at the end of the exercise and heart rate during recovery (Table 4.3). This result indicates that 10 min rest between works in the summer while wearing turnout gear is hardly effective from a physiological point of view.

Table 4.3 Differences between Break and NoBreak

Phase	Parameter	Condition		*p*-value
		Break	NoBreak	
Rest	T_{re} (℃)	37.11±0.21	37.10±0.27	0.959
	$T_{forehead}$ (℃)	36.08±0.28	36.16±0.32	0.285
	$T_{forearm}$ (℃)	35.08±0.65	35.14±0.34	1.000
	T_{toe} (℃)	31.81±3.97	30.53±4.54	0.445
	Heart rate (bpm)	69±6.2	69±4.7	0.646
At the end of the exercise	T_{re} (℃)	38.12±0.27	38.15±0.39	0.799
	$T_{forehead}$ (℃)	37.83±0.50	38.18±0.46	0.013*
	$T_{forearm}$ (℃)	37.01±0.66	37.25±0.40	0.161
	T_{toe} (℃)	39.47±0.51	39.50±0.66	0.959
	Heart rate (bpm)	169±13.3	171±8.7	0.093
Recovery	T_{re} (℃)	38.68±0.32	38.82±0.38	0.333
	$T_{forehead}$ (℃)	37.08±0.43	37.25±0.61	0.333
	$T_{forearm}$ (℃)	37.15±0.40	37.23±0.27	0.401
	T_{toe} (℃)	38.03±0.42	38.23±0.53	0.285
	Heart rate (bpm)	118±13.0	122±14.8	0.005**

4.2.2 Thermal accumulation during intermittent exercises

Rectal temperature, forearm temperatures and heart rate in the post-exercise rest periods were significantly greater than those at rest (p<0.001), and they were significantly greatest during recovery among the three phases (p<0.001), but forehead skin temperature showed no difference between at rest and the post-exercise rest periods (Figure 4.2)

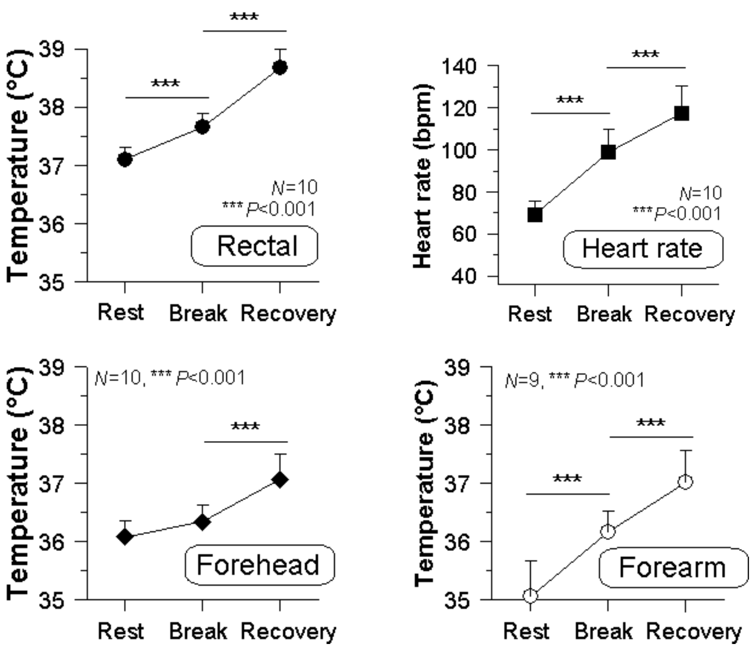


Figure 4.2 Mean rectal temperatures, skin temperatures on the forehead and forearm, and heart rate at rest, post-exercise rest and during recovery. Data were analyzed by one-way ANOVA with Tukey HSD post-hoc test. *** indicates significant difference between two states (p<0.001). Error bars represent SD.

4.2.3 Relationship between rectal temperature and skin temperature

Skin temperatures began to decrease drastically in parallel with the termination of exercise, whereas rectal temperature kept increasing. Accordingly, during exercise, the relationship between rectal temperature and skin temperature was positive approximating exponential function. In contrast, during post-exercise rest periods it showed a negative relationship. <Figure 4.3> shows the shift of slope bordering exercise and rest.

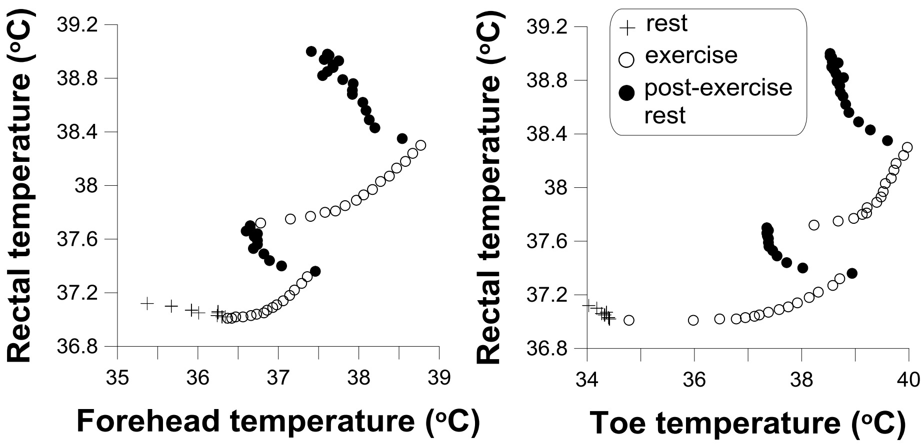


Figure 4.3 Relationship between rectal temperature and skin temperatures at the forehead and toe of one participant. Opened circles and close circles represent values during exercises and at post-exercise rest periods respectively. Data were extracted every 1 min.

4.3 [Experiment 2] Heart rate limit index using heart rate at pre-exercise rest periods

4.3.1 Development of predictive equations

Predictive equations were developed using both $HR_{absolute}$ and $HR_{relative}$ as independent variables separately. As a result of simple regression analysis with $HR_{absolute,}$ significant regression equations of $T_{re.rest}$ (R^2=0.680, (*adj*)R^2=0.665, P<0.001, Figure 4.4A) and ΔT_{re} (R^2=0.482, (*adj*)R^2=0.459, P<0.001, Figure 4.5A) were developed. The predictive equations were as follows:

$$T_{re.rest}=0.018 \cdot HR_{absolute}+35.862 \qquad \text{[Eq. 4.1]}$$

$$\Delta T_{re}=0.0004 \cdot HR_{absolute}-0.0061 \qquad \text{[Eq. 4.2]}$$

<Eq. 4.3> was made by substituting <Eq. 4.1> and <Eq. 4.2> into <Eq. 3.2>, since <Eq. 3.2> was assumed.

$$T_{re}(t)=0.018HR_{absolute} +35.862+(4\cdot HR_{absolute}-61)\cdot 10^{-4}\cdot t \qquad \text{[Eq. 4.3]}$$

Where $HR_{absolute}$ is heart rate during pre-exercise rest periods and t (min) means duration time of exercise. Likewise, significant regression equations of $T_{re.rest}$ (R^2=0.722, (*adj*)R^2=0.710, P<0.001, Figure 4.4B) and ΔTre (R^2=0.506, (*adj*)R^2=0.483, P<0.001, Figure 4.5B) were developed by $HR_{relative}$ as follows:

$$T_{re.rest}=0.035 \cdot HR_{relative}+35.830 \qquad \text{[Eq. 4.4]}$$

$$\Delta T_{re}=0.0008 \cdot HR_{relative}-0.0066 \qquad \text{[Eq. 4.5]}$$

Since <3.2> was assumed, T_{re} (t) was calculated using the following equation:

$$T_r(t)=0.035HR_{relative} +35.830+(8\cdot HR_{relative}-66)\cdot 10^{-4}\cdot t \qquad \text{[Eq. 4.6]}$$

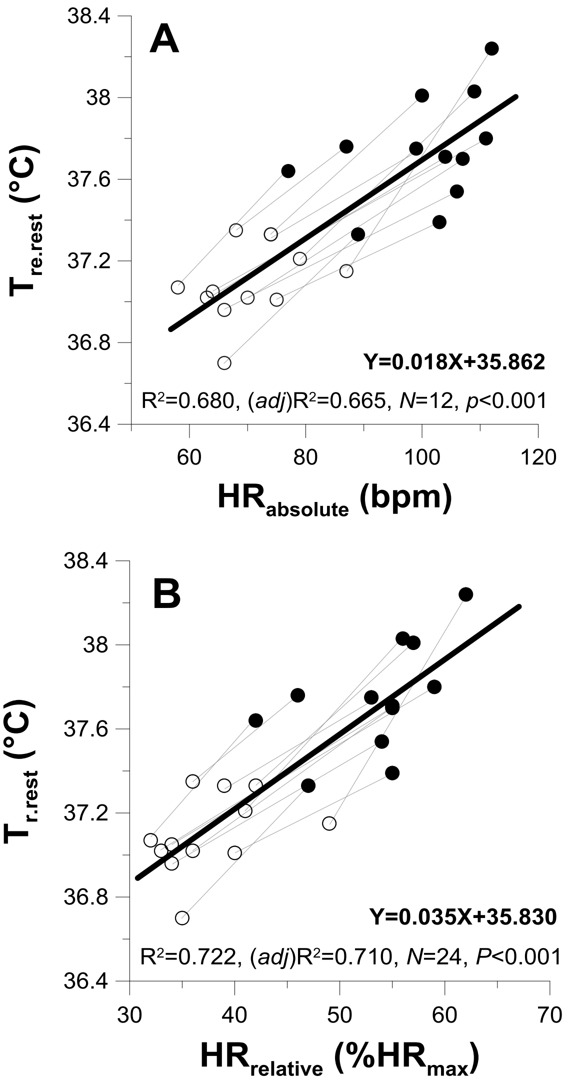


Figure 4.4 Scatter plot of rectal temperature and heart rate at pre-exercise rests. Bold line indicates significant regression line. Plot A used Absolute value of heart rate (bpm) as independent variables, while plot B used a percent of maximal heart rate (%HR_{max}). Opened circles and closed circles represent respectively first and second exercise sets consisting of pre-exercise rest and exercise.

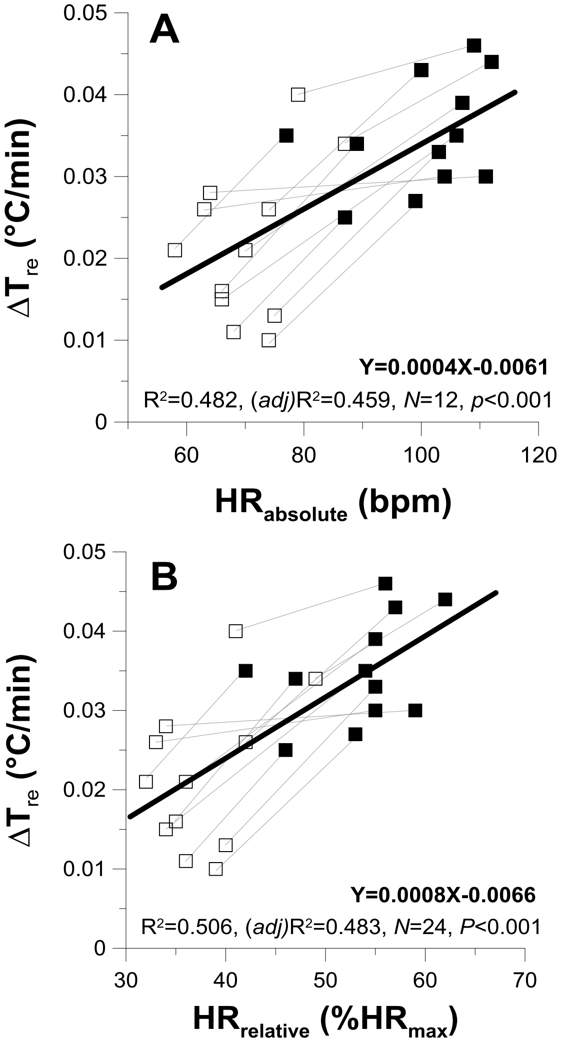
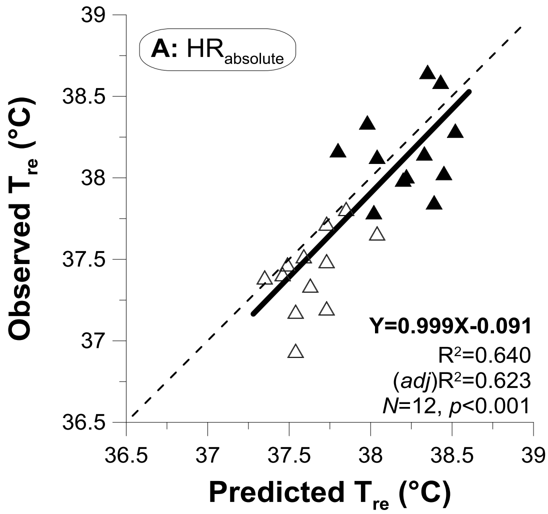


Figure 4.5 Scatter plot of change of rectal temperature during exercises and heart rate at pre-exercise rests. Bold line indicates significant regression line. Plot A used Absolute value of heart rate (bpm) as independent variables, while plot B used a percent of maximal heart rate (%HR_{max}). Opened squares and closed squares represent respectively first and second exercise sets consisting of pre-exercise rest and exercise.



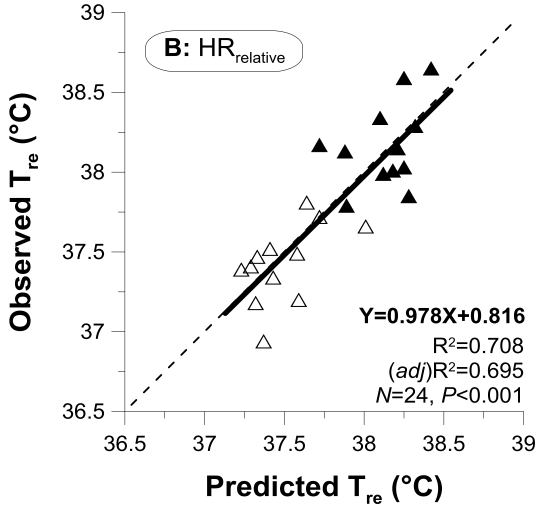


Figure 4.6 Distribution of predicted rectal temperature and observed rectal temperature. Bold line indicates significant regression line. Plot A used Absolute value of heart rate (bpm) as independent variables, while plot B used a percent of maximal heart rate (%HR_{max}). Opened triangles and closed triangles represent respectively first and second exercise sets consisting of pre-exercise rest and exercise.

Twenty-four data points could be divided by the first or second exercise set, which consists of pre-exercise rest and exercise. In order to test whether there was a significant relationship between heart rate and $T_{re.rest}$, heart rate and ΔT_{re} within each exercise set, each exercise set was regarded as an independent variable and regression analysis was conducted. The order of the exercise set is a nominal variable, so it was digitized by using dummy variables.

Firstly, when assuming that there is the reciprocal action between heart rate and the order of exercise set, a regression model was expressed as follows;

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 \qquad \text{[Eq. 4.7]}$$

In this equation, Y means $T_{re.rest}$, X_1 means heart rate, and X_2 is dummy variables indicating the order of exercise set. X_2 was digitized as follows;

If the order of exercise set is first, $X_2=0$

If the order of exercise set is second, $X_2=1$

Thus, the regression equations of samples could be reorganized as follows;

$$\text{If} \quad X_2 = 0,\ Y = \beta_0 + \beta_1 X_1 \qquad \text{[Eq. 4.8]}$$

$$\text{If} \quad X_2 = 1,\ Y = (\beta_0 + \beta_2) + (\beta_1 + \beta_3) X_1 \qquad \text{[Eq. 4.9]}$$

As a result of regression analysis, significant regression equations were not developed in regard to both exercise sets. (Table 4.4). These results inferred that there was no relationship between heart rate and $T_{re.rest}$ and heart rate and ΔT_{re} within each exercise set, but between each exercise sets.

Table 4.4 Regression equations when the order of exercise set was substituted by dummy variables

Y	**X_1**	**X_2***	**Regression equation**	**R^2**	***p*-value**
$T_{re.rest}$	$HR_{absolute}$	0	$Y = 36.478+0.009X_1$	0.140	0.232
		1	$Y = 36.725+0.10X_1$	0.172	0.181
ΔT_{re}	$HR_{absolute}$	0	$Y=-0.010+0.000X_1$	0.145	0.223
		1	$Y=0.011+0.000X_1$	0.139	0.232
$T_{re.rest}$	$HR_{relative}$	0	$Y=36.483+0.016X_1$	0.174	0.177
		1	$Y=36.379+0.025X_1$	0.310	0.060
ΔT_{re}	$HR_{relative}$	0	$Y=-0.007+0.001X1$	0.150	0.213
		1	$Y=0.006+0.001X_1$	0.207	0.137

*X_2 is dummy variables indicating the order of exercise sets

4.3.2 Validity

<Figure 4.7> shows comparisons between observed T_{re} and predicted T_{re} by $HR_{absolute}$ and $HR_{relative}$. Predicted T_{re} by $HR_{absolute}$ showed bias of 0.14, whereas Predicted T_{re} by $HR_{relative}$ rarely showed bias. 95% of all values predicted by $HR_{absolute}$ and $HR_{relative}$ were located in the range of (0.67, -0.39) and (0.49, -0.45) respectively.

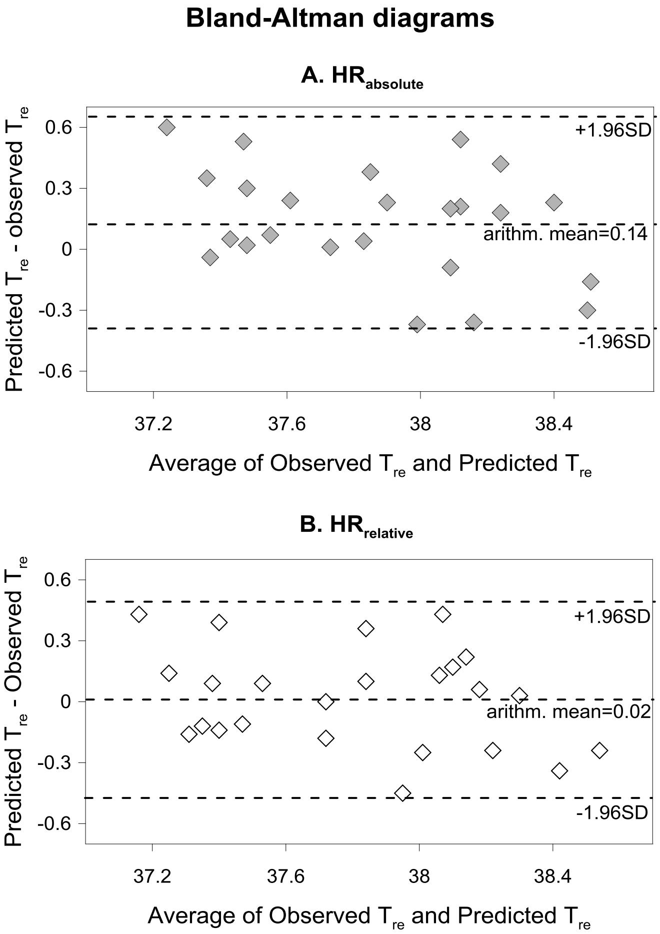
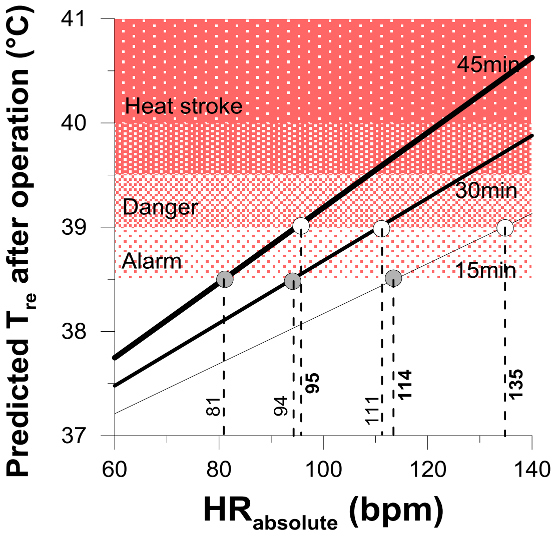


Figure 4.7 Bland-Altman plot comparing the predicted T_{re} and observed T_{re} (N=24)

4.3.3 Suggestion of heart rate limit

By substituting duration times of operation (e.g. 15, 30, 45) into <Eq. 4.3> and <Eq. 4.6>, equations of predicted T_{re} after operation and whose independent variable was solely $HR_{absolute}$ or $HR_{relative}$ were developed. Through these equations, permissible heart rate values at pre-exercise rest periods were calculated, which are shown in <Figure 4.8>. According to the results, the limit value of heart rate in which firefighting operations last 30 min is 111bpm or 57%HR_{max}. Likewise, limit values of heart rate to return to work are suggested as 95bpm or 49%HRmax in case of operating for 45 min and 135bpm or 70%HRmax in cases of operating for 15min.



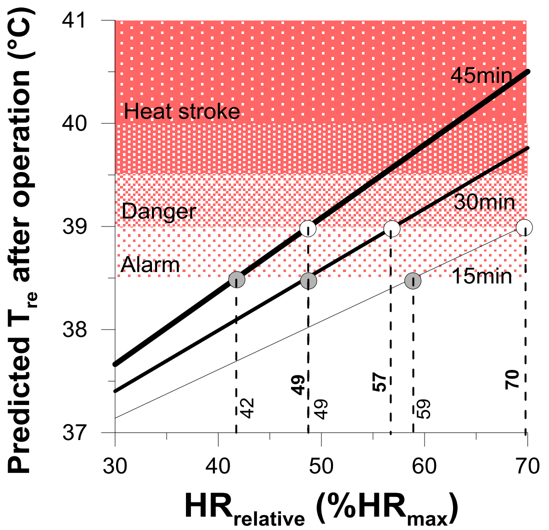


Figure 4.8 Limit value of heart rate to return to firefighting operations for 15 min, 30 min, and 45 min. Absolute value of heart rate (bpm) was used as independent variables, while plot B used a percent of maximal heart rate ($\%HR_{max}$). Plot A used Absolute value of heart rate (bpm) as independent variables, while plot B used a percent of maximal heart rate ($\%HR_{max}$).

4.3.4 Optimal time to measure heart rate

Heart rate decreased drastically in parallel with the cessation of exercise and showed a steady-state 2 min after the cessation of exercise in both exercise bouts (Figure 4.9). In the first post-exercise rest periods heart rate increased after 9 min due to preparation actions resulting from consecutive exercise.

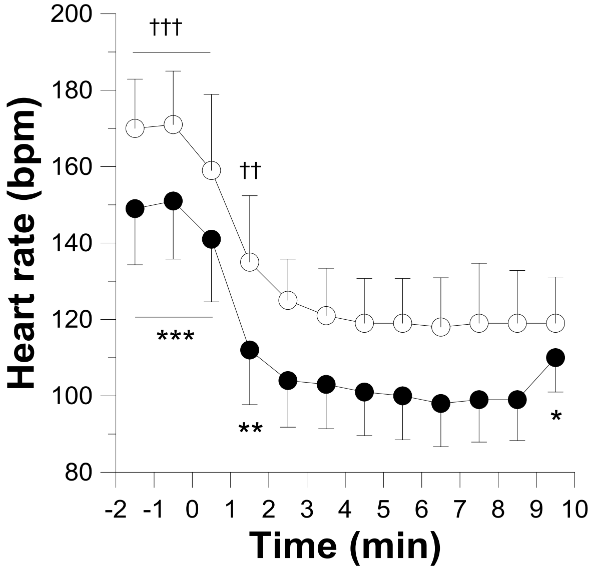


Figure 4.9 Mean change in heart rate during post-exercise rest periods for the two successive exercise/rest cycles. Closed circles and opened circles indicate heart rates during first exercise periods and following rest periods and heart rates during second exercise periods and following rest periods. * and † indicate values significantly different from the values from 6min to 7min. Error bars indicate SD.

4.3.5 Influences of exercise intensity on validity

The magnitude of error was significantly influenced by the difference between individual $\dot{V}O_{2max}$ and averaged $\dot{V}O_{2max}$ which was approximately 60 ml·kg^{-1}·min^{-1} (p<0.05, Figure 4.10). The results inferred that the validity of the prediction equation based on heart rate would be altered by the exercise intensity.

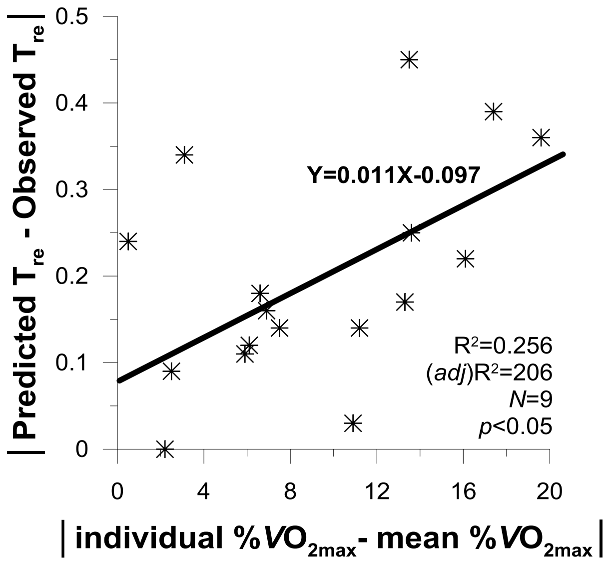


Figure 4.10 Distribution and regression line of errors and differences between individual exercise intensity (individual %$\dot{V}O_{2max}$) and averaged exercise intensity (mean %$\dot{V}O_{2max}$).

Chapter 5. Discussion

5.1 Optimal measurement sites to measure skin temperatures

The forehead was the most common location used to measure skin temperature in a clinical setting where patients are usually at rest (Table 1) and the reasons were physiological and practical. The physiological reasons include: skin temperatures obtained at the forehead are always higher and thus comparable with the blood temperature in the internal jugular vein measured with a catheter thermometer (Ball et al., 1973; Togawa et al., 1976) and the forehead is close to the center of physiological temperature regulation (Togawa et al., 1976). In addition, the main shell of the head is bone, which has the highest heat conductivity among all body tissues (Xu et al., 2013) and the head plays a key role in determining the overall personal comfort of a human (Gunga et al., 2008). As for practical reasons: the convenience and usefulness or fitting a probe with a hair band have been suggested (Gunga et al., 2008; Yamakage and Namiki, 2003) and the fact that the helmet is necessary equipment for firefighters and sensors can easily be attached (Gunga et al., 2008). On the other hand, Xu et al. (2013) reported that the forehead appeared to be unsuitable for the purpose of monitoring heat strain. In that study, R^2 was the lowest on the forehead (Smith & Havenith, 2011), since the sensor adhering to the forehead often became loose due to heavy sweating. They concluded that the measurement on the forehead is less reliable during intense exercise or heat exposure, but left the door open for reliability of forehead temperature in cases studying or using low permeability clothing (Xu et al., 2013).

In this study, which was especially limited in firefighters' protective clothing, the main reason for stability of forehead temperature was supposed as the result of the integrated influence of insulation and osculation, along with such physiological characteristics of the head. Bernard and Kenny (1994) reported that the relationship between estimated core temperature and observed core temperature was dependent on the ensemble worn over the sensors. Taylor et al. (1998) suggested that skin temperature could approach core temperature when environmental influences had been minimized and they successfully made a predictive equation of esophageal temperature by insulating the skin. In the current study, although any additional insulation of the skin on measurement sites was not included, stability of skin temperature was documented on the forehead and predictive equations with high R^2 were produced (R^2>0.8), since firefighters' protective clothing is thermally insulated clothing itself. Although data of thermal insulation regarding the combination of the helmet and hood have been minimally reported, heat loss from the forehead should be considerably low when considering the buffer effect of the helmet near the forehead, which has a role in cushioning the impact and the tight structure among the helmet, hood, and forehead. Specifically, it was assumed that the tight structure could considerably contribute to inhibit evaporation and facilitate absorption of sweating. Further investigations are required.

Along with forehead temperature, chest temperature was significantly stable against changes of environmental temperature ($p<0.05$), and predictable of rectal temperature, showing R^2 of the single regression equation was 0.816 and R^2 of the multiple regression analysis with heart rate was 0.831. The common measurement site of previous studies for the chest was the upper sternum (Fox and Solman, 1971; Xu et al., 2013). It was selected as the most representative site for measuring core body temperature because the upper sternum is anatomically close to the heart and pulmonary blood (Fox and Solman, 1971; Xu et al., 2013), is relatively flat, and has very little subcutaneous fat (Fox and Solman, 1971). Flat conformation was one reason for support, since the device, the Zero-heat flow sensor, required a considerable area, from 25mm to 80mm, to prevent dissipation of heat from the skin (Yamakage and Namiki, 2003). When comparing chest temperature with abdominal and back temperature, the thermal insulation of protective clothing did not play a great role in the stability and reliability of the skin temperature. Although thermal insulation (I_T) of heat protective clothing ensembles including coverall, trousers, jacket, shoes and socks were estimated at 2.44clo (Holmer et al., 2006), and it was common among the three sites, the abdomen and back were presented as unsuitable sites to indirectly measure rectal temperature. Especially, considering the change of temperature in the back was the greatest among the 13 measurement sites, which would be influenced by heavy sweating (Smith and Havenith, 2012).

5.2 Initial phases of increasing skin temperature

In regard to the dynamics of skin temperature along with the increase of rectal temperature, few studies have considered the existence of range of flat plateau, presented as first phase in <Figure 3.5>. When humans wear impermeable clothing, such as firefighters' protective clothing, dissipation of heat, produced by humans is hindered, resulting in the increase of microclimate temperature. The initial phase of the local warming response is evoked by a feedforward control system mediated by local activation of afferent cutaneous sensory nerves (Kellogg, Jr. 2006). Both ambient temperature and skin temperature are regarded as feedforward inputs, while skin temperature depends on both external ambient temperature and skin blood flow (Kanosue et al., 2010). In the current study, the range where activated vasodilation with steady state of rectal temperature was investigated until skin temperature approached 36.18±0.29˚C at the forehead, 35.32±0.46˚C at the chest, 36.04±0.52˚C at the upper arm and 36.70±0.35˚C, when the rectal temperature was almost 37˚C independent of measurement sites. The skin temperature range exceeding skin temperatures mentioned above was named as the effective range in the current study, which is required for the reliable prediction of rectal temperature by indirect methods.

It is comprehensible, in that the rectal temperature is not the state which requires monitoring due to heat strain when skin temperature is less than the criteria used for rectal temperature.

5.3 Heat accumulation during intermittent exercises

The core body temperature constantly maintains itself when heat loss and heat production are balanced. However, the balance could not be maintained during exercise, since the rate of heat production drastically increases with commencement of exercise, whereas heat loss increases gradually (Kenney et al., 2008). In addition, heat dissipation manifested primarily as a reduction in whole-body evaporative heat loss, since accompanied with the rapid decrease in metabolic heat production after cessation of exercise, there is a rapid decline in local skin blood flow and sweating (Kenny and Jay, 2007). This body heat imbalance occurring during exercise is called thermal inertia (Murgatroyd et al., 1993) or temporal dissociation (Webb and Annis, 1966), which induces an increase of rectal temperature. For this reason rectal temperature continuously keeps increasing irrelevant to rest periods, if heat dissipation is not fully achieved during rest periods.

The amount of heat loss determines whether heat is accumulated during rest periods or not. In the previous study, mean core temperature during three intermittent exercises did not accumulate even while wearing turnout gear (Smith et al., 2014), since personal protective clothing on participants were all removed during rests between exercises and the ambient temperature was 21℃. In the current study, partial personal protective equipment was removed such as helmet, gloves, and SCBA and the ambient temperature was set at 32℃, which was approximately equated with air temperature in the summer. Summer was chosen as the experimental environment, because the risk of heat-related illness increases in the summer and developing a precautionary method was the purpose of current study.

At the scene of a fire, the best way to relieve thermal strain is to remove all the firefighting gear, yet it is not a simple task for firefighters to quickly doff or don their clothing and equipment (Kwon et al., 2012), since donning and doffing of firefighting gear is more difficult when it is wet from firefighting (Barker et al., 2013) and firefighters are often required to re-enter after short recovery periods (Rayson et al., 2007). Therefore, heat-accumulative physiological responses are supposed to occur frequently when considering that firefighting could be prolonged until the fire is perfectly extinguished and considering the remaining time to doff and don gear.

5.4 Limitations of skin temperatures as predictive variables for rectal temperature

Prediction of rectal temperature using skin temperature has two inescapable limitations. At first, the rectal temperature predicted by skin temperature has a possibility to be inaccurate since skin temperature is directly influenced by changes in environmental temperature. Moreover, the actual range of environmental temperatures for firefighting is greater than 5℃, the amplitude of experimental temperature change in the first experiment. In the current study, forehead temperature, the most stable skin temperature against change of ambient temperature, altered 0.1℃ when ambient temperature was altered 5℃. Although it is difficult to ascertain exactly how much forehead temperature would alter under actual fluctuating ambient temperature, it most likely would be much greater than 0.1℃. Therefore, the stability against ambient temperature is one of the important characteristics which non-invasive parameters should satisfy with. At the same time, skin temperature is not a sufficiently valid variable to predict rectal temperature.

The second limitation of using skin temperature is regarding the rapid changes in temperature that occurred during exercise and resting states. In the current study, sudden changes of slope from positive to negative in the coordinate of rectal temperature and skin temperature were observed at the beginning of recovery (Figure 4.3). Augmenting validity at this range has been regarded as tantalizing problem (Gunga et al., 2008). It is a problem which needs to be solved, even if only for the upper limit value, which is measured during exercise, not rest. Skin temperature of firefighters, who return to firefighting after rest for 10 min, could quickly recover to the level just before the cessation of exercise, if heat loss is not sufficient during breaks. To negate this limitation, heat dissipation should be accelerated, which seems impractical, especially under the high ambient temperatures, considering short breaks and the difficulty doffing and donning firefighters' personal protective clothing.

5.5 Evaluating heat strain through heart rate

At any given time, heart rate (HR) can be considered as the sum of several components which are not independent of each other as follows: HR = $HR_0 + \Delta HR_M + \Delta HR_S + \Delta HR_T + \Delta HR_N + \Delta HR_E$ (ISO 9882, 1992) where HR_0 is the heart rate at rest while sitting under neutral conditions, ΔHR_M is the increase in heart rate linked with work metabolism, ΔHR_S is the increase connected with static exertion, ΔHR_T is the component connected with the thermal strain, ΔHR_N is the component due to psychological factors, and ΔHR_E is the residual component connected with rhythm of breathing, etc. That is, firefighters' heart rate during firefighting consists of HR_0, ΔHR_M, ΔHR_T, whereas during post-exercise rest periods consists of HR_0, ΔHR_S, ΔHR_T if ΔHR_N and ΔHR_E are negligible. Among them, ΔHR_S is extinguished within a few minutes (Figure 4.9). Consequently, heart rate during post-exercise rest periods could significantly reflect heat strain.

There are numerous studies exploring the relationship between heart rate and the other physiological variables. Heart rate response shows a well-established linear relationship with oxygen uptake over a wide range of exercise intensities (Astrand and Tyhming 1954; Asmussen and Hemmingsen 1958). It leads to the prediction model of $VO2_{max}$ with heart rate as an independent variable, which was named HR_{index} (Wicks et al., 2011). HR_{index} describes the ratio of heart rate during exercise to resting heart rate. The relative heart rate value with respect to maximal heart rate has been widely used as an index of exercise intensity. However, heart rate during post-exercise rest periods as an index of heat strain has rarely been investigated. In the current study, rectal temperature was predicted by heart rate during post-exercise rest periods based on the observed phenomenon that heart rate was maintained at a higher level than the initial value even after the firefighter recovered from static exertion.

Predictive error was enlarged when the relative exercise intensity of an individual was different from the averaged relative exercise intensity (Figure 4.10). This infers that the validity of predicting rectal temperature by heart rate is influenced by exercise intensity, but it does not mean that heart rate is not an adequate variable to predict rectal temperature. The predicted value of rectal temperature could be separated $T_{re.rest}$ and $\Delta T_{re} \cdot t$ as shown in <Eq. 3.2>. $T_{re.rest}$ showed a significantly stronger relationship with heart rate, whereas ΔT_{re} showed quite a weak relationship with heart rate though it was significant. ΔT_{re} means the change of rectal temperature during exercise per unit time. Increases of rectal temperature during exercise were the result of heat production through energy metabolism in the muscles. The magnitude of increase of rectal temperature is influenced by exercise intensity, ambient temperature, clothing, etc (Giovoni & Goldman, 1972). To improve the predictive validity, the method to predict ΔT_{re} should be investigated more. The predictive equation was most valid at the exercise intensity of 60%$\dot{V}O_{2max}$, which was the averaged exercise intensity. However, it is below the average exercise intensity of firefighting, which ranges from 55 to 82%$\dot{V}O_{2max}$ (Lemon & Hermiston, 1977). Hence, when predicting rectal temperature by heart rate various work intensities should be considered. It is required to be departmentalized even when suggesting a heart rate limit index.

As for the results of regression analysis, $T_{re.rest}$ and ΔT_{re} showed a significantly linear relationship with heart rate not within exercise sets but between exercise sets, which implies that heart rate could indicate the rectal temperature but there were quite a few differences among individuals in the level of heart rate at the same rectal temperature. These individual differences affecting human thermoregulation include: body surface area, body mass, body fat, maximal O_2 uptake, acclimation, etc (Havenith, 2001). Further investigations in respect to individual differences toward ΔT_{re} and how to consider them along with heart rate when predicting rectal temperature models are required.

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5.6 Comparison with existing non-invasive measurement methods of core temperature

The purposes of previous studies which studied the development of non-invasive measurement methods of core temperature varied from patient monitoring in clinical settings to monitoring the circadian rhythm of astronauts. Among them, heat strain monitoring in occupational settings is one of the most common purposes. Recently, Gunga et al. (2008) studied "Double sensor", which attached to the helmet on the vertex of the head for firefighters. The subdivision of objects is desirable in a situation of insufficient data and research, since clothing could be controlled, which is an influential factor regarding accuracy (Bernard and Kenny, 1994; Taylor et al., 1998). However, the "Double sensor" attached to the helmet of firefighters' gear, still holds several limitations especially concerning its application and accuracy. In the current study, firefighters' forehead temperature altered fewer dynamics when covered with the hood and helmet, which implies that the hood, with a flexible and filamentous structure, could reliably predict rectal temperature, which is expected, thanks to the technological advancement of sensors including temperature sensors (Sibinski et al., 2010).

However, the predictive validity of skin temperature is significantly influenced by the changes in ambient temperature and exercising states, whereas, predicting rectal temperature by heart rate during pre-exercise rest periods could be rather stable and valid. There were few previous studies that used only heart rate as an independent variable, because they had tried to evaluate heat strain during exercise but the greatest change of heart rate during exercise reflected the increase in metabolic rate.

On the other hand, this study selected the heart rate value during pre-exercise rest periods rather than during exercise. This method could be more practical than other developed or developing non-invasive measurement methods of rectal temperature. First, the sensor for measuring heart rate is more widespread than the sensor for skin temperature. Measuring heart rate in the smart wearable devices has already been developed. Second, the alarm or alert for the device could be difficult to notice by firefighters working a fire scene, since there is heavy noise and firefighters are immersed in their work. On the other hand, it is possible that firefighters could measure their heart rate without any disturbance. Finally, skin temperature could quickly recover to the level just before the cessation of exercise when firefighters return to firefighting, which results in negative effect on the work efficiency. Evaluating heat strain by heart rate during rest periods enables firefighters to manage and regulate their rest time, depending on the magnitude of alleviation of heat strain, which would enhance work efficiency.

Chapter 5. Summary and Conclusions

The current study was a series of processes to develop a non-invasive predictive method to assess core temperature in order to prevent firefighters' heat-related illness. Changes in skin temperature were induced by fluctuating ambient temperature while fully wearing protective clothing and equipment. The magnitude of changes depended on measurement sites. The forehead, chest, upper arm and toe were suggested as the stable measurement sites against changes of environmental temperature. However, the rapid changes in skin temperatures bordering exercise and rest were reported irrelevant to the measurement sites. Hence, instead of skin temperatures, heart rate at pre-exercise rest periods was suggested as the alternative. As a result, significant predictive equations with heart rate values were developed ($HR_{absolute}$; R^2=0.640, P<0.001, $HR_{relatvie}$; R^2=0.708, P<0.001). Additionally, heart rate limit values were suggested, though their reliability might decrease without an exercise intensity of 60%VO2max and air temperature of 32°C.

Despite limited experimental conditions, this study found or suggested (i) a new method for evaluating the reliability of measurement sites under fluctuating ambient temperature, (ii) heat acclimation during post-exercise rest periods in the condition of partially removing turnout gear, and (iii) a new method for evaluating heat strain and protecting firefighters from heat-related illness, all of which would be applicable in managing heat strain in a wholly precautionary way for firefighters.

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초 록

본 연구는 소방관의 비침습적 심부온 예측방법을 개발하기 위한 목표 아래 진행된 일련의 과정으로 소방관의 심부온 예측 타당도 향상을 위한 비침습적 지표인 피부온과 심박수를 분석하였고 소방작업의 중간 휴식 시 심박수를 이용한 서열 부담 평가 방법을 제안하였다. 먼저, 소방복을 착용하고 작업하는 동안 환경온도의 변화에 대해 이마, 가슴, 그리고 윗팔과 발가락의 피부온도가 다른 부위의 피부온도에 비해 외기온의 변화에 대해 가장 안정적이었지만 (p<0.05), 전신 방화복을 착용하더라도 환경온의 변화가 피부온의 변화에 영향을 주었으며 이러한 점이 피부온을 활용한 심부온 예측 시 외생 변수로 작용할 수 있음을 확인하였다. 또한 소방관의 반복 작업 시, 중간 휴식을 취하더라도 서열 부담은 축적되며, 휴식과 무관하게 꾸준히 증가하는 심부온과는 달리, 피부온은 운동의 종료와 함께 급격하게 감소하였다가 운동이 다시 시작될 때 이전의 최대값 수준으로 빠르게 회복하는 것을 관찰하였다.

이에 따라 환경온도와 반복 작업 시 중간 휴식의 영향을 받는 피부온 대신 중간 휴식 시 심박수를 이용해 직장온을 예측하였고 32℃, 60% $\dot{V}O_{2max}$ 의 강도에서 15 분, 30 분, 45 분 간 작업 중 직장온이 한계점에 도달하지 않기 위한 중간 휴식 시 심박수의 한계값을 제안하였다. 중간 휴식 시 심박수를 활용한 직장온의 예측은 작업 강도에 의한 영향을 받는다는 한계를 가진다. 하지만 기존의 서열부담 예측 방법들과 비교했을 때 심박수라는 단일 변수를 사용하여 간단하게 서열 부담을 측정할 수 있다는 장점을 가진다.

주요어: 소방관, 서열 스트레스, 반복 작업, 심부온, 서열 부담, 심박수, 산업 보건

학 번: 2013-21515