의류학박사학위논문

Exploration and Validity Evaluation of Physiological Strain Index for Workers When Wearing Personal Protective Equipment in Hot Environments

서열 환경에서 개인보호복 착용 작업자의 서열부담 추정을 위한 비침습적 항목 탐색과 지표의 타당성 평가

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Exploration and Validity Evaluation of Physiological Strain Index for Workers When Wearing Personal Protective Equipment in Hot Environments

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Abstract

Initially, physiological strain index (PSI) was developed based on rectal temperature (T_{re}) and heart rate (HR) to estimate heat strain and heat illness from workers: $5\,(T_{re}t - T_{re}0) \cdot (39.5 - T_{re}0)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR0)^{-1}$, and this method was widely used to evaluate individual thermal strain in experimental settings. However, the difficulties of measuring T_{re} in the field, and the need to directly insert the sensor into workers for measurement have hindered the further application of this method. Accordingly, the estimation of core temperature (T_c) through non-invasive measurement has been proposed in numerous studies. However, there are still some technical limitations on measurement in an actual field. Therefore, this study aimed to present a more practical, non-invasive physiological strain index. To this end, this study aimed to explore and evaluate the validity of non-invasive physiological parameters that can be used for the real-time monitoring of workers wearing personal protective equipment (PPE) in hot environments. This study was divided into two parts. In Part 1, experiments A and B were conducted to evaluate the heat strain of wearing PPE in hot environments. In Experiment A, two clothing conditions were used: 1) daily clothes and 2) full-body protective clothing under three temperature conditions (28, 33, and 38 °C) at 70% relative humidity (RH). Heat strain assessment was performed according to the 80 min experimental protocol (10 min rest – 60 min exercise – 10 min recovery). In Experiment B, PPE with four different protective levels was worn by seven subjects at 33 °C and 70% RH. The Experimental protocol consisted of 10 min rest and exercise on a treadmill until T_{re} reached 39°C, after which the recovery time was recorded if possible. The original PSI equation was modified into three non-invasive PSI equations using non-invasive parameters based on the results obtained experiments A and B. To validate the results, correlation and consistency analysis was conducted by comparing the original PSI and the newly modified non-invasive PSIs. Consequently, the forehead, foot, and toe were selected as non-invasive measurement sites for Part 1. Among the non-invasive equations, Model 2 (Non-invasive PSI;

$NIPSI_{33}$) exhibited the highest correlation and consistency with the original PSI. In addition, Model 1 (NIPSI) was also analyzed to confirm if it could achieve a more accurate individual monitoring than Model 2.

1) Model 1 (NIPSI) = $5\,(T_{sk}t - T_{sk}0) \cdot (39.5 - T_{sk}0)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR0)^{-1}$

*$T_{re}t$ replaced to $T_{forehead}$, T_{foot}, or T_{toe}; and $T_{re}0$ was replaced to $T_{sk}0$.

2) Model 2 ($NIPSI_{33}$) = $5\,(T_{sk}t - 33) \cdot (39.5 - 33)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR0)^{-1}$

*$T_{re}t$ replaced to $T_{forehead}$, T_{foot}, or T_{toe}; and $T_{re}0$ was replaced to 33 °C.

In Part 2, data sets from 13 experiments were collected and analyzed to verify the validity of the equations derived from Part 1. Rectal temperature, skin temperature, and heart rate of 123 subjects were used by comparing the original PSI, Model 1, and Model 2. Lastly, applicable conditions were suggested based on the clothing, environment, and activity level. For the Part 2 experiments, Model 2 exhibited higher correlation coefficients than Model 1. Additionally, most equations derived using the foot or toe temperature exhibited greater validity than those derived using the forehead. This indicates that among the three regions (the forehead, foot, and toe), the use of the foot or toe temperature is the most appropriate for the estimation of a worker's heat strain. However, there are limitations on the conditions which can be applied to the $NIPSI_{33}$. 1) the environment temperature must be above 30 °C, 2) the environment wearing personal protective equipment, and 3) a state in which work or exercise over a certain period has been performed, indicating the applicability of the above situation. This research paper can aid in the development of a heat strain monitoring system that can prevent heat-related illness by estimating the heat strain of workers wearing full-body protective clothing in a high-temperature environment.

Keywords: Physiological Strain Index (PSI), Non-invasive, Heat strain, Personal protective equipment (PPE), Skin temperature, Heart rate

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Non-invasive physiological strain index using skin temperature and fixed initial temperature of 37°C ($NIPSI_{37}$)

Physiological strain index (PSI)

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Personal protective clothing (PPC)

Personal protective equipment (PPE)

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Rectal temperature (T_{re})

Rectal temperature at any time t ($T_{re}t$)

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Skin temperature at any time t ($T_{sk}t$)

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Chapter 1. Introduction

Owing to the COVID-19 pandemic since early 2020, the use of personal protective clothing and protective gear (Personal Protective Equipment, PPE) has attracted increasing attention for the protection of the human body from harmful environments, such as infectious viruses. Exposure to extreme temperatures, particularly heat, affects the human body temperature, and poses dangers to the human health. The human body temperature is maintained around 37 °C by the human thermoregulation system, which facilitates heat loss by activating vasodilation and sweating in cases of exposure to hot environments. As mentioned previously, PPE refers to various types of protective clothing and gear worn on the head (helmet), eye and face (goggles and mask), hand (gloves), respiratory organs (self-contained breath apparatus, SCBA) for protection from external harmful environments. In the last few decades, numerous studies (Ramsey, 1978, Kenney, 1987, Montain et al., 1994, Holmér, 1995, 2006, McLellan et al., 1996, Bernard, 1999, O'connor, 1999, Havenith et al., 2011, Epstein et al., 2013, Zhao et al., 2022) have evaluated the physiological strain when wearing PPE in the heat. These studies reported that the wearing PPE, particularly in hot environments, caused severe physiological strain on the human body, such as the heat-related cramps, heat exhaustion, heat syncope, and heat stroke. In addition, these studies reported the various levels of heat stress caused by the use of various ensembles of protective clothing.

To reduce incidences of heat-related illnesses at an individual level, the physiological strain index (PSI) was developed by Moran et al. (1998a). The PSI is a monitoring tool calculated using rectal temperature (Tre) and heart rate (HR) measures, and it aims to reflect the combined strain of the cardiovascular and thermoregulatory systems. Both parameters contribute equally to the evaluation of physiological strain. The PSI is as follows: $5\cdot(T_{re}t - T_{re}0)\cdot(39.5 - T_{re}0)^{-1} + 5\cdot(HRt - HR0)\cdot(180 - HR0)^{-1}$. In this equation, Tret and HRt are simultaneous measurements that can be taken at any time (t), whereas $T_{re}0$ and $HR0$ are the initial time values of the rectal temperature and heart rate, respectively. Physiological strain is used to classify individuals into certain risk categories, and is described on a universal scale of 0–10, with 0 representing no physiological strain and 10 representing the highest physiological strain (over 7.5 is considered a high risk for thermal injury (Moran et al., 1998b, Buller et al., 2008)). Previous studies have validated the ability of this index to distinguish different levels of thermal strain under different heat stress, including both hot-dry and hot-wet environments, and differing hydration levels, genders, with/without different PPEs (Moran et al., 1999a, Moran et al., 1998b, Moran, 2000), work rate (Gotshall et al., 2001), and different working clothes (Kalyani and Jamshidi, 2009, Dehghan et al., 2014). These studies have confirmed the ability of PSI to confirm the close relationship between environmental heat stress and the cardiovascular and thermoregulatory systems. Recent studies have evaluated the application of PSI under both laboratory and field conditions. To enhance the accurate evaluation of physiological strain, studies have modified the evaluation of the original PSI using skin temperature rather than core temperature (Holm et al., 2016), modifying critical core temperature to T_c-to-T_{sk} gradient (Buller et al., 2016), or converting the form of core temperature (Byrne and Lee, 2019, Mac et al., 2021). These modifications have simplified and enhanced the application of PSI and the interpretation of other indices. However, some factors have limited the practical measurement of the rectal temperature as a critical variable, such as the difficulties in collecting data from invasive measurements in a field occupational setting. In addition, although the telemetric pill used for measuring the intestinal temperature has been developed and used for decades (O'Brien et al., 1998, Yuce et al., 2009, Ruddock et al., 2014) and recently validated by Gosselin et al. (2019) and Notley et al. (2021), there are still certain limitations. For example, it is not only directly invasive but it is also expensive, and can be rejected by workers. Therefore, studies have developed the use of a subjective sensation, the perceptual strain index (PeSI), for reflecting the physiological reaction of wearers (Tikuisis et al., 2002, Dehghan and Sartang, 2015, Borg et al., 2015, 2017). However, it is still difficult to accurately and precisely predict the thermal strain because of the high degree of inter-individual variation.

In summary, the rectal temperature used in the original PSI can pose inconveniences in terms of measurement and practical applicability. However, it is the temperature that most accurately reflects the heat strain in the body. To enable the real-time monitoring of the heat strain of workers, it is essential to develop a non-invasive alternative parameter that can reflect the rectal temperature. Thus, the objective of this study was: 1) to explore skin regions for a non-invasive parameter that can substitute the rectal temperature, 2) to verify a non-invasive PSI using a non-invasive parameter that can be used for the real-time monitoring and prediction of the heat strain of workers wearing PPE in hot environments. The findings of this study are expected to be applied to smart wearable devices that will be used in extreme occupational environment in the future or personal protective clothing/equipment that can be used for real-time physiological monitoring when working in scorching environments.

Chapter 2. Theoretical background

2.1 Personal protective equipment (PPE) and protection levels

PPE is classified according to the various internationally accepted standards, and the most representative organizations are the International Standards Organization (ISO), the Occupational Safety and Health Administration (OSHA)/the U.S. Environmental Protection Agency (EPA). Several nations also have their own PPE standards, such as the National Fire Protection Association (NFPA), the American Society of Testing and Materials (ASTM), the European Norm (EN), the British Standards Institution (BSI), the Deutsches Institute fur Normung (DIN), the Japanese Industrial Standards (JIS), the China State Bureau of Technical Supervision (CSBTS), and the Korea Industrial Standards (KS). The classification criteria for PPE can be divided according to the following published standards, and the four organization standards are introduced below.

A) OSHA/EPA

The Occupational Safety and Health Administration (OSHA) and the U.S. Environmental Protection Agency (EPA) have published guidelines for four distinct levels of PPE (OSHA 29 CFR 1910. 120). Each category includes types of equipment that employees should use to perform job tasks based on what they are likely to encounter in any given setting. The levels of protective equipment and when to use the four levels of PPE are presented in Figure 1, Table 1.

Figure 1. Personal protective equipment based on OSHA Levels of chemical protection.

Table 1. Protection levels of personal protective equipment by OSHA and EPA

Classification standard	Protection level	Description	Required
OSHA 29 CFR 1910. 120	Level A	• The highest level of protection for the skin, eye, and mucous membrane • Protection against exposure to vapors, gases, particles, mist, liquids, and hazardous chemical sources • Used within highly-toxic environments	• Chemical-resistant body suit (fully encapsulated) • Positive pressure, self-contained breathing apparatus approved by the National Institute for Occupational Safety and Health (NIOSH) • A set of chemical-resistant gloves, and boots with steel toes and shanks on the outside of the suit
	Level B	• The highest level of protection for respiratory organs and a lesser level of protection for the skin and eye than Level A • Protection against gases, particles, mist, liquids, and hazardous chemical sources	• Positive pressure, full-facepiece self-contained breathing apparatus (SCBA), or positive pressure air respirator with escape SCBA approved by NIOSH • Hooded chemical-resistant clothing (overalls and long-sleeved jacket; coveralls; one or

		two-piece chemical-splash suit; disposable chemical-resistant overalls) • A set of chemical-resistant gloves • A set of chemical resistant boots with steel toes and shanks on the outside of the suit • Two-way radio communications are also required.
Level C	• Used when the types and concentrations of airborne substance is known • Used when there is only slight chance of exposure with the skin and eyes • For protection against particles, liquids, chemical sources	• Full-face or half-mask, air-purifying respirator (NIOSH approved) • Hooded chemical resistant clothing (one-piece coverall, two-piece chemical-splash suit; disposable chemical-resistant overalls) • Chemical resistant gloves, boots (disposable), hard hat, escape mask and face shield
Level D	• Considered the minimum line of protection from hazardous environments • No air respirator is necessary	• Coverall like a work uniform • Chemical resistant gloves, boots (disposable), hard hat, escape mask, and face shield

B) ISO and EU standards

The ISO is a worldwide federation of national standards. Regarding the protective clothing standards, ISO 16602:2007(e) provides a specific classification of general performance requirements. It classifies coveralls and suits into six types with descriptions and requirements for each needed environment (Table 2).

Table 2. Protection levels of personal protective equipment according to ISO 16602: 2007(e)

Classification standard	Type	Description	Required
ISO 16602:2007	Type 1 EN 943-1	• "*Gas-tight*" chemical protective suits • Protection against liquid and gaseous chemicals. • Divided into Type 1a (Self-contained breathing apparatus worn on the inside), Type 1b (Self-contained breathing apparatus worn on the outside), Type 1c (With air supply via a compressed air hose system) - More or less, equivalent to US *Level A*	• Gas-proof • Fully sealed suits
	Type 2 EN 943-1	• "*Non-gas-tight*" chemical protective suits • Protection against dust, liquids, and vapor chemicals. • More or less equivalent to US *Level A*	• Limited gas-tightness • Prevent dust, liquids, and vapors from penetrating at over pressure
	Type 3 EN 14605	• "*Liquid-tight*" chemical protective suits • Protection against liquid chemicals for a limited period	• Liquid-proof protection • The suits must have welded seams.
	Type 4 EN 14605	• "*Spray-tight*" chemical protective suits • More or less, equivalent to US level C	• Splash-proof protection • Type 4B protects against biologically contaminated particles
	Type 5 EN ISO 13982-1	• Particulate suits • With or without gloves and boots for protection against airborne solid and dry particulates for a limited period	• Protection against harmful substances • Type 5B protects against biologically contaminated particles

	Type 6 EN 13034	• Full body chemical protective suit with limited spray-tight connections between suits • More or less equivalent to US level D	• Limited splash-proof protection • Protection when there is a risk of splashing on the suit (EN 13034) • Against biologically contaminated particles (EN 14126)

C) The NFPA

Table 3 shows the summary of the NFPA standards for protective clothing based on expected dermal protection from suits, such as chemical vapor, chemical liquid, particulate, and liquid-borne viruses. These are also in line with OSHA/EPA levels as levels A to D. Figure 2 and Table 3 presents a representative picture from NFPA standards of protective clothing.

Table 3. NFPA standards for protective clothing

Classification standard	Class	Expected dermal protection from suit(s)				OSHA/EPA Level
		Chemical		Particulate	Liquid-borne viruses	
		Vapor	Liquid			
NFPA 1991 ~ 1999	1991 (2016)	O	O	O	O	A
	1994 Class1 (2018)	O	O	O	O	A
	1994 Class 2 (2018)	O	O	O	O	B
	1992 (2018)		O			B
	1994 Class 3	O	O	O	O	C
	1994 Class4			O	O	C
	1999 Single-Use or Multiple-Use 2018)				O	C

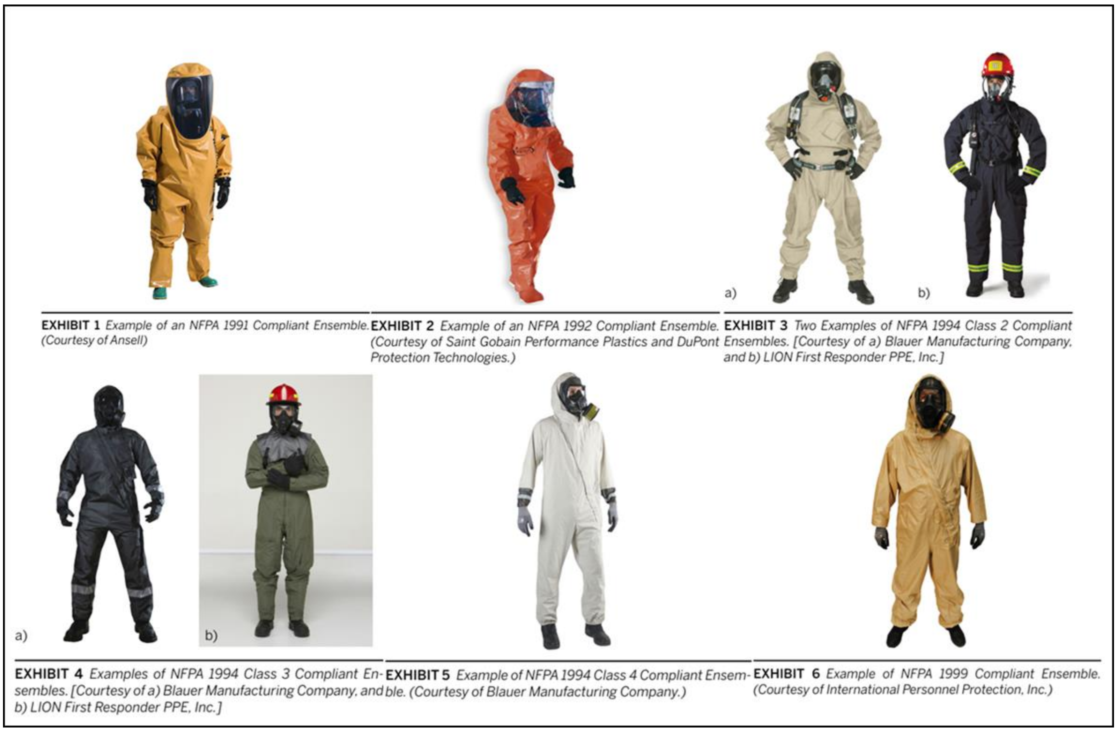

Figure 2. NFPA standards of protective clothing. *Note: Figure was obtained from the NFPA risk-based selection of chemical-protective clothing (2018).

D) Korean Fire Institute (KFI)

The KFI classifies the Korean standard for protective clothing into three categories. Level A refers to protective clothing used at fire site related to leakage of hazardous chemicals owing to its flame retardancy and heat protection properties. Level B refers to protective clothing used at the site of leakage of hazardous chemicals that do not require flame retardancy and heat protection. Level C refers to protective clothing that do not belong to levels A and B, and can be used in the field. As described previously, a rating system according to the level of protection of various protective clothing is used globally. With an increase in the level of protection of protective clothing, the physiological strain caused by the clothing increase; however, despite the increase in the physiological strain induced by the clothing, the protection level cannot be reduced or downgraded. Therefore, the only way to keep workers safe from hyperthermia or heat disorder is to predict the physiological heat strain via real-time monitoring.

2.2 Heat stress and heat strain

The thermal homeostasis of the body is aimed at achieving a balance between heat production and heat dissipation. The primary factors important for this balance include energy metabolism, clothing thermal properties, and ambient climatic conditions. This indicates that if the thermal homeostasis of the body breaks down and external heat sources are continuously accumulated in the body, it may cause heat strain, such as hyperthermia and/or heatstroke.

Thermal stress and Thermal strain were defined by IUPS Thermal Commission (2001), and heat stress and heat strain are part of those terms. First, the thermal stress, which is a part of heat stress, is any change in the thermal relation between a temperature regulator on the body and its environment. If the change is uncompensated by temperature regulation, it will result in hyperthermia or hypothermia. Thermal strain is 1) any deviation of the body temperature induced by sustained thermal stress that cannot be fully compensated by temperature regulation; 2) any activation of thermo-effector activities in response to thermal stress that causes sustained changes in the state of other, nonthermal, regulatory systems. Core temperature does not represent a specific anatomical location. Nevertheless, it corresponds to the temperature of inner tissues, which are not easily changed by circulatory adjustment and environmental effect (IUPS thermal Commission, 2001, Taylor et al., 2014). According to Fanger (1973), the thermal environment and the two behavioral factors influencing human comfort is constituted of four main physical parameters (Table 4). They reported ambient temperature, radiant temperature, humidity, and air movement as environmental variables and metabolic rate and clothing insulation as behavioral variables affecting human response to the thermal environment. Thus, these six parameters must consider heat stress caused by the thermal environment.

Table 4. Six fundamental parameters for determining thermal environment and comfort

	Parameters	Symbol
Environmental	1. Dry-bulb temperature (air temperature)	T_a
	2. Black-globe temperature (mean radiant temperature)	T_g
	3. Wet-bulb temperature (vapor pressure in ambient air)	T_w
	4. Wind velocity (relative air velocity)	V
Behavioral	5. Activity level (Metabolic rate)	M
	6. Insulation (thermal resistance of clothing)	clo

Heat stress is commonly assessed in terms of a heat stress index (HSI), which integrates one or more of the thermal, physical, and personal factors affecting heat transfer between the environment and person as a quantitative composite measure. To date, numerous HSI has been developed, and these indices can be classified based on physical factors of the environment, thermal comfort assessment, heat balance, and physiological strain. The most representative HSI, 'the WBGT index,' was developed by Yaglou and Minard (1957) to control heat casualties at military training centers for the first time. The WBGT combines the effect of four main climatic factors contributing to heat stress: air temperature, humidity, air velocity, and radiation. The WBGT index has been developed as follows: $0.7\ T_{nwb} + 0.3\ T_g$ for indoor without solar, and $0.7\ T_{nwb} + 0.2\ T_g + 0.1\ T_{db}$ for outdoor conditions with solar exposure, where T_{nwb} indicates the natural wet bulb temperature combined with the effect of humidity and air velocity; T_g is 'the globe temperature' as radiation, and T_{db} is 'the dry bulb temperature' as dry bulb temperature. Among the available heat stress indices, the WBGT index was recommended by NIOSH as the standard index for industrial use. Subsequently, this was supported by OSHA and the American Conference of Governmental Industrial Hygienists (ACGIH).

However, the WBGT index has both advantages and disadvantages. According to Beshir and Ramsey (1988), there are five advantages of the WBGT index: 1) simple to use for the measurement and calculation of heat stress, 2) does not require the separate measurement of the air velocity, 3) it is a reliable indicator and has a reasonable degree of precision, 4) it is practical and applicable for industrial purposes, 5) it exhibits a high correlation with the physiological reactions caused by heat exposure. The disadvantages of this index includes: 1) poor estimation under low humidity conditions, 2) increased inconsistencies owing to higher air temperature and work rates, 3) the physiological meaning of the same WBGT value may be independent of the climatic factors, 4) Does not consider the metabolic workload, 5) high initial cost of integrated electronic instruments and their vulnerability to electronic failure, 6) possible damage of the electronic circuit and/or the plastic case of the integrated instrument by high temperatures caused by the exposure of the instrument for an extended period. Therefore, it is necessary to have an index that further reflects the physiological response of the human body (considering disadvantages 3 and 4).

2.3 Significance of monitoring heat strain in the workplace

Workers in numerous industries must perform hard work under high thermal stress conditions, which increases the risk of heat-related illnesses, and can even lead to a sudden increase in body temperature, which results in death. The assessment of heat stress alone could result in the over- or under-protection of workers from heat-related illness (Meade et al. 2015, 2016, Lamarche et al. 2017). The underestimation would result in the early termination of work and a reduction in the productivity of more heat-tolerant workers. In contrast, the overestimation of heat stress would not assure the safety of workers who may be vulnerable to even mild heat.

Generally, efforts to alleviate work-related heat injury have focused on the assessment of environmental heat stress rather than on the associated physiological strain. However, it is known that the physiological response of workers to a given heat stress is affected by inter-individual factors (e.g., age, sex, and chronic disease), intra-individual factors (e.g., medication use, fitness, acclimation, and hydration state.), and/or the management of workers (e.g., shift duration and illness; Notley et al. 2018). Accordingly, the absence of evaluating physiological responses results in difficulties in individually protecting workers from heat-related injuries. Figure 3 shows the currently available methods for preventing heat-related illness during work in hot environments, and divides the associated level of protection (None–High) of each required measurement and method. The image indicates that more physiological response monitoring should be completed with an increase in the required level of protection.

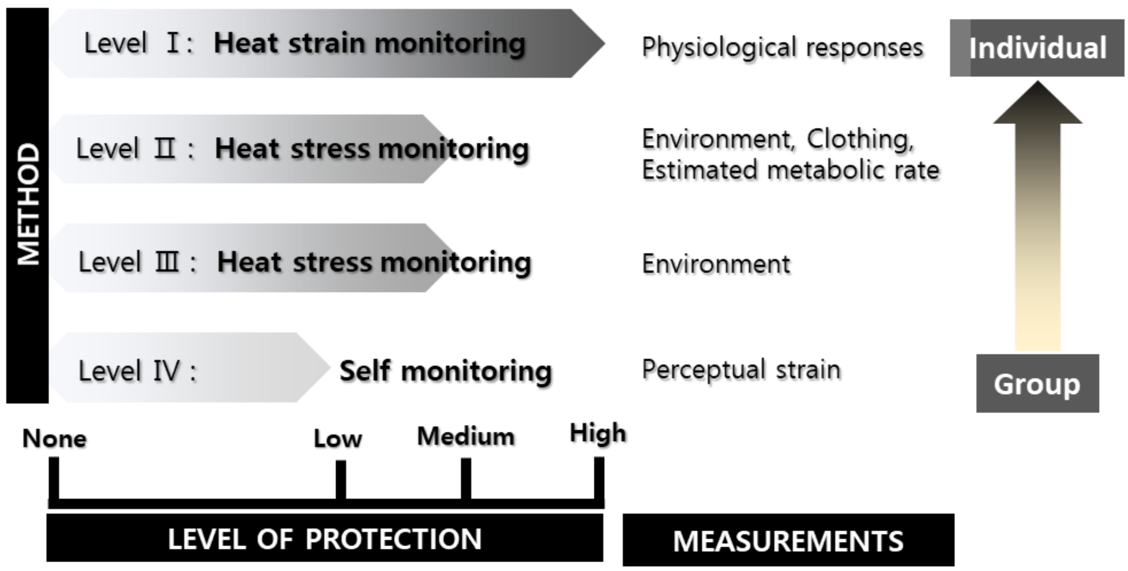

Figure 3. Illustration of the methods available for preventing heat-related illness during work in hot environments and the associated level of protection offered by each (low (level IV), moderate (levels III and II), and high (level I)), including self-monitoring using either environmental parameters alone or a combination of environmental, clothing, and metabolic data with the monitoring of physiological data using wearable technologies (Figure was modified from Notley et al., 2018).

2.4 Determination parameters of thermal or heat strain

As mentioned previously, heat strain indicates any deviation from the body temperature induced by sustained heat stress and not fully compensated by temperature regulation. In addition, it refers to any activation of thermo-effector activities in response to thermal stress that causes sustained changes in the state of the thermoregulatory system. Typically, thermal or heat strain is determined by measuring several combinations of core temperature (T_c), skin temperature (T_{sk}), heart rate (HR), and sweat rate or water loss. Rectal temperature (T_{re}) as a Tc indicates thermal strain over a large temperature range from 38.5–41 °C depending on the environmental condition, clothing, and fitness of the individual (Sawka and Young, 2006, Byrne and Lee, 2019). The body surface generally represents the medium between the core and external environment, indicating that T_{sk} plays an important role in the management of the human thermoregulatory strain along with body core temperature. Accordingly, T_{sk} has been reported to be influenced not only by environmental (e.g., ambient temperature, humidity) and clothing (e.g., clothing insulation and permeability) parameters but also by heat production and heat loss response (sweating and skin blood flow). In hotter environments, or when protective clothing is worn, the skin temperature increases and becomes more uniform with an increase in cutaneous vasodilatation owing to an increase in the transfer of heat to the skin surface (Werner and Reents, 1980). This indicates that skin temperatures from various regions may be used to estimate T_c and, ultimately, occupational heat strain. The HR is based on the combination of the sympathetic and parasympathetic nervous systems, and it is the speed of the heartbeat, expressed as the number of beats per minute (bpm). Owing to the physiological mechanism of the heart rate, it is quite related to T_c in the human's thermoregulatory system. Typically, owing to the action of the baroreceptor reflex, HR increases under heat stress to compensate for the reduction in arterial blood pressure caused by cutaneous vasodilation. Thus, the combinations of T_c, T_{sk}, and HR under heat stress should be considered to evaluate heat strain. Until now, however, none of these parameters has been individually used to accurately evaluate the heat strain based on the working environment.

2.5 Skin temperature as a non-invasive parameter

Core temperature (T_c) as an invasive parameter

When evaluating heat strain, most indices use the rectal or intragastric temperature as the T_c. True T_c is obtained from the blood as the intrapulmonary artery temperature; however, this method is highly invasive and impractical under all settings except controlled medical settings (Easton et al., 2007, Lim et al., 2008). However, obtaining invasive T_c measurements in the pulmonary artery is impractical in real-world work environments (e.g., disaster, firefighting, military training, or during athletic activities; Laxminarayan et al., 2018). When T_c is measured to determine the thermal state of an individual in the field and laboratory settings, it is typically recorded in the abdominal, thoracic, or cranial cavities, with rectal or esophageal temperatures being the typical standard (Casa et al., 2007). For exercise monitoring, T_{re} is the accepted gold-standard measure of the T_c, particularly in indoor laboratory settings (Casa et al., 2007, Ganio et al., 2009, Huggins et al., 2012, Lim et al., 2008). However, the invasiveness of temperature sensors and the discomfort caused by long-term monitoring cannot be used in outdoor environments related to fieldwork (Easton et al., 2007, Moran and Mendal, 2002). Ingestible thermometer pills, which have been used successfully in field settings in the last decade (Lee et al., 2010), are considered a reliable means to measure T_c. However, the high cost and impractical application for the continuous measurement of numerous people for long-duration activities have limited the further application of this method. Moreover, Taylor et al. (2014) reported that resting T_c in humans varies according to the measurement sites. Among the temperatures measured from various regions, T_{re} exhibited the least variation (Figure 4). This study seeks to determine non-invasive parameters that accurately reflects the rectal temperature (no other core temperatures).

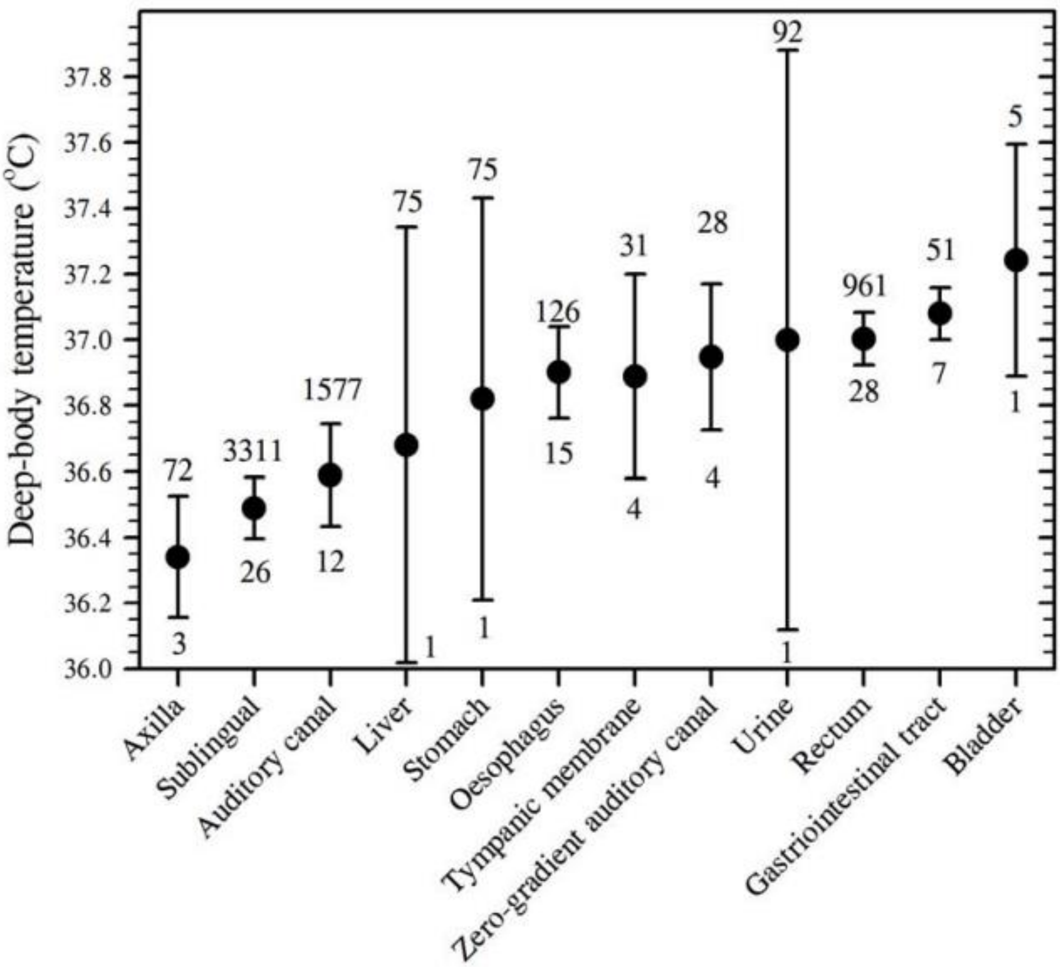

Figure 4. Variability and distribution of the core temperatures in resting and normothermic individuals, according to the measurement sites. *Note: A closed circle means the average temperature, and bars show 95% confidence intervals (Figure was extracted from Taylor er al., 2014).

Skin temperature (T_{sk}) as a non-invasive parameter

As reported in several previous studies (Moran and Mendal, 2002, Casa et al., 2007, Lim et al., 2008, Ganio et al., 2009, Huggins et al., 2012), non-invasive methods to measure core temperature through axillary or tympanic temperatures, as well as gold-standard rectal measurements during exercise, are yet to be developed. Since the first attempt by Fox and Solman (Fox and Solman, 1971), several attempts have been made for the non-invasive measurement of T_c (Taylor et al., 1998, Gunga et al., 2008). For example, a previous study developed a zero-heat flow principle consisting of a heat flux sensor, a heating disc, and a servo control system (Xu et al., 2013). However, Xu et al. (2013) reported the inability of this method to achieve sustained field applications owing to the power requirement. Among variables used to evaluate heat strain, T_{sk} is a notable variable that represents the medium between the core and the external environment. As T_{sk} can be measured non-invasively, it has been combined with the heart rate to predict physiological strain during exercise in the heat. T_{sk} is influenced by high ambient temperature, humidity, clothing insulation, and permeability. Particularly, the use of PPE in the heat increases skin temperature and its uniformity owing to cutaneous vasodilatation and heat transfer to the skin surface (Werner and Reents, 1980). Niedermann et al. (2014) also presented a T_c estimation equation based on the determination of two independent factors derived from the principal-components analysis, which relies on three skin temperatures, heart rates, and two skin heat fluxes. However, this method requires measurement from several regions of the body, and the flux sensors used are affected by sweating, which limit its further application.

Recently, several studies have reported that skin temperature modulates exercise intensity (Schlader et al., 2011, Schulze et al., 2015) during exercise in the heat. In addition, to develop indirect methods for measuring the core temperature, studies have proposed the estimation of T_c and monitoring of heat strain using T_{sk} (Fox and Solman, 1971, Taylor et al., 1998, Yokota et al., 2005, Gunga et al., 2008, Buller et al., 2008, 2013, Xu et al., 2013), HR with T_{sk} (Niedermann et al., 2014) and mean T_{sk} (Maclean et al., 2021). These studies have demonstrated the application of T_{sk} for the estimation of the heat strain index or for monitoring heat stress. Certain T_{sk} may also be able to estimate core temperatures that predict individualized risk levels in real fields. Particularly, when workers wear encapsulating and/or impermeable PPE, they have less tolerance time with work compared to the non-encapsulating and/or permeable PPE worn and exhibited lower T_c and higher T_{sk} (Montain et al., 1994, McLellan and Havenith, 2016).

Based on these studies, several products have been developed for the measurement of T_{sk} for the estimation of T_c, by insulating skin temperature, using wireless skin-temperature sensors (zero-gradient T_{sk}) including button-sized thermo-sensors (e.g., iButton, Maxim Integrated, San Jose, Calif., USA), thermochromic thermometers (i.e., liquid crystal strips), and infrared thermography. However, the T_{sk} tends to be susceptible to changes in environmental temperatures, which vary with measurement regions that are also influenced by the clothing. Therefore, the investigation of measurement skin regions for more accurate and reliable non-invasive methods is essential. Previous research has suggested that measurement regions (Taylor and Amos, 1997, Xu et al., 2013), type of clothing (Bernard and Kenny, 1994, Taylor et al., 1998), and environmental situations (Taylor et al., 1998, Gunga et al. 2008, Teunissen et al., 2011) should be considered to deduce the skin regions for non-invasive measurement methods.

2.6 Physiological strain index using non-invasive measurements

The PSI was developed to reduce incidences of heat-related illnesses at an individual level (Moran et al., 1998b). The PSI is a “real-time” monitoring tool and is calculated using the rectal temperature and heart rate to reflect the combination of the thermoregulatory and cardiovascular systems, with both parameters contributing equally to the evaluation of the physiological strain. PSI is described on a universal scale of 0–10 and is used to classify individuals into certain risk categories, with 0 representing no physiological strain, 10 representing the highest physiological strain, and above 7.5 being considered high risk for thermal injury (Buller et al., 2008, Moran et al., 1998b). Tikuisis et al. (2002) established the perceptual strain index (PeSI) based on thermal sensation (TS). The PeSI formula is similar to that of PSI, and is considered a possible alternative to PSI when the physiological parameters are unavailable. As physiological parameters have been available for over 50 years, recent computing power and wearable sensors will enable the provision of a better application for the individual level.

Various researchers have attempted to increase the accuracy and practicability of the heat strain by modifying PSI and evaluating heat strain (Buller et al., 2014, Byrne and Lee, 2019, Davey et al., 2021, Mac et al., 2021). First, certain studies have demonstrated the modification/replacement of the core temperature. For example, Buller et al. (2014) demonstrated an adaptive PSI (aPSI), in which the critical core temperature (T_c critical) setting was modified using the T_c-T_{sk} gradient that effectively accounts for the clothing situation differences between athletes and workers clothed in PPE. Byrne and Lee (2019) aimed to determine whether the PSI in its original or modified form can identify heat strain on a scale of 0-10. To this end, they proposed an increase in the critical core temperature, which should be 41 °C of T_c and age-predicted maximal HR. Second, the form of heart rate could be modified. Mac et al. (2021) changed the heart rate and examined the selection of individuals at risk of heat-related index using a modified PSI (mPSI) in a field-based setting. They proposed the mPSI using the median heart rate rather than the initial heart rate owing to the difficulty in obtaining an initial rest heart rate value, especially in the fieldwork environment.

Davey et al. (2021) comprehensively compared the original PSI with a modified PSI consisting of fixed rectal temperature or temperature sensation and thermal comfort and adaptive PSI. They found that the PSI does not reliably identify individuals, and its validity as a physiological safety index is questionable. However, they also still have limitations that invasive parameters have made the PSI. Accordingly, several studies have attempted the non-invasive measurement of T_c using T_{sk}, such as the forehead (Kistemaker et al., 2006, Kimberger et al., 2009, Mitchell et al., 2015, Holm et al., 2016), tympanic (Boano et al., 2013), chest temperature (Welles et al., 2018, Tokizawa et al., 2022), and the combination of T_{sk}, HF, and HR (Eggenberger et al., 2018, Welles et al., 2018). Tokizawa et al. (2022) reported that the chest temperature can provide a moderate estimation of T_c during low-intensity and acute exercise under heat conditions. However, if the amount of sweat from the chest is not negligible, it may not work in PSI, even if the intensity is low. In this regard, these areas are unsuitable for wearable devices or smart protective clothing applications. There are still limitations regarding the validity of measurement sites, such as the forehead, chest, or thigh.

Therefore, this study attempted to investigate non-invasive parameters that can replace rectal temperature and derive physiological strain indicators using these parameters. This study is expected to play an important role in the individual monitoring and evaluation of the heat strain in real-time when wearing PPE in a hot environment.

Chapter 3. Methods

3.1 Research framework

This study consisted of two parts. Part 1 is composed of two experiments to investigate a skin temperature measurement region for replacing the rectal temperature in the original PSI (Figure 5). Experiment A was performed in 2018 and aimed to evaluate the heat strain and how the heat strain is affected by different clothing and environments. Clothing conditions were daily summer wear and protective clothing in different environments: 28 (neutral), 33 (hot), and 38 °C (very hot) at 70% relative humidity. Subsequently, Experiment B was performed to investigate the difference in heat strain according to the level of protection in a hot environment (33 °C, 70% RH). Thereafter, both experiments were integrated, and the region of skin temperature was first explored by correlations and consistency (limit of agreement with 95%CI) analysis (Bland and Altman, 2007) with the rectal temperature. Thereafter, we compared the new non-invasive PSI using skin temperature and heart rate, which best reflects the rectal temperature, using the same analysis above for the original PSI.

In Part 2, data sets from 13 experiments were collected and analyzed to verify the validity of the equations derived from Part 1. The 13 experiments were all related to the evaluation of the heat strain when wearing protective clothing in various environments, different protection levels, and different activities. The original PSI and modified non-invasive PSI were calculated using the rectal temperature, skin temperature, and heart rate data of 123 subjects. Additionally, the relationship between the original PSI and the modified non-invasive PSI was examined using correlational analysis and scatter plots. Lastly, optimal conditions for the practical application of this method were presented based on clothing, environment, and activity level, and the limitations of the study are presented. Fifteen experimental data from Part 1 and Part 2 were utilized throughout the research process.

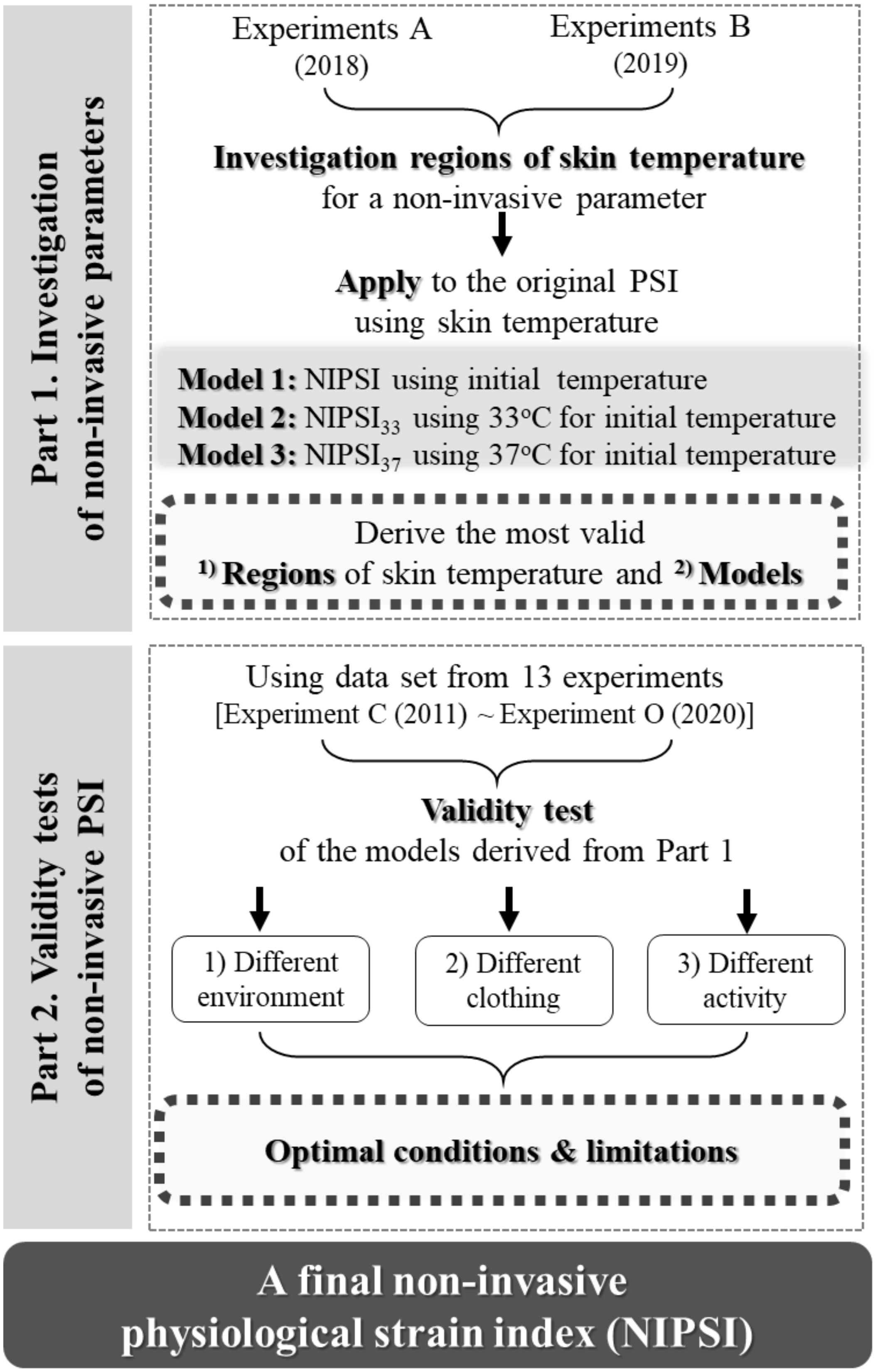

Figure 5. Research framework based on investigation and validity assessment.

3.2 [Part 1] Investigation of non-invasive parameters

3.2.1 Ethical approval and subjects

Part 1 was composed of two experiments and approved by the Institutional Review Board of Seoul National University as Experiment A (IRB #1806/003-002) and Experiment B (IRB # 1911/002-012). All subjects were informed of the purpose, methods, and potential risks of the experiments before a final determination of participation; after that, written consent was obtained. The subjects were judged to have no specific disease and to be healthy to participate in the experiment through preliminary health checkups. Sixteen young males participated in the two experiments comprising of neutral (25–29 °C, 50% RH) or hot (over 30 °C) and humid (over 60% RH) environments with protective clothing conditions (Table 5). The subjects were instructed to refrain from alcohol, medication, and heavy exercise for 24 h prior to the testing day. They also abstained from any food and caffeine for 3 h before all the tests and ensured they were not tired. All the tests were conducted from 08:00 am to 12:00 pm to obtain a stable rectal temperature. All subjects were free of known cardiovascular and respiratory dysfunction. On a particular day, they performed a maximal graded exercise test to determine maximal oxygen consumption (VO_{2max}) and heart rate (HR_{max}) before conducting experimental protocols.

Table 5. Physical characteristics of the participants in Experiment A (2018) and Experiment B (2019)

	Experiment A (2018)	Experiment B (2019)
Sex	Male	Male
The number of subjects	9	7
Age (years)	21 ± 2	24 ± 3
Height (cm)	175 ± 4	177 ± 5
Weight (kg)	70.1 ± 7.9	72.6 ± 8.6
BMI	22.8 ± 2.2	23.0 ± 2.3
BSA (m^2)	1.9 ± 0.0	1.9 ± 0.1
VO_{2max} ($ml \cdot min^{-1} \cdot kg^{-1}$)	52.1 ± 9.0	52.6 ± 5.6
HR_{max} (bpm)	197.9 ± 2.9	197.1 ± 1.3

*Abbreviations: BMI—body mass index; BSA—body surface area, VO_{2max}—Maximal oxygen consumption; HR_{max}—maximal heart rate.

3.2.2 Experimental procedure and protocols

The experimental procedure and protocols are presented in Table 6. Experiment A was performed in 2018 and Experiment B in 2019. The results of Experiment A, which compared heat strain under various clothing and environmental conditions, were utilized to perform Experiment B in a hot and humid environment (33°C, 70%RH) with different levels of protective equipment. The first step in both experiments was to explore a regional skin temperature capable of replacing the core (rectal) temperature in the original PSI equation. After exploring regional skin temperature, a modified non-invasive PSI was formed using the explored regional skin temperature and heart rate.

Table 6. Summary of experimental conditions, protocols, and measurements of Experiment A (2018) and Experiment B (2019)

	Experiment A (2018)	Experiment B (2019)
Environmental condition (°C & %RH)	1) 28 °C & 70% RH 2) 33 °C & 70% RH 3) 38 °C & 70% RH	33 °C & 70% RH
Clothing conditions	• Two conditions 1) Summer wear (Short T-shirts, Short pants, socks, and shoes) 2) Personal protective clothing (Summer wear + Dupont, Tyvek 400)	• Four levels of personal protective clothing conditions 1) Level A: Flame and vapor-barrier chemical protection (ONESUIT® Pro 2) 2) Level B: Vapor-barrier chemical protection (Dupont, Tychem® ThermoPro 6000FR) 3) Level C: Water-barrier protection (Dupont, Tychem C 2000) 4) Level D: Particle-barrier protection (Dupont, Tyvek 400)
Protocols	• Total 80 min : Rest 10 min–Exercise 60 min (5 km/h, 0% slope) – Recovery 10 min	• Different duration from each other : Rest 10 min–Exercise until rectal temperature reaches 39.0 °C (5 km/h, 0% slope) – Recovery 20 min if possible
Measurements	• Rectal temperature • Ear-canal temperature • Skin temperature (8 sites: forehead, chest, back, forearm, hand, thigh, calf, foot) • Heart rate • Total sweat rate • Local sweat rate (absorption paper method) • Subjective sensation (thermal sensation, thermal comfort, sweat sensation, thirst, and RPE scale) • Energy expenditure	• Rectal temperature • Ear-canal temperature • Skin temperature (9 sites: forehead, chest, back, forearm, hand, thigh, calf, foot, and toe) • Heart rate • Total sweat rate • Subjective sensation (thermal sensation, thermal comfort, sweat sensation, thirst, and RPE scale) • Energy expenditure

*Abbreviation: SW—Summer Wear, PC—Protective clothing; RH—Relative Humidity; RPE—Rating Perceived Exertion

Experiment A (2018)

Data recorded in Experiment A were utilized in the investigation for a new skin temperature measurement region. The experiments were performed at 28, 33, 38 °C and 70% RH in a climatic chamber maintained as a typical summer season in South Korea. The high-temperature environmental conditions (33 and 38 °C) were selected according to the level of heat wave warnings in Korea. The experimental ensemble included underwear (cotton 100%), a short-sleeved T-shirt (cotton 100%), short pants (cotton 100%), socks and shoes (running sneakers) as baseline clothing, and a Tyvek 400 (Particle-barrier protective Dupont, Level D in OSHA) in protective clothing condition (Figure 6). Tyvek 400 (Level D) was selected because it is the most frequently used full-body protective suit worn by workers for medical sites and disasters. The protection level of Level D is not that high among protective clothing. Nevertheless, additional shoes, gloves, goggles, and masks are worn to protect the whole body, so Level D was selected to limit the amount of heat strain caused. Upon arrival at the laboratory, subjects drank 300 ml of water to prevent thirst and dehydration and began each trial with a 10 min initial rest in a sitting position on a chair. Thereafter, the subjects performed 60 min of walking on a treadmill for 5 $km \cdot h^{-1}$ (approximately 135 $W \cdot m^{-2}$) and took a final recovery for 10 min. The exercise road was approximately 50–60 % of VO_{2max}. To exclude the influence of the order of participation in the experiment, the order of participation was randomly assigned to all subjects. To minimize the impact of participation in previous experiments, the following experiments were conducted at intervals of at least 48 h.

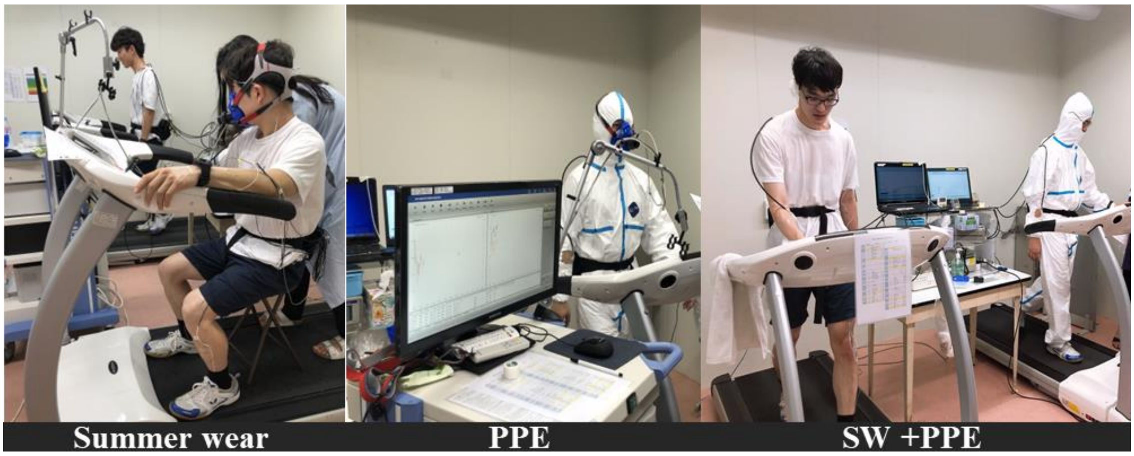

Figure 6. [Experiment A] Subjects during heat tolerance test in summer wear (SW) and personal protective equipment (PPE) condition.

Experiment B (2019)

Experiment B was designed to evaluate the heat tolerance of protective clothing and search for the additional skin temperature as a parameter of the heat strain index. All experiments were conducted in a climatic chamber maintained at an air temperature of 33 °C, 70% RH, and an airflow of below 0.05 m/s, commonly occurring as a heatwave in South Korea. Upon arriving, subjects drank 300 ml of water to prevent thirst and dehydration during experiments. After attaching all the sensors to the body, subjects wore underwear, long sleeves t-shirts, long pants, socks, and each level (A, B, C, and D) of protective clothing (Table 7). Figure 7 shows each level of the protective suit at neutral status (standing pose) and during exercise in the experiments. The experimental trial comprised of 10 min rest on a chair followed by walking 5 km·h^{-1} on a treadmill until a rectal temperature of 39.0 °C was achieved. After the rectal temperature reached 39.0 °C, subjects were required to have a recovery period of at least 5 min or a maximum of 20 min, if possible. Therefore, the duration time of each experiment was dissimilar. If the subject wanted to stop the trial, the experiment was terminated. During the recovery period, the upper body part of protective clothing was removed or zipped off.

Table 7. [Experiment B] Characteristics of the PPE used for the experiments: Levels A, B, C, and D

	Level A	Level B	Level C	Level D
Standing				
Walking				
Product model	ONESUIT® Pro 2 (Encapsulated suit)	Dupont, Tychem® ThermoPro 6000FR	Dupont, Tychem C 2000	Dupont, Tyvek 400
Size	One size	Large	Large	Large
Specification of protection	Flame and vapor-barrier chemical protective	Vapor-barrier chemical protective	Water-barrier protective	Particle-barrier protective
Protective Level (OSHA)	A	B	C	D
Protective Type (EN14605, ISO 16602)	1, 2	3	4	5, 6
Material (out layer)	Polytetrafluoroethylene composite (CORETECH®)	Laminated Polyethylene	Laminated Polyethylene	Polyethylene
Basic clothing mass (g)	1,105			
PPE mass (g)	4,218 ± 10 (SCBA: 7,090 ± 10)	1,099 ± 11 (No SCBA)	313 ± 1 (No SCBA)	149 ± 1 (No SCBA)
Total clothing mass (g)	12,413	2,204	1,418	1,254
Total insulation (I_T, clo)	1.32	1.30	1.12	1.12
Water vapor resistance (R_{et}, $m^2 \cdot Pa \cdot W^{-1}$)	73.7	61.9	69.5	48.1

Figure 7. [Experiment B] Each level of protective equipment at the neutral status and during exercise in the experiments.

3.2.3 Measurements

The common measurements for experiments A and B were as follows: The rectal temperature (T_{re}) was recorded at 16 cm beyond the anal sphincter using a thermistor for rectal temperature and a data logger (LT-8A: Skin Temp & Humidity Logger, Gram Corporation, Japan) every 5 s. Ear-canal temperature (T_{ec}) was measured using a sensor assembled by a thermistor probe inserted 1 cm into the external auditory meatus. The ear hole was covered with rubber clay and sanitary cotton to completely insulate the auditory canal. Skin temperatures were measured every 5 s using thermistor probes at nine body regions [the forehead, chest, upper back, forearm, hand, thigh, calf, foot, and toe] (Figure 8). The HR was also recorded continuously every 5 s using a polar electrode and a chest belt (RC3, Polar Electro Oy, Finland)(Figure 8). To estimate the total sweat rate, subjects weighed on a calibrated scale (Resolution 1g; ID2, Mettler-Toledo, Germany) before and after each trial. The environmental temperature and RH in the climatic chamber were measured every minute using a thermo-hygrograph (Thermo Recorder TR-72U, T & D Corporation, Japan). According to Dubois (1916) and Lee et al. (2008), body surface area was calculated. The subjective sensation was also measured as thermal sensation, thermal comfort, sweat sensation, thirst, and RPE scale, but the data was excluded in this study. Local sweat rates in Experiment A were measured using the absorbent paper methods (using moisture absorbent papers: 2×2 cm^2 and by weighing on an electronic scale: AB204; Mettler-Toledo, Switzerland; sensitivity 0.1 mg) to examine regional differences in the chest quantitatively and back; however, the data was not used for this study. In Experiment B, Total thermal insulation (I_T)and water vapor resistance (R_{et}) were measured using the thermal manikin (Newton, ThermoMetrics, Northwest, US). The maximal oxygen consumption test was conducted by continuously collecting inhaled and exhaled gas using a gas analyzer (Quark b^2 , COSMED Company, Italy) for all subjects. The results were considered in the experimental protocols.

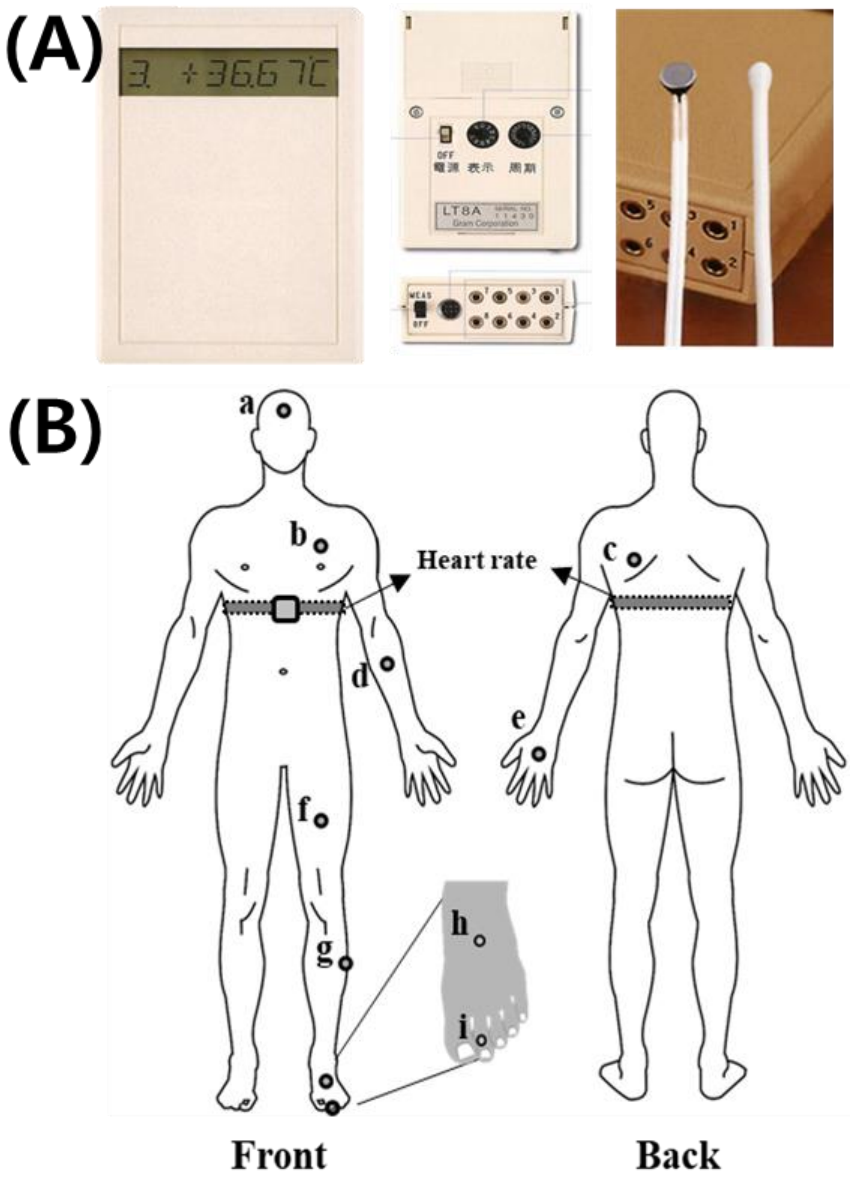

Figure 8. Data logger with skin thermistor (A: left) and rectal probe (A: right) and measurement regions of nine skin temperatures (B: a: forehead, b: chest, c: back, d: forearm, e: hand, f: thigh, g: calf, h: foot, i: toe) and heart rate.

3.2.4 Modified equations of physiological strain index

The heat strain was evaluated using the PSI proposed by Moran et al. (1998a), which is an indicator based on the thermoregulator system (rectal temperature) and cardiovascular response (heart rate) (Eq. 1).

Original PSI

$= 5\,(T_{re}t - T_{re}0) \cdot (39.5 - T_{re}0)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR0)^{-1}$

(Eq. 1)

*$T_{re}t$: the maximal value of rectal temperature at t period when is 3 min before the end of the exercise,
$T_{re}0$, the initial value of rectal temperature 3 min end of rest
*HRt: the maximal value of heart rate at t period, which is the same as the rectal temperature
HR0, the initial value of the heart rate
*The maximum increase in rectal temperature and heart rate was set at 3 °C (36.5–39.5 °C) and 120 bpm (60–180 bpm), respectively.

The original PSI was modified by substituting the rectal temperature with eight or nine regions' skin temperatures. First, Model 1 was an equation for replacing the rectal temperature with skin temperature at time t and initial time 0 (Model 1, Eq. 2). Model 2 was modified from Model 1(Eq. 3), which is a fixed initial temperature in 33 °C rather than using initial skin temperature. The temperature (33 °C) was derived from the representative mean skin temperature. Lastly, Model 3 was about another fixed initial temperature model, a fixed initial temperature in 37 °C, which is based on the representative temperature of the core temperature in the resting period of humans (Model 3, Eq. 4). This is the reason the initial temperature of the non-invasive PSI was fixed to 33 °C and 37 °C to further analyze the feasibility of simplifying the non-invasive index by replacing the rectal temperature of the original PSI with the skin temperature. The PSI stabilized the rectal temperature using the initial values. This study evaluated the validity of three non-invasive equations using 37 °C, commonly known as average core temperature during rest and neutral environment, and 33 °C, known as mean skin temperature during stabilization. This experiment aimed to determine if the heat strain can be predicted only at the time t intuitively without using the initial temperature value.

Model 1 (Non-invasive PSI, NIPSI)

$$= 5\,(T_{sk}t - T_{sk}0) \cdot (39.5 - T_{sk}0)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR\,0)^{-1} \qquad \text{(Eq. 2)}$$

Model 2 (Non-invasive PSI fixed initial temperature of 33 °C, $NIPSI_{33}$)

$$= 5\,(T_{sk}t - 33) \cdot (39.5 - 33)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR\,0)^{-1} \qquad \text{(Eq. 3)}$$

Model 3 (Non-invasive PSI fixed initial temperature of 37 °C, $NIPSI_{37}$)

$$= 5\,(T_{sk}t - 37) \cdot (39.5 - 37)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR\,0)^{-1} \qquad \text{(Eq. 4)}$$

3.2.5 Data analysis

The temperature and heart rate data were collected and continuously measured every 5 s in the two experiments. To determine the reasonable time to measure the stabilized temperature and heart rate data, data obtained every 3 min before the end of each period (rest, exercise, recovery) in Experiment A) and every 2 min before the end of the recovery period for Experiment B were averaged and analyzed using one-way analyses of variance (ANOVA) with LSD post hoc test as a representative value of the valid period. From Experiment A, comparisons of the heat strain using temperature and heart rate data were made on the grouped data for each measured data (rectal temperature, skin temperatures, heart rate), and a paired *t*-test and repeated measure ANOVA was conducted. For Experiment B, the difference in heat strain among the four levels of protective clothing was evaluated using repeated measure ANOVA. The correlation between the temperatures and non-invasive PSIs was investigated using Pearson correlation analysis. An agreement was evaluated using systematic bias (mean difference) and 95% limits of agreement (LoA), accounting for repeated measures calculated between non-invasive PSIs (Bland and Altman, 2007). All statistical analyses were performed using SPSS 23.0, and the statistical significance was set at $P < 0.05$. Descriptive data are presented as mean ± standard deviation (SD).

This study utilized three references of an acceptable agreement with rectal temperature and the original PSI to determine a reasonable region for rectal temperature. 1) correlation coefficient (r) should be over 0.7 or the coefficient of determination (r^2) show over 0.49, 2) the mean difference should be within ± 0.5 °C and limits of agreement between ± 1 °C, 3) temperature at maximal points should be over 39 °C, which is the starting temperature of the rectal temperature on heat strain.

Generally, labeling systems in Pearson correlation analysis are used to roughly categorize r values: correlation coefficients are considered: $r \geq 0.9$ as very high correlations, $0.7 \leq r \leq 0.9$ as high correlations, $0.4 \leq r \leq 0.7$ as moderate correlation, and $r \leq 0.4$ as low correlation (Taylor, 1990, Asuero et al., 2006, Dancey and Reidy, 2007, Schober and Schwarte, 2018). Several researchers have proposed an acceptable variation from a criterion measure to examine the absolute differences in temperature. Gunga et al. (2008) proposed ± 0.5 °C as an upper limit for the variation between a T_{re} and their double sensor device, which measure chest temperature. Bach et al. (2015) also suggested a mean difference within ± 0.5 °C with limits of agreement between ± 1 °C as an acceptable agreement of temperature. In related studies, Casa et al. (2007) and Ganio et al. (2009) used ± 0.27 °C as the cut-off for an acceptable bias observed between criterion measures and non-invasive methods. Others have reported variation ranging from 0.3–0.5 °C; thus, there is a general agreement in the literature of roughly ± 0.25–0.50 °C as an acceptable variation from a criterion measure (Farnell et al., 2005, Hooper and Andrews, 2006, Kistemaker et al., 2006). Lastly, the maximum temperature should exceed 39 °C to intuitively show the risk standard of the core (rectal) temperature and support to estimate heat strain for workers.

3.3 [Part 2] Validity of the non-invasive PSIs

For the data sampling, a total of 13 experiments, which were conducted using PPE, were reviewed.

3.3.1 Overall description of 13 experiments and key features

This session describes the objectives, key results, and a summaries of 11 experiments published as papers, master's dissertation (Experiment J), and reports (Experiment N) (Table 8). A detailed condition of 13 experiments on the environment, clothing conditions, exercise, and experimental protocol is summarized in section 3.3.3 (Table 9).

1) Experiment C (2009): Published, Lee et al. (2011)

Experiment C was performed to evaluate the heat strain of nuclear power plant workers and to investigate the validity of infrared tympanic temperature (IR_T_{ty}) as a thermal index in hot environments and compared the rectal temperature at various depths of 4, 8, 16 cm from the anal sphincter. The experiment was performed under twelve experimental conditions: two activities (rest and exercise) × three levels of personal protective clothing (Control, high-density polyethylene coverall: HDPC, polyvinyl chloride coverall: PVC) × two air temperature (25 and 32 °C, and 50%RH). The results revealed that the PSI obtained using IR_T_{ty} did not underestimate the original PSI, and also overestimate the PSI when wearing PPC (HDPC and PVC) at 32 °C.

2) Experiment D (2010) Published, Bakri et al. (2012)

Experiment D aimed to examine the effects of firefighters' self-contained breathing apparatus (SCBA) weight and its harness design on the physiological and subjective responses. Four tests were performed in a neutral (22 °C, 40%RH) and hot (32 °C, 40%RH) environment. The study highlights that the combined effect of lighter SCBA and new harness design could reduce oxygen consumption in partial conditions, and hot air temperature only gives a partial effect on the thermoregulatory system that only result in differences in a variation of rectal temperature. The additional weight of SCBA and the new harness design did not significantly affect the rectal temperature.

3) *Experiment E (2011):Published, Lee et al. (2012)*

The purpose of Experiment E was to investigate the influences of the amount or surface area of menthol application on physiological and psychological heat strain, as well as body regional influences with/without protective clothing. Cutaneous thermal threshold test and exercise test were performed at 28 °C, 50%RH, and 0.8% of applied menthol on the face and neck, upper body, and/ or the whole body with firefighter's protective clothing and normal clothing. The study revealed that menthol application was beneficial for a perceptual cool sensation but detrimental in terms of body heat storage; thus, menthol as a cooling countermeasure would be advantageous for relatively shorter periods of operations and works with light clothing, rather than for longer periods of operations in an encapsulated PPE.

4) Experiment F (2011): *Published, Bakri et al. (2022)*

This study mainly aimed to evaluate the physiological responses of two groups (heavy bodyweight and light body weight) during PPE standard test. All groups performed a 5.5 $km \cdot hr^{-1}$ treadmill exercise under 0.967 kg sports attire as a control condition and 18.974 kg personal protective equipment as the PPE condition, at air temperatures of 32 °C and 60%RH. The results revealed that the differences only occurred within each group with volunteers using PPE or control clothing. In addition, the physical condition of these volunteers was similar owing to their daily structured exercise despite differences in body weight between both groups. In a standard PPE test, the bodyweight of volunteers is not considered relevant if they are well trained.

5) Experiment G (2011): Published, Lee et al. (2014)

Experiment G was conducted to investigate the physiological and subjective responses of the European (EU), Japanese (JP), and United States (US) firefighter's helmets, gloves, and boots for international standardization. The experiment was performed at 32 °C, 60%RH using three different clothing mass conditions: 9.4, 8.2, and 10.1 kg. The results revealed that a 0.5-kg reduction in helmet mass and a 1.1-kg reduction in boots mass during exercise resulted in a significant decrease in head and leg temperature and subjective perceptions. International, European, or American standards on firefighters' helmets, boots, or gloves specify minimum requirements for the protection of firefighters, whereas comfort functions are relatively neglected. In addition, the structural differences in the officially approved helmets, gloves, and boots can reduce regional thermoregulatory burdens and improve subjective perceptions.

6) Experiment H (2012): Published, Lee et al. (2014)

Experiment H aimed to investigate the component contributions of PPE on physiological strain in firefighters during exercise and recovery. All tests were performed in a laboratory where the environment was maintained at 28 °C, 40%RH. They evaluated the effects of heat production and dissipation on eight clothing combinations of PPE, removing one or more components from the entire ensemble. The results revealed that removing the boot during exercise was more advantageous for alleviating metabolic heat production than removing other sub-equipment, such as self-contained breathing apparatus, helmet, or gloves. This study indicated that metabolic benefit is not proportional to the load carried.

7) Experiment I (2014): Published, Kim and Lee (2016)

Experiment I aimed to explore stable and valid measurement sites of skin temperatures as a non-invasive variable for predicting deep-body temperature while wearing firefighters' PPE during air temperature changes. The air temperature periodically fluctuated from 29.5 to 35.5 °C with an amplitude of 6 °C. This study chose rectal temperature as a deep-body temperature and 12 skin temperature regions were measured. The results revealed that the forehead and chest were the most valid sites for predicting the rectal temperature and it could be valid as a non-invasive variable for an individual wearing PPE in specific condition which is changing ambient temperature.

8) Experiment J (2014): Kim (2015, Master's dissertation)

Experiment J aimed to analyze skin temperature and heart rate, which are non-invasive indicators for improving the validity of firefighters' heart temperature prediction, and proposed an evaluation method of heat strain using heart rate during mid-break of firefighting work. The skin temperatures of the forehead, chest and upper arms, and toes differed from the environmental temperature change while wearing a firefighting suit. Compared to the other skin temperature, it was the most stable against the change in ambient temperature (P < 0.05). However, it was confirmed that even when wearing a full-body fire protective suit, the changes of environmental temperature affected to the change in skin temperature. This point can act as an exogenous variable when predicting deep temperature using skin temperature.

9) *Experiment K (2015): Published, Kim and Lee (2023)*

Experiment K was performed to investigate heat strain while wearing pesticide protective clothing (PPC) with different physical properties in hot environments. Eight young males participated in the experiment under three PPC conditions [polyester/cotton work clothing (I_T = 1.26 clo, R_{et} = 42.0 m^{-2}·PaW^{-1}), Tyvek coverall (1.16 clo, 47.5 m^{-2}·PaW^{-1}), and commonly used nylon suit with a microporous membrane (1.42 clo, 54.1 m^{-2}·PaW^{-1})] and two environmental conditions (32 °C at 50%RH and 32 °C at 80%RH). All physiological variables (rectal and mean skin temperature, heart rate, and physiological strain index) and most subjective perceptions exhibited greater values at 80%RH at 50%RH environment (all P<0.05). These results indicate that the 30% higher humidity induced a greater physiological burden. However, physiological or subjective burden would not always be proportional or inversely proportional to the physical property level of PPC, but was affected more by heat exchange modes between the human body and ambient environments.

10) Experiment L (2016): Published, Baek et al. (2018)

Experiment L aimed to evaluate physiological and subjective responses while wearing the Shikoro-type helmet, which is an all-in-one style (hood and helmet) for firefighters compared to typical hoods and helmets from US and Korea. Eight real firefighters participated in this study and all tests were conducted at 32 °C, 70%RH. The results revealed that the Shikoro-type, as an all-in-one type, reduced local skin temperature on the face and neck, thus, this kind of helmet had thermal benefits on the head.

11) Experiment M (2017): Published, Kim et al. (2020)

Experiment M investigated the separate and combined effects of skin cooling and cold fluid ingestion on the alleviation of heat strain when wearing fire-protective clothing at an air temperature of 30 °C and 50%RH. Real firefighters participated in the experiment under the following condition: control (no treatment), drinking only (DO), cooling only (CO), and both cooling and drinking (CD). The main finding of this study was that the combined effect of skin cooling and fluid ingestion was more influential during recovery than during exercise. In addition, there were no significant positive effects of cooling or drinking on rectal temperature during exercise.

12) Experiment N (2019): Research project report, Defense Agency for Technology and Quality (2020) A study on how to improve the performance of combat suits using commercial technology.

13) Experiment O (2020): Published, Lee et al. (2021)

Experiment O aimed to evaluate discomfort levels of healthcare workers wearing PPE to protect from COVID-19 in a neutral (25 °C, 50%RH) and a hot and humid environment (33 °C, 70%RH).

Six types of PPE (0.18–0.177 clo in thermal insulation, 0.227–0.319 $kPa \cdot m^{-2} \cdot W^{-1}$ in water evaporative resistance) were selected, and the experiments were performed under neutral conditions, except condition 1, 3, 5, 6, which were in a hot and humid environment. The results revealed that six types of PPEs could be classified as three categorizes in terms of discomfort at 33 °C and 70%RH. In addition, there were no relationships between thermal insulation and overall thermal sensation or comfort, and using a powered air purifying respirator was beneficial only in a neutral environment.

3.3.2 Characteristics of subjects in 13 experiments

All the data related to personal protective clothing were approved by each organization of the ethical review board. The summary of the physical characteristics in the 13 experiments is described in **Table 8**.

Table 8. [Experiment C–O] Physical characteristics of subjects from the 13 experiments

Experiment (year)	N	Age (year)	Height (cm)	Weight (kg)	BMI (kg/m^2)	BSA (m^2)	VO_{2max} (ml/min/kg)	HR_{max} (bpm)
C (2009)	8	24 ± 3	173.0± 3.9	66.3 ± 9.7	22.1 ± 3.0	1.8 ± 0.1	48 ± 17	193 ± 8
D (2010)	8	22 ± 2	171.6± 1.3	60.5 ± 6.2	20.5 ± 1.8	1.7 ± 0.0	50 ± 6	195 ± 9
E (2011)	8	21 ± 1	170.6± 2.0	60.6 ± 3.4	20.8 ± 1.1	1.7 ± 0.0	-	-
F (2011)	19	26 ± 1	175.5± 5.4	71.0 ± 6.8	23.2 ± 2.6	1.9 ± 0.1	52 ± 5	190 ± 10
G (2011)	8	32 ± 3	173.7± 4.4	59.4 ± 0.0	22.5 ±2.2	1.8 ± 0.1	-	-
H (2012)	8	39 ± 6	173.9± 3.8	74.2 ± 10.0	24.5 ±2.7	1.9 ± 0.1	42 ± 5	197 ± 6
I (2014)	8	39 ± 7	173.6± 4.5	77.9 ±10.9	25.7 ± 2.5	2.0 ± 0.2	42 ± 4	188 ± 5
J (2014)	12	37 ± 7	175.4± 5.0	75.8 ± 9.1	24.6 ± 2.4	2.0 ± 0.1	45 ± 7	188 ± 6
K (2015)	8	22 ± 2	180.6± 5.6	76.7 ± 9.0	23.5 ± 2.3	2.0 ± 0.1	-	187 ± 9
L (2016)	8	38 ± 7	173.9± 3.9	75.3 ± 6.7	25.0 ± 1.9	-	-	-
M (2017)	8	23 ± 3	171.9± 3.9	68.3 ± 7.6	-	1.8 ± 0.1	-	-
N (2019)	12	-	-	-	-	-	-	-
O (2020)	8	23 ± 3	179.4± 4.0	74.0 ± 5.8	23.0 ± 2.2	1.8 ± 0.0	50 ± 4	199 ± 11
Total N	123							

*Note: '-' means missing data. Abbreviations: BMI–Body mass index; BSA–Body surface area; VO_{2max}–Maximal oxygen consumption; HR_{max}–Maximal heart rate.

3.3.3 Experimental conditions and protocols

The summary of the environmental, clothing conditions, exercise, and protocol duration of the 13 experiments is described in Table 9, and all condition are summarized in Table 10.

Table 9. [Experiments C–O] Summary of the 13 experiments on environmental and clothing conditions, exercise, protocol durations

No.	Experiment (year)	N	Environmental condition	Clothing condition (Total mass of equipment)	Exercise	Protocol duration
1	C (2009)	8	[1]25 °C, [2]32 °C 50% RH	1) Control (*Daily clothes*, 590 g), 2) Personal protective clothing (Level D, 787 g), 3) Personal protective clothing (Level D) + Vinyl cover (1245 g)	*Two different protocols* 1) Rest (Sitting pose) 2) Exercise (2.74km/h, 10% slope)	1) 60 min for rest 2) 80 min for exercise (10REST/ 20EXE x 2/ 20RCV)
2	D (2010)	8	[1]22 °C, [2]32 °C 40% RH	1) Control (Fire protective clothing) 2) Type A protective clothing + SCBA (heavy 11 kg) 3) Type B protective clothing + SCBA (light 6.4 kg) 4) Type C protective clothing + SCBA (light 6.4 kg) + wider shoulder strip	6 km/h 0% slope	60 min (10REST/ 30EXE / 20RCV)
3	E (2011)	8	28 °C 40% RH	1) *Daily clothes* (Short t-shirt, short pants, 1 kg) 2) Fire protective clothing (8.3 kg)	6 km/h 0% slope	60 min (10REST/ 30EXE / 20RCV)
4	F (2011)	19	32 °C 60% RH	Fire protective clothing (8.3 kg)	*Two different protocols*	60 min (10REST/ 30EXE / 20RCV)

					1) 5.5km/h (Absolute intensity) 2) VO_{2max} 40% (Relative intensity)	
5	G (2011)	8	32 °C 60% RH	1. Japanese Fire protective clothing (8.2 kg) 2. American Fire protective clothing (10.1 kg) 3. European Fire protective clothing (9.4 kg)	6 km/h 0% slope	60 min (10REST/ 30EXE / 20RCV)
6	H (2012)	8	28 °C 40% RH	1. Control: *Daily clothes* (1.3 kg) 2. Full PPE (15.1 kg) 3. Full PPC +No SCBA (8 kg) 4. Full PPE +No Helmet (13.8 kg) 5. Full PPE +No Gloves (14.9 kg) 6. Full PPE +No Boots (13.1 kg) 7. Full PPE +No Jacket & Pants (11.8 kg) 8. Full PPE +No Helmet, boots, hood (11.6 kg)	5.5 km/h 1% slope	60 min (10REST/ 30EXE / 20RCV)
7	I (2014)	8	32.4 °C (29.5–35.5) 50% RH	Korean fire protective clothing (7.75 kg)	4.5 km/h 1% slope	90 min (20REST/ 60EXE / 10RCV)
8	J (2014)	12	32 °C 43% RH	Korean fire protective clothing + SCBA (15 kg)	5 km/h 0% slope	*Two different protocols* 1) 60 min (No rest) 2) 70 min (One 10 min mid rest)

9	K (2015)	8	32 °C [1]50% RH [2]80% RH	1. *Daily clothes*: Polyester/cotton long-sleeved shirt and long pants 2.Tyvek® 600 coverall with surged and over-taped seam (Type 4, 5, 6) 3. Tychem C (impermeable coverall made with polyethylene coated HDPE) 4. Nylon fabric with a microporous membrane long-sleeved jacket and long pants	Walking on a stepping box (25 step/min)	*Two different protocols* 1) 80 min (10REST/60EXE/10RCV) : Clothing condition 1,2,4 2) 65 min (10REST/45EXE/10RCV) : Clothing condition 3
10	L (2016)	8	32 °C 70% RH	Fire protective clothing different condition with 1. Japanese helmet (all-in-one) 2. US hood and helmet 3. Korean hood and helmet	5 km/h 0% slope	60 min (10REST/30EXE /20RCV)
11	M (2017)	8	30 °C 50% RH	Fire protective clothing different condition with 1. Control (no drink, 1050 g) 2. CO: Cooling only (1340 g) 3. DO: Drinking only (2740 g) 4. CD: Cooling and Drinking (6525 g)	5.5 km/h 0% slope	60 min (10REST/30EXE /20RCV)
12	N (2019)	12	24 °C 50% RH	Korean military uniform different condition with 1. Control (Only military uniform) 2. Type M water repelling agent 3. Type T water repelling agent	4 km/h 4% slope	120 min (20REST/40EXE/10REST/ 40EXE/10RCV)

13	O (2020)	8	[1]25 °C, 50% RH [2]33 °C, 70% RH	Six combinations of PPE consist of Tyvek, gown, apron, mask, goggle, and boots 1. Gown with open back + surgical mask* 2. Gown + mask (KF94) 3. Tyvek 400 (Level D) + mask (KF94)* 4. Gown + Tyvek 400 (Level D) + mask (N95) 5. Tyvek 800J (Level C) + mask (N95)* 6. Tyvek 800J (Level C) + PAPR*	4 km/h 0% slope	90 min (10REST/60EXE/20RCV) *Only conditions no.1, no. 3, no. 5, no. 6 were conducted in 33°C and 70%RH.
Total subjects		123				

*Abbreviations: RH—relative humidity; *Daily clothes*—basic cotton clothing; PPE—Personal protective equipment; PPC—Personal protective clothing; FPE—Fire protective equipment; HDPE—High density polyethylene; CON—control condition wearing basic protective clothing; REST—rest period; EXE—Exercise period; RCV—Recovery period; SCBA—Self-Contained Breath Apparatus; PAPR—Powered air purifying respirator; EU—European union; US—the United states; JP—Japan; KOR—Korea; KF—Korean filter.

Table 10. Summary of all the conditions in the 13 experiments C–O

Condition no.	Experiments C–O												
	C	D	E	F	G	H	I	J	K	L	M	N	O
1	25 **REST** *Daily clothes*	22 No SCBA	28 *Daily clothes* No-Menthol	32 FPE Pre-Relative	32 PPE (EU)	28 *Daily clothes*	33 FPE	32 FPE +SCBA	32 (50%RH) *Daily clothes*	32 Helmet (KOR)	30 CON	24 CON	33 CON
2	25 **REST** Tyvek	22 Heavy SCBA	28 *Daily clothes* Upper Body -Menthol	32 FPE Pre-Absolute	32 PPE (US)	28 Full FPE			32 (50%RH) Tyvek	32 Helmet (US)	30 Cooling	24 Water Repellent (M type)	33 CON + KF94
3	25 **REST** Vinyl	22 Light SCBA	28 FPE No-Menthol	32 FPE Post-Relative	32 PPE (JP)	28 No SCBA			32 (50%RH) Tychem	32 Helmet (JP)	30 Drinking	24 Water Repellent (T type)	33 PPC (Level D) + KF94
4	32 **REST** *Daily clothes*	22 Light SCBA +Wider Strap	28 FPE Face -Menthol	32 FPE Post-Absolute		28 No Helmet			32 (50%RH) Nylon		30 Cooling +Drinking		33 PPC (Level D) + N95
5	32 **REST** Tyvek	32 No SCBA	28 FPE Upper Body -Menthol			28 No Gloves			32 (70%RH) *Daily clothes*				33 PPC (Level C) + N95
6	32 **REST** Vinyl	32 Heavy SCBA	28 FPE Whole Body -Menthol			28 No Boots			32 (70%RH) Tyvek				33 PPC (Level C) + PAPR

7	25 **EXE** *Daily clothes*	32 Light SCBA	28 No Jacket, Pants	32 (70%RH) Tychem	25 CON
8	25 **EXE** Tyvek	32 Light SCBA + Wider Strap	28 No Helmet, Hood, Boots, Gloves	32 (70%RH) Nylon	25 PPC (Level D) + KF94
9	25 **EXE** Vinyl				25 PPC (Level C) + N95
10	32 **EXE** *Daily clothes*				25 PPC (Level C) + PAPR
11	32 **EXE** Tyvek				
12	32 **EXE** Vinyl				

1) Neutral	**2) Neutral**	**3)Hot**	**4) Hot**	**5) Hot-humid**	**6) Hot-humid**
Daily clothes	**PPE**	***Daily clothes***	**PPE**	***Daily clothes***	**PPE**

*Note: The order of expression: air temperature (%Relative Humidity) – activities (only in Experiment C) –clothing (and/or) treatments. *Abbreviations: RH—relative humidity; *Daily clothes*—basic cotton clothing; PPE—Personal protective equipment; PPC—Personal protective clothing; FPE—Fire protective equipment (Korean fire protective clothing); CON—control condition wearing basic protective clothing; **REST**—rest condition; **EXE**—Exercise condition; SCBA—Self-Contained Breath Apparatus; PAPR—Powered air purifying respirator; EU—European union; US—the United states; JP—Japan; KOR—Korea; KF—Korean filter.

3.3.4 Procedure of data collection and measurements

The rectal, forehead, foot, or toe skin temperature data and heart rate were extracted and collected in 13 experiments, and were used to calculate the PSI for evaluating heat strain and analyzed every 5 s. Most of the experimental data conducted in Korea included the following measurements. The rectal temperature was measured using a thermistor probe inserted 16 cm beyond the anal sphincter of the rectum. Skin temperature was measured on the forehead, chest or back, forearm, hand, thigh, calf, foot, or toe (LT-8A, Gram Ltd., Japan). Heart rate was typically measured every 5 s continuously. When several studies had measured every 1 s using an HR monitor (RS400, Polar Electro, Finland), it was averaged to every 5 s. For the maximal oxygen consumption test (VO_{2max} test) and before each trial, the respirometer was calibrated with room air, a standard gas mixture (4% CO_2, 16% O_2, and balance nitrogen), and the volume was calibrated using a 3-liter syringe.

3.3.5 Data analysis

To assess the validity, the original PSI and non-invasive PSIs under the conditions of each experiment were used. As the temperature data and heart rate data in this study are continuous variables, the validity of the non-invasive PSIs was demonstrated through Pearson correlation analysis with the original PSI. Residual plots were drawn using box-whisker plots to demonstrate the distribution of residuals by the equations. There, the significant bias of the residuals was confirmed using a one-sample *t*-test, compared with 0.

Chapter 4. Results and Discussion

4.1 [Part 1] Investigation of non-invasive parameters

4.1.1 Rectal, ear-canal temperature and heart rate for the evaluation of the heat strain

Owing to the different experimental protocols, Experiments A and B were divided, as shown in Figures 9 and 10. When the rectal temperature and heart rate were used, the PSI at the end of the exercise at each trial was 1.9 ± 0.7 (SW) and 2.3 ± 0.6 (PPE) at 28 °C, 2.5 ± 0.6 (SW) and 3.8 ± 0.8 (PPE) at 33 °C, and 4.9 ± 1.8 (SW) and 6.8 ± 0.7 (PPE) at 38 °C (Figure 9). The PSI before the termination of the exercise in Experiment B was 8.8 ± 0.4 (Level A), 8.3 ± 0.9 (Level B), 8.6 ± 0.4 (Level C), and 8.4 ± 0.5 (Level D) at 33 °C (Figure 10). Regarding recovery periods, the PSI was 7.9 ± 0.4 (Level A), 7.7 ± 0.7 (Level B), 8.1 ± 0.7 (Level C), and 7.5 ± 0.4 (Level D). However, there was a lack of recovery data because four of seven subjects were terminated because they reached a rectal temperature of 39.3 °C.

In both experiments, the rectal temperature and ear-canal temperature exhibited a similar tendency as the core temperature. However, the ear-canal temperature did not increase as significantly as the rectal temperature except at 38 °C 70% RH. In addition, some considerable variation was observed depending on the clothing and environment. Nunnley et al. (1992) reported that T_{sk} could be convergent to T_c or reversed above thermal equilibrium when wearing protective clothing. However, it was pointed out that this reversal phenomenon does not cause severe heat strain, and if the work is stopped when convergence occurs, the loss of work capacity may occur. Accordingly, in this study, the ear-canal temperature, as T_c close to the T_{sk}, was measured, and a phenomenon in which the ear-canal temperature increases at a higher rate than the rectal temperature was observed at 28 °C when wearing PPE (Figure 9D).

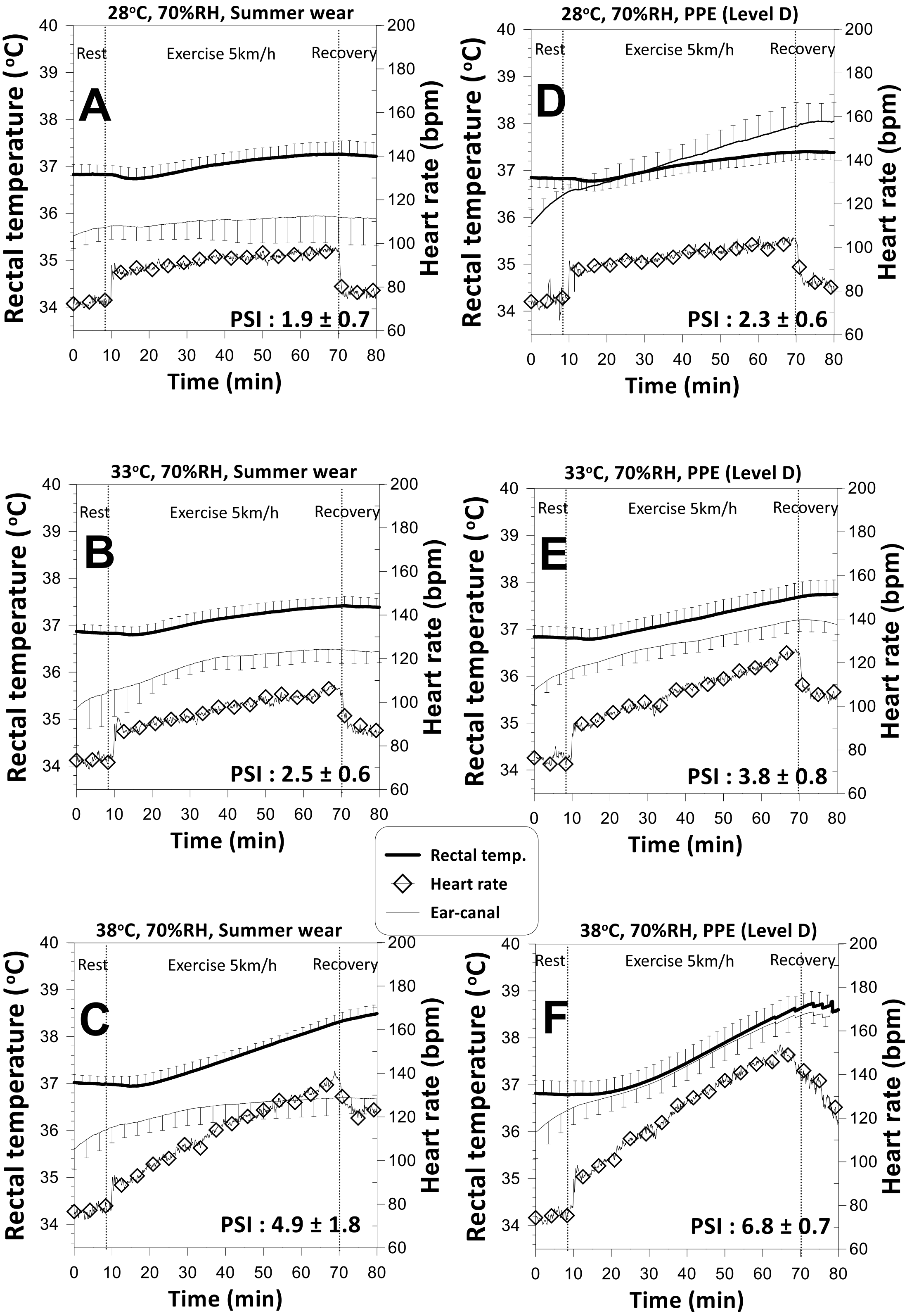

Figure 9. Time courses of rectal, ear-canal temperature, and heart rate when wearing summer wear (SW, Summer wear, short T-shirts and shorts pants) at 28 °C (A, D), 33 °C (B, E), and 38 °C (C, F) with 70% RH from Experiment A (N = 9). *Note: PSI is presented as mean ± SD.

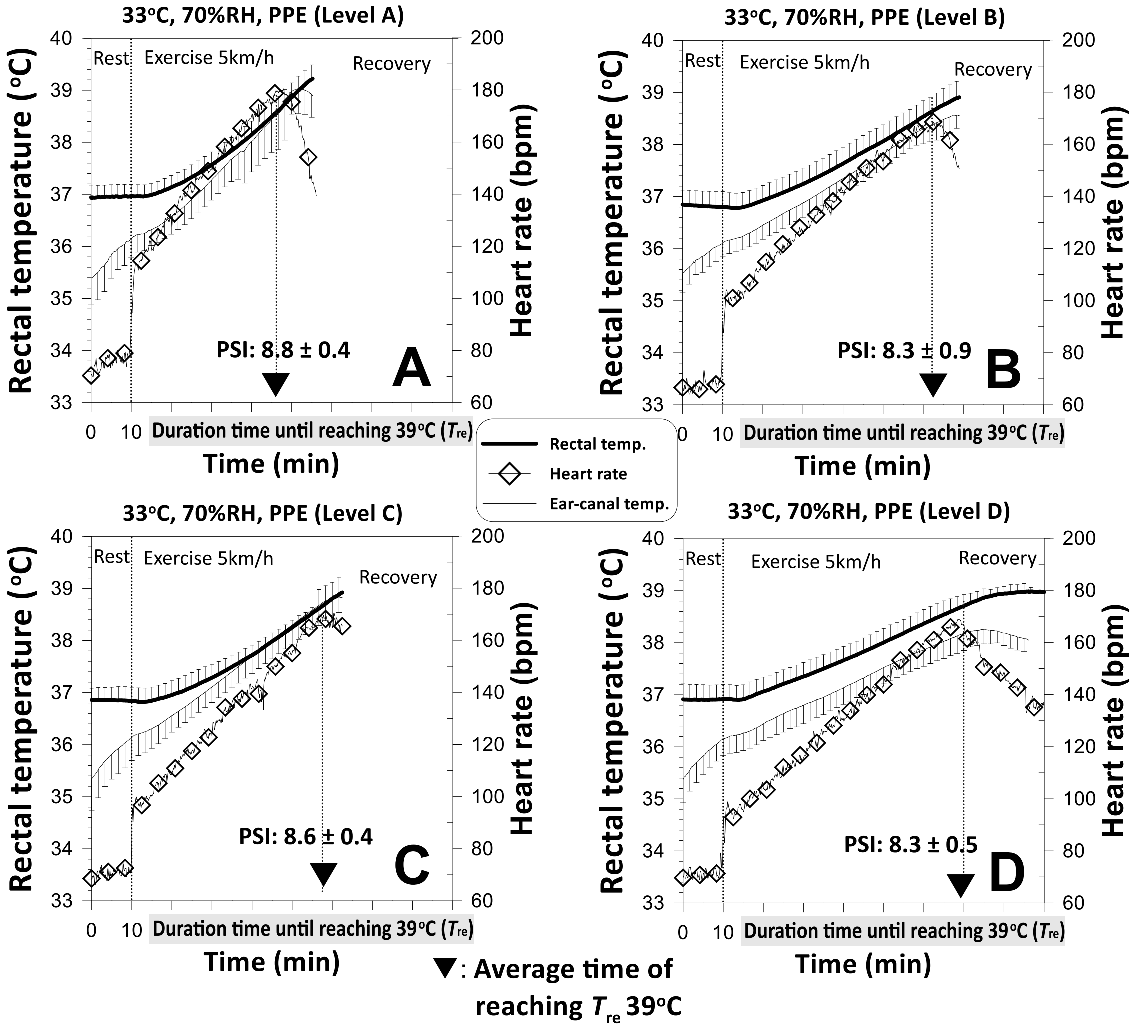

Figure 10. Time courses of the average rectal, ear-canal temperature, and heart rate when wearing each level of PPE at 33 °C and 70% RH from Experiment B (N=9). *Note : '▼' indicates the average time of reaching T_{re} 39°C. PSI is presented as mean ± SD.

4.1.2 Correlations of temperatures in rectal temperature with regional skin temperatures

In this session, before developing a non-invasive physiological strain index, we explored a region of the skin temperature that strongly correlates with the rectal temperature. Accordingly, correlation analysis was performed on the rectal, ear-canal, and nine regional skin temperatures (forehead, chest, back, forearm, hand, thigh, calf, foot, and toe) obtained from both experiments. The results revealed that most skin temperatures are significantly and strongly correlated with the rectal temperature. In more detail, the rectal temperature at 33 °C was demonstrated to exhibit a strong correlation with seven skin temperature regions at the last 3 min of the exercise period (Figure 11) in the following order: the foot (r = 0.823, P < 0.001), calf (r = 0.871, P < 0.001), chest (r = 0.856, P < 0.001), thigh (r = 0.836, P < 0.001), forehead (r = 0.735, P < 0.001), back (r = 0.732, P < 0.001), forearm (r = 0.720, P<0.001), whereas there was no significant correlation with the hand (r = 0.331, p = 0.210) and toe (r = 0.325, p = 0.091). However, it is noteworthy that most of the toe temperature was above 38 °C, as if close to the distribution of the rectal temperature.

Figure 12 shows the recovery period, and the correlations disappeared (back: r = 0.438, p = 0.089, forearm: r = 0.463, p = 0.071) or decreased (chest: r = 0.659, P < 0.001). In contrast, the toe (r = 0.734, P < 0.001) exhibited a significant correlation with the rectal temperature. One of the other core temperatures, the temperature in the ear canal (r = 0.981, P < 0.001, N = 16), compared to the correlation coefficient of skin temperature, exhibited a higher correlation value than skin temperature.

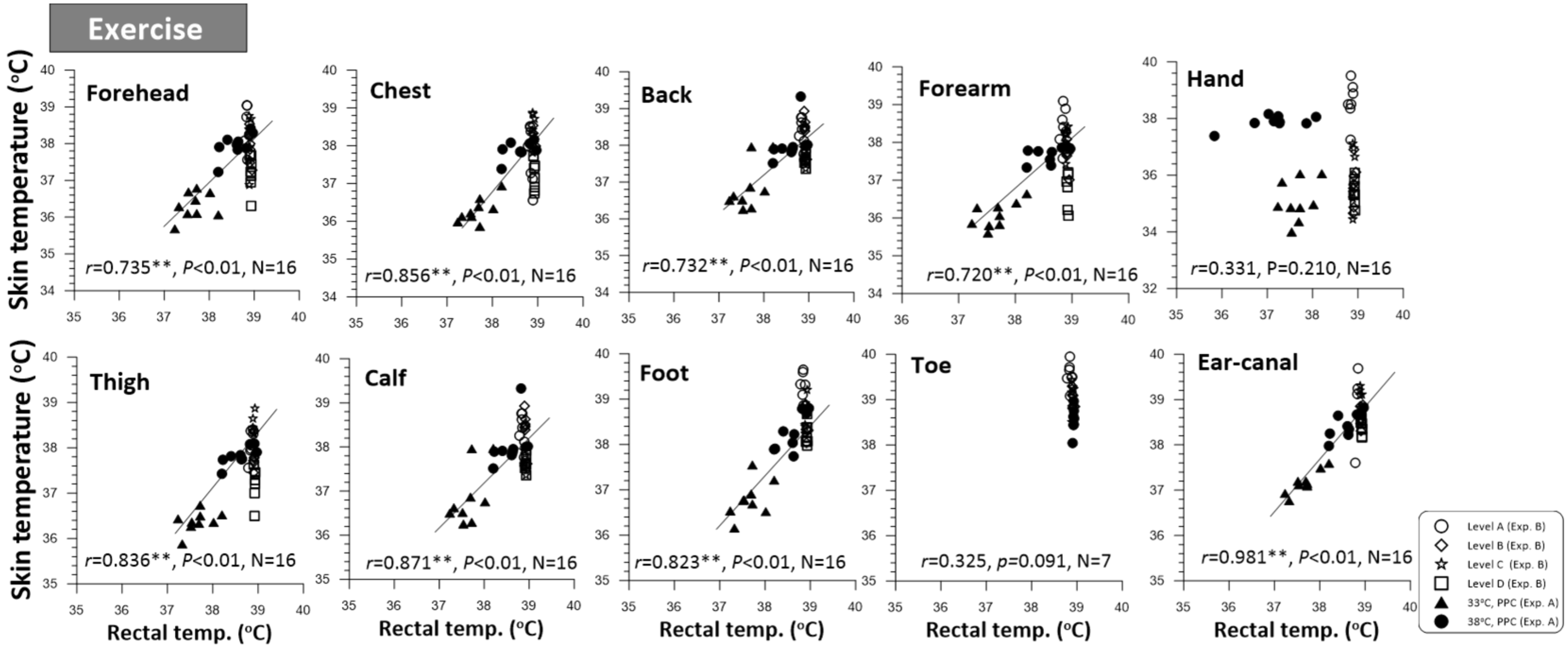

Figure 11. Relationships between the rectal temperature and each skin temperature at the last 3 min of the exercise period. *Note: The number of patients was 46 in both Experiments A (N = 9) and Experiment B (N = 7).

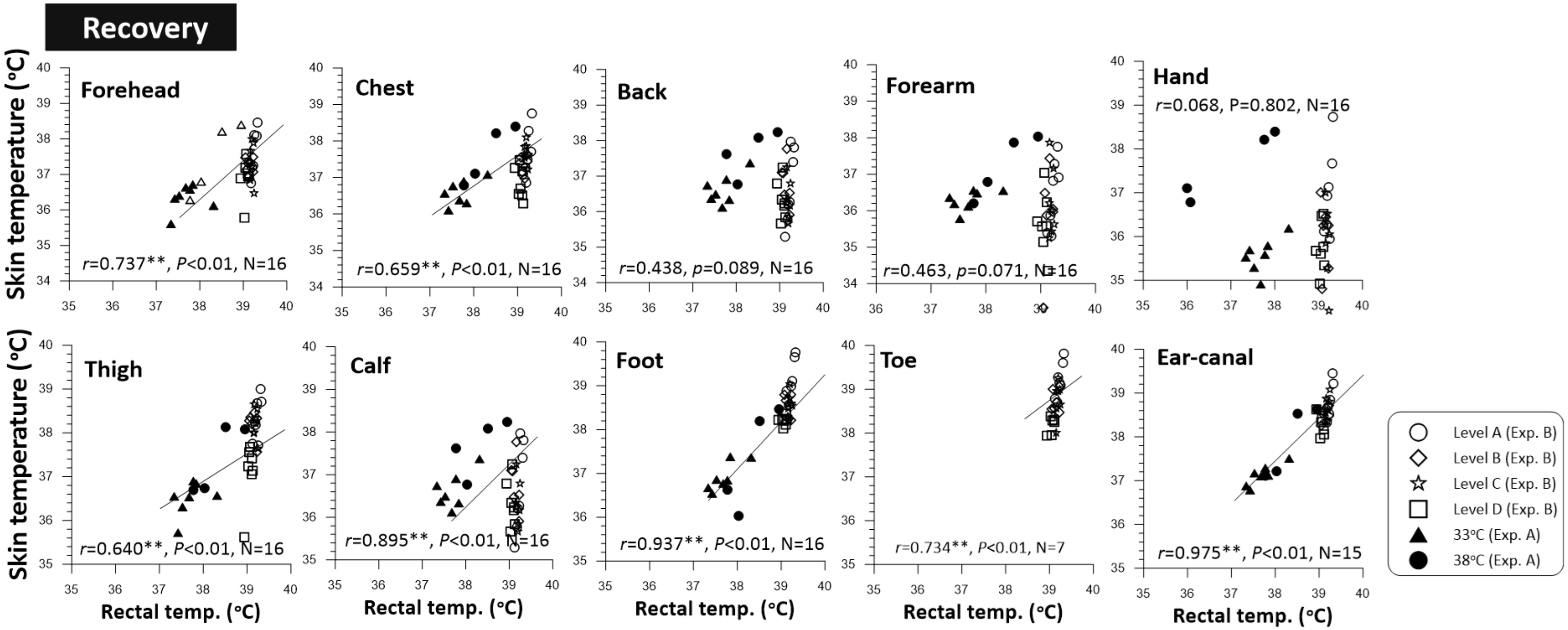

Figure 12. Relationships between the rectal temperature and each skin temperature at the last 3 min of the recovery period. *Note: Data were analyzed by integrating 33 °C with the PPE conditions. The number of cases was 44–46 from both Experiment A (N = 9) and Experiment B (N = 7), 28 for the toe temperature from only Experiment B (N = 7).

Compared to that at 33 °C, the upper part of the body (chest, back, forearm) except the forehead exhibited no significant correlations with the rectal temperature during exercise. In the recovery period, only the thigh (r=0.893, P<0.05), foot (r = 0.904, P < 0.05), and ear-canal (r = 0.911, P < 0.05) showed significant correlations (Table 11).

Table 11. Correlation coefficients of rectal, ear-canal temperatures with eight skin temperature at 38 °C with PPE condition from Experiment A results only

	Periods of protocol								
	Exercise			Recovery 1			Recovery 2		
Region	*r*	*P value*	N	*r*	*P value*	N	*r*	*P value*	N
Forehead	0.712*	0.032	9	0.550	0.258	6	0.629	0.567	3
Chest	0.549	0.126	9	0.689	0.130	6	0.645	0.554	3
Back	0.478	0.193	9	0.629	0.181	6	0.719	0.489	3
Forearm	0.473	0.198	9	0.789	0.062	6	0.765	0.446	3
Hand	0.532	0.140	9	0.650	0.163	6	0.616	0.577	3
Thigh	0.815**	0.007	9	0.893*	0.016	6	0.357	0.767	3
Calf	0.756*	0.018	9	0.809	0.051	6	0.758	0.242	4
Foot	0.748*	0.020	9	0.904*	0.013	6	0.909	0.091	4
Ear-canal	0.791*	0.011	9	0.911*	0.012	6	0.664	0.538	3

*Note: $^{*}P$ < 0.05, $^{**}P$ < 0.001, *r:* Pearson correlation coefficient.

4.1.3 Consistency between the rectal temperature and regional skin temperatures

Consistency between rectal and regional skin temperatures was calculated as a mean with standard deviations, upper and lower 95% of the limit of agreement (Table 12). The least mean difference was observed in the toe temperature at -0.15 ± 0.47 of 95%LoA [-1.06–0.77] during exercise and 0.32 ± 0.46 of 95%LoA [-0.58 ~ 1.22] during recovery. In order of small mean differences, the toe was the smallest, followed by the ear-canal (0.49 ± 0.49 of 95%LoA [-0.47–1.45]), foot, (0.52 ± 0.49 of 95%LoA [-0.43–1.47]), and back (1.17 ± 0.95 of 95%LoA [-0.70–3.03]) during the exercise period.

Table 12. Mean difference and limit of agreement between the rectal temperature, nine skin temperature, and ear-canal temperature at the last 3min of exercise and recovery period from Experiment A and Experiment B (unit: °C)

	Periods of protocol							
	Exercise				Recovery			
Region	Mean	SD	Upper 95%LoA	Lower 95%LoA	Mean	SD	Upper 95%LoA	Lower 95%LoA
Forehead	1.3	0.8	2.7	-0.2	1.4	0.7	2.7	0.1
Chest	1.6	1.1	3.8	-0.5	1.6	1.0	3.6	-0.3
Back	1.2	1.0	3.0	-0.7	1.5	0.8	3.1	-0.1
Forearm	1.9	1.3	4.5	-0.6	2.2	1.1	4.3	0.0
Hand	2.6	1.4	5.3	-0.1	2.6	1.1	4.8	0.4
Thigh	1.6	1.0	3.5	-0.4	1.4	0.9	3.2	-0.3
Calf	1.4	1.1	3.6	-0.9	1.2	1.1	3.3	-0.9
Foot*	0.5	0.5	1.5	-0.4	0.5	0.4	1.4	-0.3
Toe*	-0.1	0.5	0.8	-1.1	0.3	0.5	1.2	-0.6
Ear-canal*	0.5	0.5	1.5	-0.5	0.5	0.5	1.4	-0.4

*Note: The region met the acceptability criteria of a mean difference within ± 0.5 °C and LoA of ± 1 °C.

The Bland-Altman plots limit of agreement (LoA) at the recovery period integrating Experiments A and B are shown in Figure 13. Although the toe temperature was not correlated with the rectal temperature (see in Figure 11), it exhibited the least bias with the rectal temperature (Figure 13). Ramanathan (1964) proposed the thigh as a representative average skin temperature region based on a significant difference of 0.17 °C. In this study, the toe skin temperature at the end of the exercise period exhibited a mean difference of –0.15 ± 0.47 and 95% LoA [0.77–1.06] with the rectal temperature, which is consistent with the reference for LoA with an average difference of < 0.5 °C and LoA of ± 1.0 °C which was used as an acceptable consensus in McLean et al. (2021). They suggested that the regions suitable for the average skin temperature under various clothing conditions are the chest, back, and thigh. However, the temperature measured in the lower body was only the thigh, which seemed to lack insufficient measurement area from the lower body part, considering the portion ratio. Skin temperature measurement requires careful consideration in terms of the number of regions measured and the location (Taylor and Amos, 1997, Xu et al., 2013), as well as the type of measurement device. It is also influenced by clothing (Bernard and Kenny, 1994, Taylor et al., 1998) and the ambient environment (Taylor et al., 1998, Gunga et al., 2008, Teunissen et al., 2011). Therefore, the results of this study can be considered more reasonable because it measured in more detail, the distal part of the human body (foot and toe). In addition, the maximum skin temperature was only distributed above 39 °C in the toes at the end of the exercise termination of experiments (Figure 14).

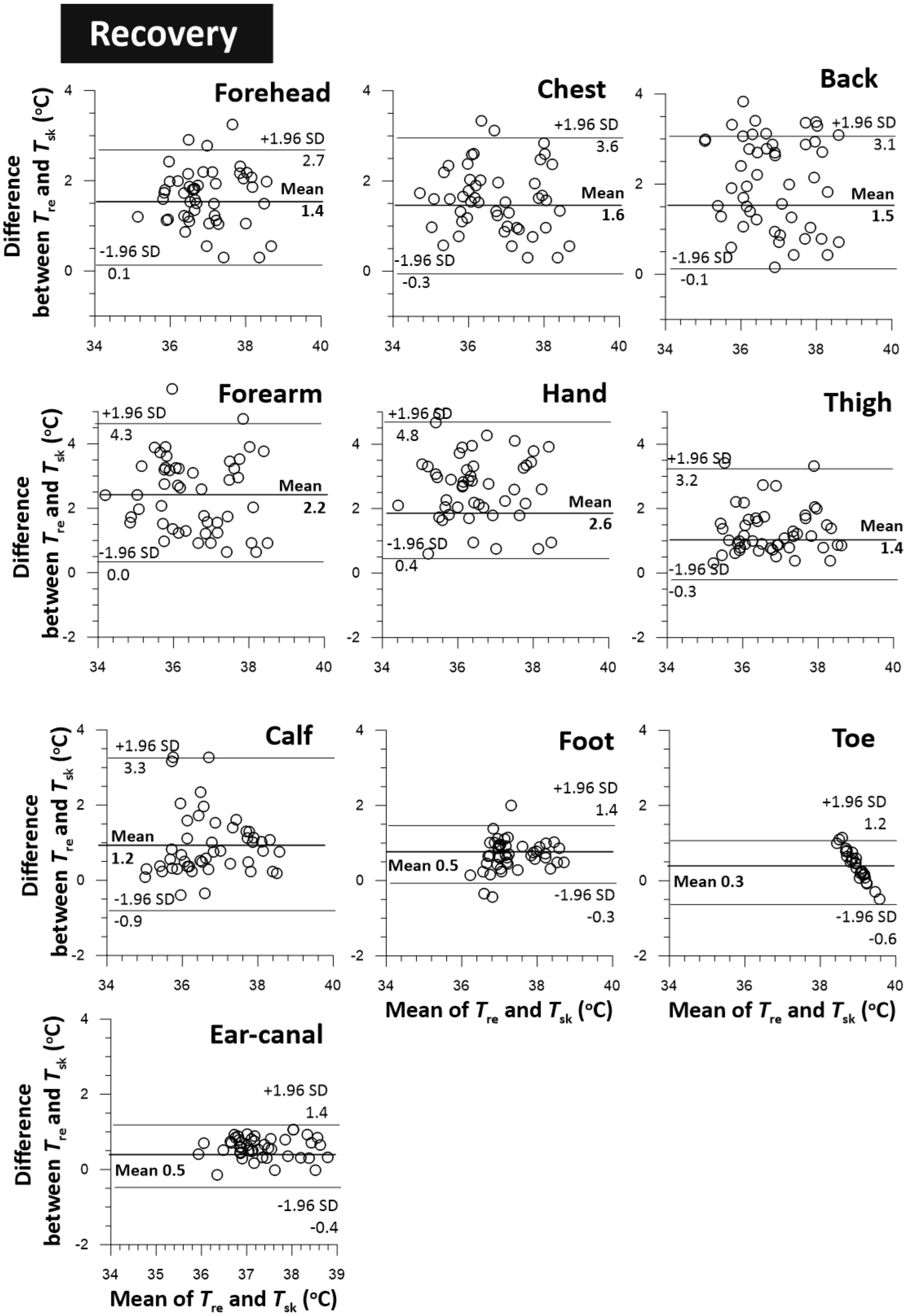

Figure 13. Bland-Altman plots with 95%LoA at the recovery period from Experiments A and B for the forehead, chest, back, forearm, hand, thigh, calf, foot, toe, and ear-canal temperatures. *Note: Mean differences between the rectal and skin temperature in the y-axis, mean rectal and skin temperature in the x-axis. Data expressed mean differences with LoA in 95%CI.

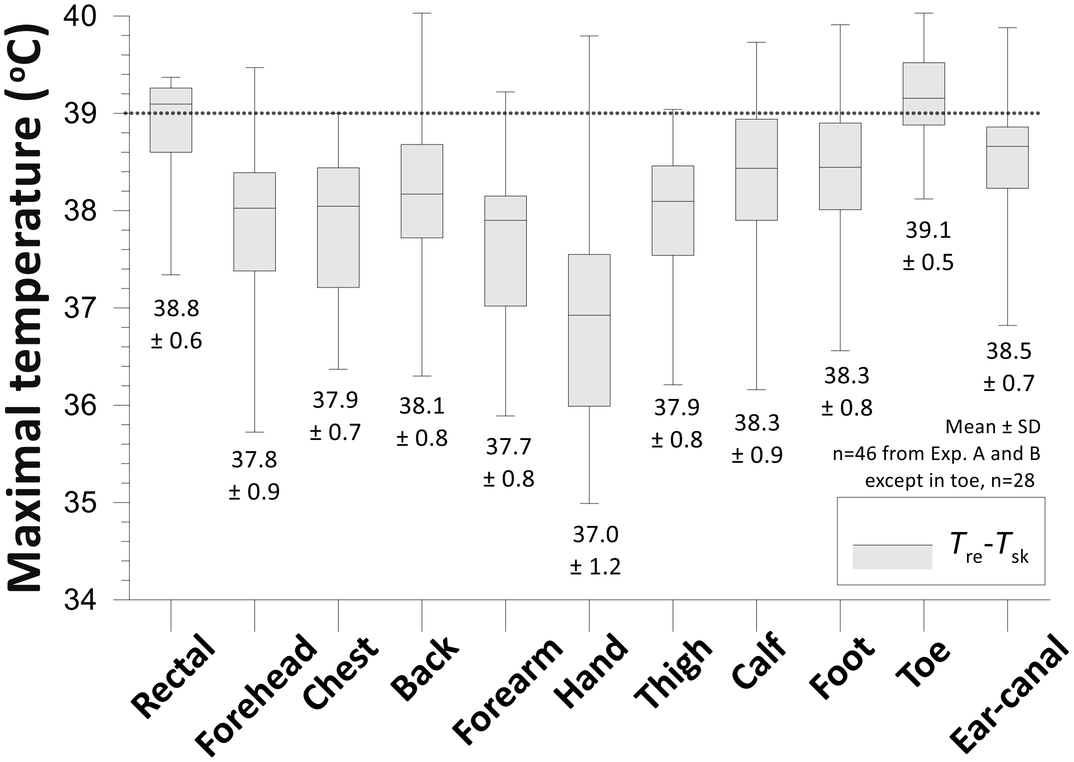

Figure 14. Maximum rectal, nine skin regions, ear-canal temperatures with PPE conditions from both experiments. *Note: Data presented as mean ± SD. The number of subjects was calculated for all conditions. In the box-whisker plots, the horizontal bars in the box are medians, error bars are minimum and maximum values, and the upper and lower line of a box are the 75th and 25th percentile of the values.

Therefore, based on the results of correlation analysis and Bland-Altman analysis of the two experiments, the torso temperature (chest, back, forearm, and hand) should be excluded in the next session owing to its low correlation and slight gap of discrepancy with the rectal temperature. Moreover, the correlation (r > 0.7), mean difference ≤ 0.5 °C, and LoA ± 1.0 °C in both experiments indicates that the skin site with the most similar distribution to the rectal temperature was the foot region . Nevertheless, this study also analyzed the forehead temperature. Forehead temperature is clinically used to screen rapidly (Patel et al., 1996, Eshraghi et al., 2014) and could be estimated as T_c (Pryor et al., 2012, Xu et al., 2013, Park and Waterhouse, 2014). In addition, according to the anatomical structure, there is a temporal artery that supplies blood to the skin of the forehead, which causes vasocontraction and vasodilation of skin vessels in the event of hypothermia or hyperthermia (Kistemaker et al., 2006). In contrast, Park and Waterhouse (2014) assessed the possible use of the forehead temperature for the estimation of rectal temperature; however, they concluded that rectal temperature cannot be inferred from forehead temperature and suggested it can only be applied to sedentary subjects with a comfortable environment. Therefore, there is some bias for the applicable measurement sites for replacing T_{re} with T_{sk}. Thus, this study included the forehead temperature in the analysis to determine if the forehead temperature can be used to estimate T_c when wearing protective clothing in the heat.

4.1.4 Modified equations of the original physiological strain index

Based on the temperature correlation and consistency observations from experiments A and B, the foot and toe temperature are tentatively the most reflective and representative of the rectal temperature (Figure 12–14, and Table 11, 12). Although the forehead temperature does not satisfy the three references, the equation was developed and included the forehead temperature along with the foot and toe temperature. As explained in section 4.1.3, as there are some biased opinions of various researchers on the forehead temperature, this study attempted to analyze whether the forehead temperature proposed by the previous knowledge can be practically applied in an occupational workplace.

First, the original PSI was reformed using the forehead, foot, and toe temperatures, as follows:

1) Model 1: NIPSI (Non-invasive PSI)

$$= 5\,(T_{sk}t - T_{sk}0) \cdot (39.5 - T_{sk}0)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR0)^{-1} \qquad \text{(Eq. 5)}$$

*$T_{re}t$ was replaced to $T_{forehead,}$ $T_{foot,}$ or $T_{toe,}$ and $T_{re}0$ was replaced to $T_{forehead}0$, $T_{foot}0$, or $T_{toe}0$.

2) Model 2: $NIPSI_{33}$ (Non-invasive PSI, fixed initial temperature of 33 °C)

$$= 5\,(T_{sk}t - 33) \cdot (39.5 - 33)^{-1} + 5\,(HRt - HR0) \cdot (180 - HR0)^{-1} \qquad \text{(Eq. 6)}$$

*$T_{re}t$ was replaced to $T_{forehead,}$ $T_{foot,}$ or $T_{toe,}$ and $T_{re}0$ was replaced to 33°C

3) Model 3: $NIPSI_{37}$ (Non-invasive PSI, fixed initial temperature of 37 °C)

$$= 5\,(T_{sk}t - 37) \cdot (39.5 - 37)^{-1} + 5(HRt - HR0) \cdot (180 - HR0)^{-1} \qquad \text{(Eq. 7)}$$

*$T_{re}t$ replaced to $T_{forehead,}$ $T_{foot,}$ or $T_{toe,}$ and $T_{re}0$ was replaced to 37°C

All non-invasive PSIs exhibited a strong positive correlation with the original PSI equation (Figure 15). In addition, among these indices, Model 2 exhibited a higher correlation coefficient (*r*) at three skin temperatures compared to Model 1 and Model 3. $NIPSI_{33toe}$ not only exhibited the highest correlation coefficient (r = 0.943, P < 0.001, n = 28, Figure 15F), but also the distribution of points is almost identical with the original PSI.

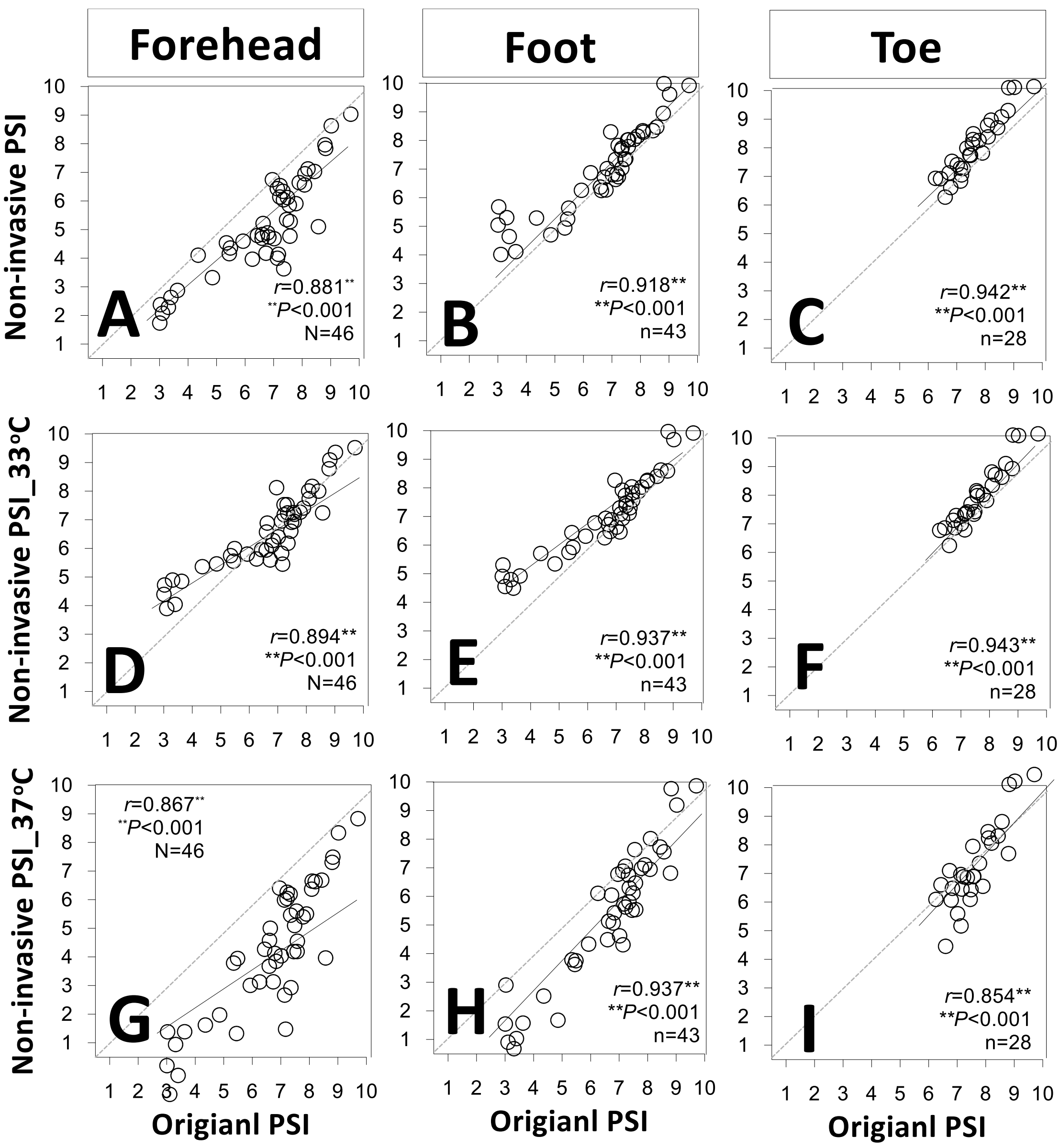

Figure 15. Correlations between the original PSI and non-invasive PSIs using forehead, foot, and toe skin temperature with initial, fixed initial (33 °C), and 37 °C temperature [A, B, C: Model 1; D, E, F: Model 2; G, H, I: Model 3].

Bland-Altman plots presented the LoA with 95%CI of NIPSI, $NIPSI_{33}$, and $NIPSI_{37}$ (Figure 16), and $NIPSI_{33}$ with toe temperature exhibited the smallest mean difference of -0.31 with ± 95%CI [-1.03, 0.41]. Although the toe temperature had no significant correlation with the rectal temperature, once converted to the index, it exhibited a strong correlation with the original PSI. The reason why the temperature distribution is not correlated is that the correlation analysis only shows the directionality of the data, and the results show that the rectal temperature and toe temperature have almost the same distribution, 38.8 ± 0.6 °C (rectal temperature) and 39.1 ± 0.5 °C (toe temperature, Figure 13, 14). And their mean difference was also believed to be because these were only 0.1 ± 0.5 °C at the last 3min exercise period (Table 12).

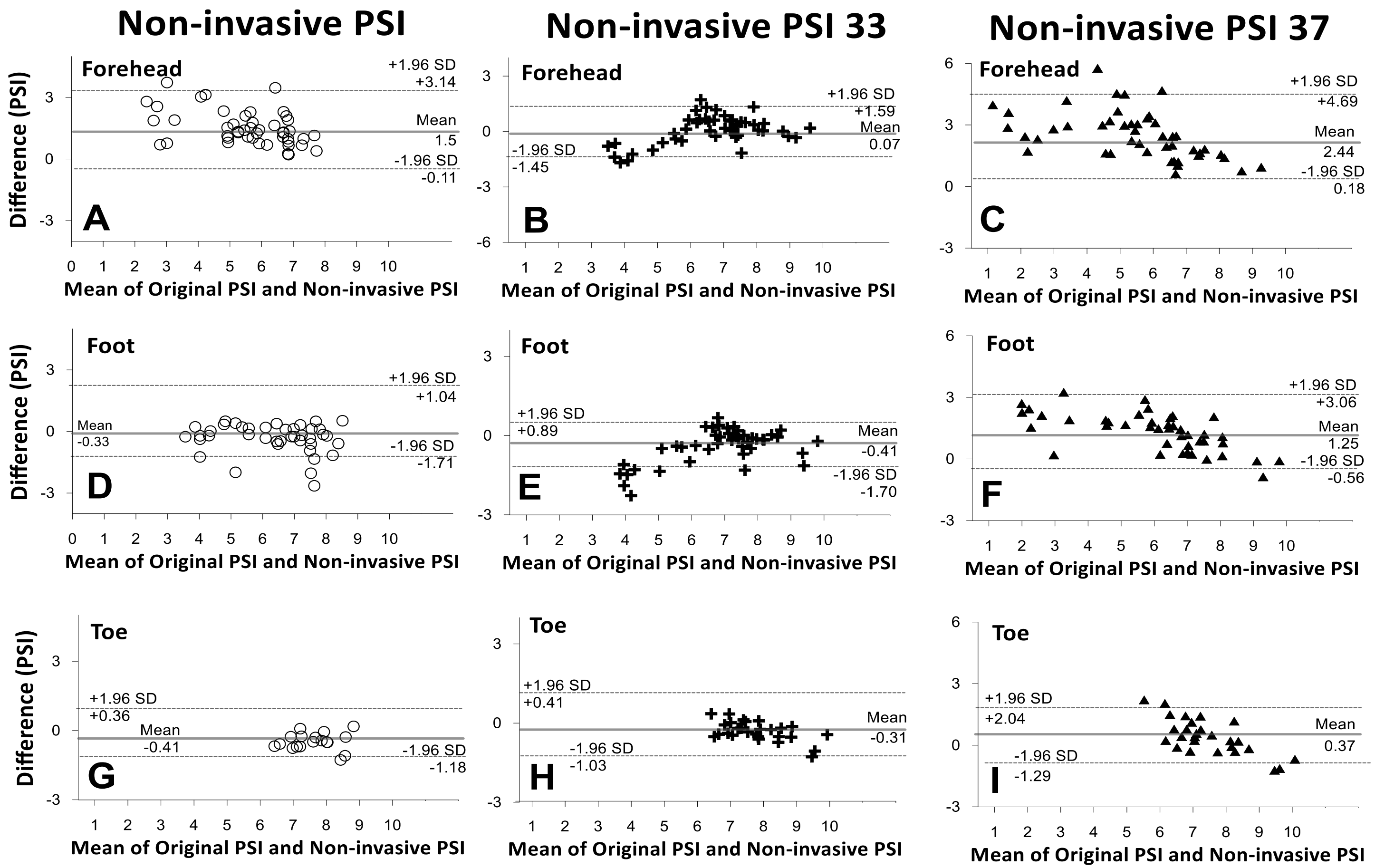

Figure 16. Bland-Altman plots with LoA in 95%CI of NIPSI, $NIPSI_{33}$, and $NIPSI_{37}$ using forehead, foot, and toe. *Note: Difference values of the NIPSIs in the y-axis, mean values of the NIPSIs (1st row: using initial temperature, 2nd: using 33 °C for initial temperature, 3rd: using 37 °C for initial temperature). Data expressed mean as differences with LoA in 95%CI.

4.1.5 Summary

In summary, in Part 1, the foot or toe skin temperature exhibited the highest correlation with rectal temperature. In addition, the highest consistency was observed in the foot area (foot and toe). Based on these results, a non-invasive PSI, in which the rectal temperature was substituted with the foot and toe skin temperature was developed, and this modified PSI exhibited a high consistency with the original PSI. Moreover, among the two indices that fixed the initial temperature, the index fixed to 33 °C was more suitable for satisfying the simplicity of the index. Although this study have tried to focus on individual heat strain monitoring with more experimental data, the index using the initial temperature demonstrated not to be validated as the index using fixed initial temperature. Therefore, the validity will be examined using the NIPSI with the initial foot/toe/forehead skin temperature (Model 1) and the $NIPSI_{33}$ (Model 2). The two candidate equations are as follows:

Model 1 (NIPSI)

$= 5\ (T_{sk}t - T_{sk}0) \cdot (39.5 - T_{sk}0)^{-1} + 5\ (HRt - HR0) \cdot (180 - HR0)^{-1}$

*$T_{re}t$ was replaced to $T_{forehead,}$ $T_{foot,}$ or T_{toe} and $T_{re}0$ was replaced to $T_{sk}0$.

Model 2 ($NIPSI_{33}$)

$= 5\ (T_{sk}t - 33) \cdot (39.5 - 33)^{-1} + 5\ (HRt - HR0) \cdot (180 - HR0)^{-1}$

*$T_{re}t$ was replaced to $T_{forehead,}$ $T_{foot,}$ or T_{toe} and $T_{re}0$ was replaced to 33°C.

4.2 [Part 2] Validity of the non-invasive PSIs

4.2.1 Validity of the non-invasive PSIs in different environments

NIPSI (Model 1) and $NIPSI_{33}$ (Model 2) were calculated at the end of the exercise period for the 13 experiments, and the conditions of wearing PPE were extracted. The comparison of the non-invasive PSIs between different environmental conditions is as follows: neutral (22–28 °C colored light grey), hot (over 30 °C with moderate humidity (40–50% RH colored grey), and high humidity (70–80%RH colored black) environments (Figure 17).

Condition no.	Experiments C–O												
	C	D	E	F	G	H	I	J	K	L	M	N	O
1	25 **REST** *Daily clothes*	22 No SCBA	28 *Daily clothes* No -Menthol	32 FPE Pre-Relative	32 PPE (EU)	28 *Daily clothes*	33 FPE	32 FPE + SCBA	32 (50%RH) *Daily clothes*	32 Helmet (KOR)	30 CON	24 CON	33 CON
2	25 **REST** Tyvek	22 Heavy SCBA	28 *Daily clothes* Upper Body -Menthol	32 FPE Pre-Absolute	32 PPE (US)	28 Full FPE			32 (50%RH) Tyvek	32 Helmet (US)	30 Cooling	24 Water Repellent (M type)	33 CON + KF94
3	25 **REST** Vinyl	22 Light SCBA	28 FPE No -Menthol	32 FPE Post-Relative	32 PPE (JP)	28 No SCBA			32 (50%RH) Tychem	32 Helmet (JP)	30 Drinking	24 Water Repellent (T type)	33 PPC (Level D) + KF94
4	32 **REST** *Daily clothes*	22 Light SCBA + Wider Strap	28 FPE Face -Menthol	32 FPE Post-Absolute		28 No Helmet			32 (50%RH) Nylon		30 Cooling +Drinking		33 PPC (Level D) + N95
5	32 **REST** Tyvek	32 No SCBA	28 FPE Upper Body -Menthol			28 No Gloves			32 (70%RH) *Daily clothes*				33 PPC (Level C) + N95
6	32 **REST** Vinyl	32 Heavy SCBA	28 FPE Whole Body -Menthol			28 No Boots			32 (70%RH) Tyvek				33 PPC (Level C) + PAPR
7	25 **EXE** *Daily clothes*	32 Light SCBA				28 No Jacket, Pants			32 (70%RH) Tychem				25 CON
8	25 **EXE** Tyvek	32 Light SCBA + Wider Strap				28 No Helmet, Hood, Boots, Gloves			32 (70%RH) Nylon				25 PPC (Level D) + KF94

9	25 **EXE** Vinyl												25 PPC (Level C) + N95
10	32 **EXE** *Daily clothes*												25 PPC (Level C) + PAPR
11	32 **EXE** Tyvek												
12	32 Exe Vinyl							Neutral *Daily clothes*	Neutral PPE	Hot *Daily clothes*	Hot PPE	Hot-humid *Daily clothes*	Hot-humid PPE

Figure 17. Environmental and clothing conditions when PPE was worn in the 13 experiments. *Note: Meaning of the colored boxes are as follows: light grey—neutral; medium grey—Hot and moderate relative humidity; black—Hot and high relative humidity. The clothing condition named ‘Daily clothes’ indicates basic cotton clothing; other PPE consists of various PPC with Tyvek, Tychem, Nylon, Vinyl, and FPE (Fire Protective Equipment).

At all environmental temperatures, the non-invasive PSIs with the initial temperature of 33 °C exhibited a strong correlation with the original PSI, and the coefficient value was higher in the neutral environment than in hot environments in the three regions (Table 13), and the NIPSIs obtained using the initial temperature exhibited a similar tendency. There were no differences between the residuals of the original PSI and the NIPSIs in the neutral and hot with 70%RH environment (Figure 18). However, the $NIPSI_{33}$ with forehead and foot temperature at hot environments with 50% RH exhibited significant differences in the one-sample *t*-test.

Among the skin temperature regions, although the forehead temperature seems closer to 0 in neutral and hot environments with 50%RH, the temperature variation was smaller in the toe and foot. To understand why the index of the forehead and foot in hot environments with 50%RH was more different in hot environment, a correlation analysis of the indices was conducted for each experiment (Table 14).

Table 13. Correlation coefficients between the original PSI and NIPSIs using forehead, foot, and toe temperature under neutral or hot temperature with 50% RH, and hot temperature with 70% RH at the last 3 min of exercise while wearing PPE

Environ-mental condition	Region	$NIPSI_{33}$			NIPSI		
		Forehead	Foot	Toe	Forehead	Foot	Toe
Neutral PPE	*r*	0.897**	0.971**	0.972**	0.887**	0.957**	0.925**
	P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	n	101	101	59	100	100	59
Hot with 50%RH PPE	*r*	0.749**	0.807**	0.853**	0.175**	0.419**	0.828**
	P-value	<0.001	<0.001	<0.001	0.005	<0.001	<0.001
	n	313	265	147	261	213	147
Hot with 70%RH PPE	*r*	0.767**	0.809**		0.513*	0.590**	
	P-value	<0.001	<0.001		0.021	0.004	
	n	20	22		20	22	

*Note: PPE—Personal protective equipment; RH—Relative humidity; *r*: Pearson correlation coefficient; NIPSI: Non-invasive physiological strain index; $NIPSI_{33}$:Non-invasive physiological strain index with initial temperature fixed to 33 °C. $^{*}P < 0.05$, $^{**}P < 0.01$.

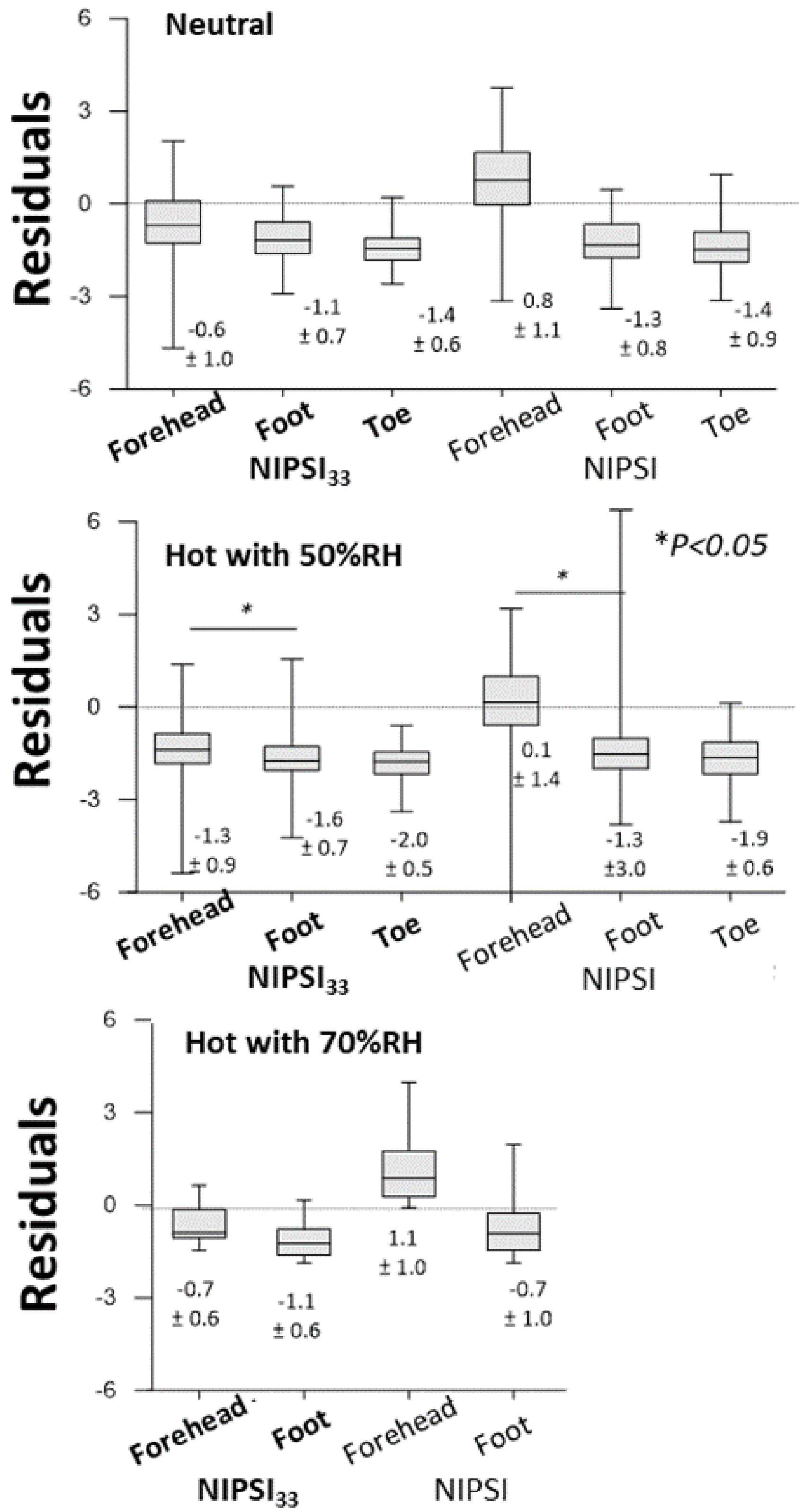

Figure 18. Residual distributions of each non-invasive PSIs at neutral, hot with 50%, 70%RH environments when wearing PPE. *Note: NIPSI: Non-invasive physiological strain index, $NIPSI_{33}$: Non-invasive physiological strain index with fixed initial temperature to 33 °C. $^*P < 0.05$.

Table 14. Correlation coefficients between the original PSI and NIPSIs using forehead, foot, and toe temperature in hot environments with 50%RH and 70%RH at the last 3 min of exercise while wearing personal protective equipment from each experiment

			$NIPSI_{33}$			NIPSI		
	Experiment	Region	Forehead	Foot	Toe	Forehead	Foot	Toe
Hot with 50% RH PPE	C	*r*	0.897^{**}	0.962^{**}		0.756^{**}	0.921^{**}	
		P value	<0.001	<0.001		0.001	<0.001	
		n	16	16		16	16	
	D	*r*	0.902^{**}	0.948^{**}	0.939^{**}	0.872^{**}	0.915^{**}	0.901^{**}
		P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		n	31	31	31	31	31	31
	F	*r*	0.909^{**}	0.876^{**}	0.937^{**}	0.859^{**}	0.842^{**}	0.905^{**}
		P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		n	49	48	51	49	48	51
	G	*r*	0.812^{**}	0.919^{**}		0.413^{*}	0.787^{**}	
		P value	<0.001	<0.001		0.045	<0.001	
		n	24	24		24	24	
	H	*r*	0.736^{**}	0.766^{**}				
		P value	<0.001	<0.001				
		n	52	52				
	I	*r*	0.866^{*}	0.965^{**}	0.957^{**}	0.833^{*}	0.951^{**}	0.852^{*}
		P value	0.012	<0.001	0.001	0.020	0.001	0.015
		n	7	7	7	7	7	7

*Note: PPE—Personal protective equipment; RH—Relative humidity; *r*: Pearson correlation coefficient, NIPSI: Non-invasive physiological strain index, $NIPSI_{33}$: Non-invasive physiological strain index with initial temperature fixed to 33 °C. $^{*}P < 0.05$, $^{**}P < 0.001$.

Table 14. (Cont.) Correlation coefficients between the original PSI and NIPSIs using forehead, foot, and toe temperature in hot environments with 50%RH and 70%RH at the last 3 min of exercise while wearing personal protective equipment from each experiment

			$NIPSI_{33}$			NIPSI		
	Experiment	Region	Forehead	Foot	Toe	Forehead	Foot	Toe
Hot with 50%RH PPE	J	*r*	0.895**	0.907**	0.902**	0.796**	0.952**	0.899**
		P value	<0.001	<0.001	<0.001	0.003	<0.001	<0.001
		n	11	10	11	11	10	11
	K	*r*	0.824**	0.916**		0.781**	0.830**	
		P value	<0.001	<0.001		<0.001	<0.001	
		n	22	22		22	22	
	L	*r*	0.553**	0.845**		0.487*	0.396	
		P value	0.009	<0.001		0.030	0.076	
		n	21	21		20	21	
	M	*r*	0.667**	0.635**		0.506**	0.603**	
		P value	<0.001	<0.001		0.004	<0.001	
		n	31	31		31	30	
	O	*r*	0.911**	0.965**		0.851**	0.891**	
		P value	<0.001	<0.001		<0.001	<0.001	
		n	46	46		46	46	
Hot with 70%RH PPE	K	*r*	0.681**	0.809**		0.497*	0.590**	
		P value	0.001	<0.001		0.022	0.004	
		n	21	22		21	22	

*Note: PPE—Personal protective equipment; RH—Relative humidity; *r*: Pearson correlation coefficient, NIPSI: Non-invasive physiological strain index; $NIPSI_{33}$: Non-invasive physiological strain index with initial temperature fixed to 33 °C. $^{*}P < 0.05$, $^{**}P < 0.001$.

The coefficients observed in experiments L and M were lower than those observed in others ($NIPSI_{33}$ in Experiment L: forehead, $r = 0.553$, $P < 0.01$; foot, $r = 0.845$, $P < 0.001$) ($NIPSI_{33}$ in Experiment M: forehead, $r = 0.667$, $P < 0.001$; foot, $r = 0.635$, $P < 0.001$)(Table 15). Experiment L was conducted to evaluate the heat strain while wearing fire protective clothing (FPC) with different fire hoods under heat stress. This may have been responsible for the variation in the coefficient, as the measurement of the forehead temperature was unstable regardless of the ambient temperature owing to the wearing of the fire hood and helmet fit. Indeed, in Experiment L, a variation of the forehead temperature (40.0 ± 1.7 °C) at the end of exercise and recovery was significantly higher than those of the rectal (38.2 ± 0.3 °C) and foot temperature (38.2 ± 0.4 °C). According to Pandolf and Goldman (1978), if heat dissipation from the core to the environment is minimized by skin insulation or exposed to uncompensable heat stress conditions, T_{sk} will converge with T_c, and the temperature of the skin will eventually reflect changes in the T_c.

Furthermore, several studies have compared the consistency of cotton-insulated skin and rectal temperature (Bogh and colleagues, 1994, Thomas et al., 2004, Richmond et al., 2013). Bogh et al. (1994) reported that the insulated skin temperature measurement using cotton wool insulation material could not be replaced with T_{re}, especially during physical activity. That is, unless insulated material is adequately applied on the skin surface or measurement environment, the rectal temperature cannot be easily estimated. In contrast, Bernard and Kenney (1994) suggested that insulated skin temperature alone could be a surrogate measure of T_{re} using a copper disk covered with an insulator that is 4.2 cm in diameter and 0.8 cm thick. This indicates that the measurement site should be completely insulated. Thus, this study which observed a relatively high correlation in foot regions was consistent with Bernard and Kenny (1994) that the measurement region of skin temperature for non-invasive PSIs should be completely insulated from the ambient environment, which is similar to situations of the core temperature.

As Experiment M was performed to evaluate heat strain while wearing FPC and a cooling vest or drinking cooling water in the vest, this might result in the distribution of skin temperature being relatively lower or somewhat different than others. Thus, the $NIPSI_{33}$ could be more applicable in the situation without the efforts to reduce heat strain, even in heat exposure.

The comparison of the correlation for each skin region reveal that the correlations were distributed higher in the foot and toe temperature than in the forehead.

4.2.2 Validity between the non-invasive PSIs in different types of clothing

In addition to the results of 4.2.1, the validity of different clothing conditions was evaluated during exercise between neutral and hot environments (Figure 19). '*Daily clothes*' conditions were obtained from Experiments C, E, H, and K and added to the results.

Condition no.	**Experiment C–Experiment O**												
	C	D	E	F	G	H	I	J	K	L	M	N	O
1	25 **REST** *Daily clothes*	22 No SCBA	28 *Daily clothes* No-Menthol	32 FPE Pre-Relative	32 PPE (EU)	28 *Daily clothes*	33 FPE	32 FPE +SCBA	32 (50%RH) *Daily clothes*	32 Helmet (KOR)	30 CON	24 CON	33 CON
2	25 **REST** Tyvek	22 Heavy SCBA	28 *Daily clothes* Upper Body -Menthol	32 FPE Pre-Absolute	32 PPE (US)	28 Full FPE			32 (50%RH) Tyvek	32 Helmet (US)	30 Cooling	24 Water Repellent (M type)	33 CON + KF94
3	25 **REST** Vinyl	22 Light SCBA	28 FPE No-Menthol	32 FPE Post-Relative	32 PPE (JP)	28 No SCBA			32 (50%RH) Tychem	32 Helmet (JP)	30 Drinking	24 Water Repellent (T type)	33 PPC (Level D) + KF94
4	32 **REST** *Daily clothes*	22 Light SCBA +Wider Strap	28 FPE Face -Menthol	32 FPE Post-Absolute		28 No Helmet			32 (50%RH) Nylon		30 Cooling +Drinking		33 PPC (Level D) + N95
5	32 **REST** Tyvek	32 No SCBA	28 FPE Upper Body -Menthol			28 No Gloves			32 (70%RH) ***Daily clothes***				33 PPC (Level C) + N95
6	32 **REST** Vinyl	32 Heavy SCBA	28 FPE Whole Body -Menthol			28 No Boots			32 (70%RH) Tyvek				33 PPC (Level C) + PAPR
7	25 **EXE** *Daily clothes*	32 Light SCBA				28 No Jacket, Pants			32 (70%RH) Tychem				25 CON
8	25 **EXE** Tyvek	32 Light SCBA + Wider Strap				28 No Helmet, Hood, Boots, Gloves			32 (70%RH) Nylon				25 PPC (Level D) + KF94

9	25 **EXE** Vinyl												25 PPC (Level C) + N95
10	32 **EXE** *Daily clothes*												25 PPC (Level C) + PAPR
11	32 **EXE** Tyvek												
12	32 Exe Vinyl						n/a	Neutral *Daily clothes*	Neutral PPE	Hot *Daily clothes*	Hot PPE	Hot-humid *Daily clothes*	Hot-humid PPE

Figure 19. Environmental and clothing conditions in 13 experiments for different clothing and different environment. *Note: Colored boxes mean as follows: light grey—'Neutral'; medium grey—'Hot and moderate relative humidity'; black—'Hot and high relative humidity'. Clothing condition named 'Daily clothes' indicates cotton basic clothing; other PPEs consist of various PPC with Tyvek, Tychem, Nylon, Vinyl, FPE (Fire Protective Equipment). Each dotted box indicates 'Daily clothes' as a cotton basic clothing.

In addition, $NIPSI_{33}$ were strongly correlated with the original PSI in all the three environments (Table 15). Particularly, the correlation coefficients using foot temperature in $NIPSI_{33}$ ($r = 0.807$ in the hot and 50% RH, $P < 0.001$; $r = 0.809$ in the hot and 70% RH, $P < 0.001$) were significantly higher than in NIPSI ($r = 0.419$ in the hot and 50%RH, $P < 0.001$; $r = 0.590$ in the hot and 70%RH, p = 0.004). Moreover, the correlation coefficients were higher in $NIPSI_{33}$ (not only the foot temperature, but also the forehead ($r = 0.749$, $P < 0.001$) temperature) than in NIPSI ($r = 0.175$, p = 0.005) in the hot temperature with 50% RH. These results further confirm that fixing an initial temperature at 33 °C is more suitable for non-invasive PSI than using initial temperature of the skin temperature.

Table 15. Correlation coefficients of the original PSI with $NIPSI_{33}$ and NIPSI in neutral and hot environment with 50% RH and 70% RH at the last 3 min of exercise while wearing '*Daily clothes*' and 'PPE'

			$NIPSI_{33}$			NIPSI		
			Forehead	Foot	Toe	Forehead	Foot	Toe
Neutral	*Daily clothes*	*r*	0.754^{**}	0.715^{**}	0.744^{**}	0.620^{**}	0.661^{**}	0.757^{**}
		P value	<0.001	<0.001	0.001	0.002	0.001	0.001
		n	30	30	16	23	23	16
	PPE	*r*	0.897^{**}	0.971^{**}	0.972^{**}	0.887^{**}	0.957^{**}	0.925^{**}
		P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		n	101	101	59	100	100	59
Hot with 50%RH	*Daily clothes*	*r*	0.846^{**}	0.935^{**}		0.714^{**}	0.773^{**}	
		P value	<0.001	<0.001		0.003	0.001	
		n	15	15		15	15	
	PPE	*r*	0.749^{**}	0.807^{**}	0.853^{**}	0.175^{**}	0.419^{**}	0.828^{**}
		P value	<0.001	<0.001	<0.001	0.005	<0.001	<0.001
		n	313	265	147	261	213	147
Hot with 70%RH	*Daily clothes*	*r*	0.934^{**}	0.825^{*}		0.967^{**}	0.779^{*}	
		P value	0.002	0.022		<0.001	0.039	
		n	7	7		7	7	
	PPE	*r*	0.767^{**}	0.809^{**}		0.513^{*}	0.590^{**}	
		P value	<0.001	<0.001		0.021	0.004	
		n	20	22		20	22	

*Note: PPE—Personal protective equipment; RH—Relative humidity; *r*: Pearson correlation coefficient; NIPSI, Non-invasive physiological strain index; $NIPSI_{33}$, Non-invasive physiological strain index with fixed initial temperature to 33 °C. $^{*}P < 0.05$, $^{**}P < 0.001$.

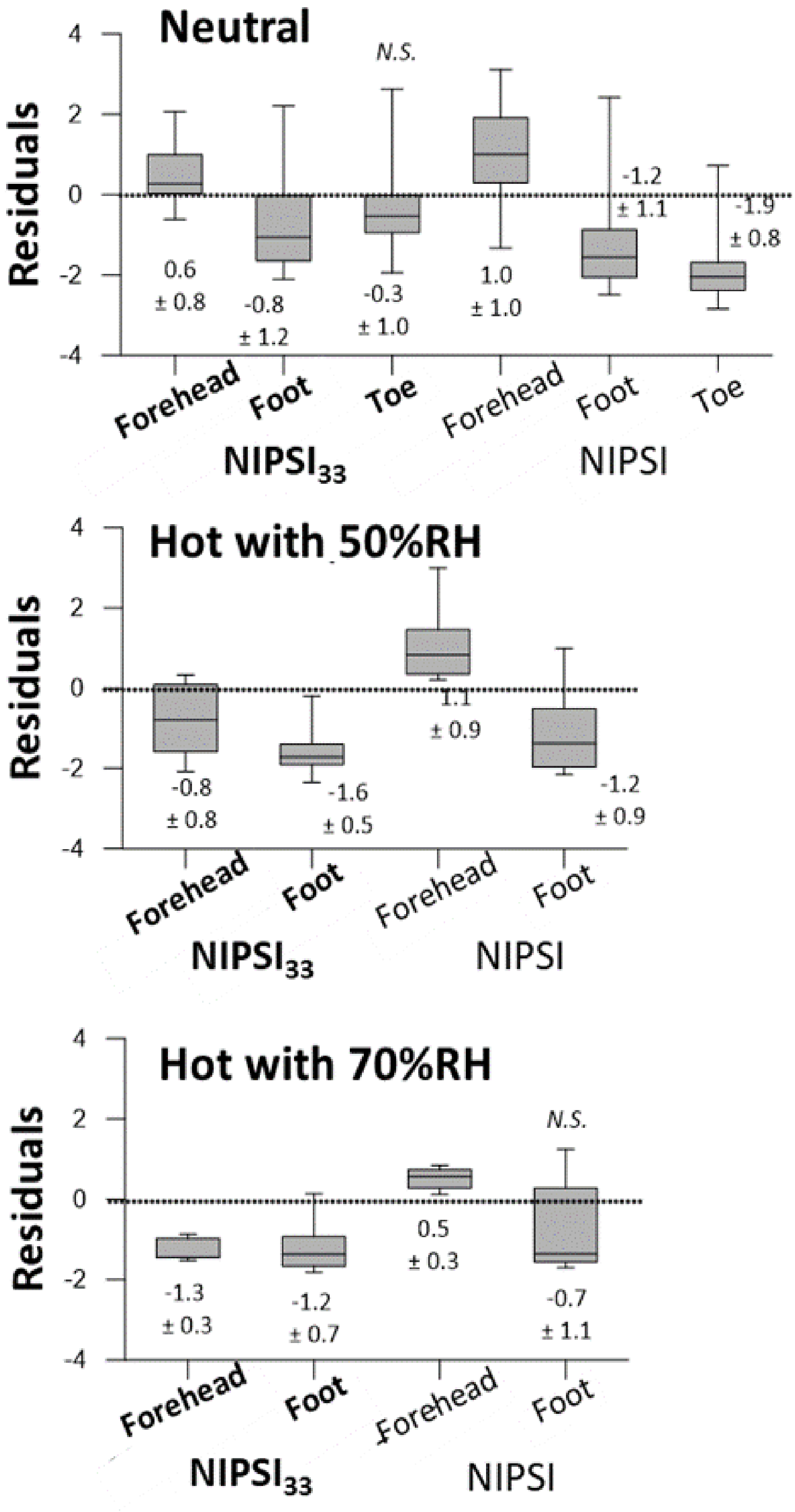

Figure 20. Residual distributions of each non-invasive PSIs in neutral and hot environments at 50%RH, hot environment at 70%RH when wearing '*Daily clothes*'. *Note: $NIPSI_{33}$ indicates a non-invasive physiological strain index using a fixed initial temperature of 33 °C.

The comparison of the two non-invasive PSIs revealed that $NIPSI_{33}$ exhibited higher correlations than NIPSI under all conditions. These results further confirm that it is more efficient to simplify the index without using the initial skin temperature. No significant difference was observed between the toe temperature at $NIPSI_{33}$ in neutral environments and '0'; foot temperature in hot and humid environments and '0' (Figure 20). The other indices show significant differences from zero except for those two indices ($NIPSI_{33\_\mathbf{toe}}$ in neutral and $NIPSI_{33\_\mathbf{foot}}$ in hot and humid environments). The diversity of experimental conditions in hot environment with 50%RH could be a reasonable reason for interpreting those significant differences (Mean ± SD in $NIPSI_{33}$: forehead: 0.6 ± 0.8; foot: -0.8 ± 1.2; toe: -0.3 ± 1.0 at neutral; forehead: 0.8 ± 0.8; foot: -1.6 ± 1.5 at hot with 50%RH).

4.2.3 Validity between various activities, environments, and clothing conditions

In this section, a validity test was conducted under different environments, clothing conditions, and activities using data from Experiment C, which consisted of all conditions categorized into eight conditions (Figure 21).

Condition no.	Experiment C–Experiment O												
	C	D	E	F	G	H	I	J	K	L	M	N	O
1	25 **REST** ***Daily clothes***	22 No SCBA	28 *Daily clothes* No-Menthol	32 FPE Pre-Relative	32 PPE (EU)	28 *Daily clothes*	33 FPE	32 FPE +SCBA	32 (50%RH) *Daily clothes*	32 Helmet (KOR)	30 CON	24 CON	33 CON
2	25 **REST** Tyvek	22 Heavy SCBA	28 *Daily clothes* Upper Body -Menthol	32 FPE Pre- Absolute	32 PPE (US)	28 Full FPE			32 (50%RH) Tyvek	32 Helmet (US)	30 Cooling	24 Water Repellent (M type)	33 CON + KF94
3	25 **REST** Vinyl	22 Light SCBA	28 FPE No-Menthol	32 FPE Post- Relative	32 PPE (JP)	28 No SCBA			32 (50%RH) Tychem	32 Helmet (JP)	30 Drinking	24 Water Repellent (T type)	33 PPC (Level D) + KF94
4	32 **REST** ***Daily clothes***	22 Light SCBA +Wider Strap	28 FPE Face -Menthol	32 FPE Post- Absolute		28 No Helmet			32 (50%RH) Nylon		30 Cooling +Drinking		33 PPC (Level D) + N95
5	32 **REST** Tyvek	32 No SCBA	28 FPE Upper Body -Menthol			28 No Gloves			32 (70%RH) ***Daily clothes***				33 PPC (Level C) + N95
6	32 **REST** Vinyl	32 Heavy SCBA	28 FPE Whole Body -Menthol			28 No Boots			32 (70%RH) Tyvek				33 PPC (Level C) + PAPR
7	25 **EXE** ***Daily clothes***	32 Light SCBA				28 No Jacket, Pants			32 (70%RH) Tychem				25 CON

8	25 **EXE** Tyvek	32 Light SCBA + Wider Strap				28 No Helmet, Hood, Boots, Gloves			32 (70%RH) Nylon				25 PPC (Level D) + KF94
9	25 **EXE** Vinyl												25 PPC (Level C) + N95
10	32 **EXE** ***Daily clothes***												25 PPC (Level C) + PAPR
11	32 **EXE** Tyvek							**REST**		**EXE**			
12	32 **EXE** Vinyl						n/a	Neutral *Daily clothes*	Neutral PPE	Hot *Daily clothes*	Hot PPE		

Figure 21. Various environments, clothing, and activities conditions in Experiment C. *Note: Meaning of colored boxes are as follows: light grey—'Neutral'; medium grey—'Hot and moderate relative humidity'. Clothing condition named '*Daily clothes*' indicates a cotton basic clothing (dotted box); other PPE consist of various PPC with Tyvek, Tychem, Nylon, Vinyl, FPE (Fire Protective Equipment).

Based on the above results, the NIPSIs was excluded in this session. The rest (sedentary posture during 60 min) and exercise (moderate-intensity exercise during 80 min) conditions were compared based on each $NIPSI_{33}$, it was confirmed that more indices and higher correlation coefficients were distributed under the exercise conditions (**Table 16**). Particularly, there were higher significant correlations when wearing PPE than when wearing '*daily clothes*' in hot and neutral environments (Figure 22A), and the $NIPSI_{33}$ using the foot temperature in all PPE conditions exhibited significant correlations ($0.760 < r < 0.992$, $P < 0.01$, Figure 22).

Table 16. Correlation coefficients of the original PSI with $NIPSI_{33}$ in the neutral, hot environment with 50% RH while wearing daily clothes and personal protective equipment at the last 3 min rest and exercise periods

			Rest		Exercise	
		$NIPSI_{33}$	Forehead	Foot	Forehead	Foot
Neutral	*Daily clothes*	r	0.675	-0.192	0.631	0.789*
		P value	0.067	0.648	0.129	0.035
		n	8	8	7	7
	PPE	r	0.512	0.760**	0.877**	0.992**
		P value	0.061	0.002	<0.001	<0.001
		n	14	14	13	13
Hot with 50%RH	*Daily clothes*	r	0.245	-0.458	0.545	0.880**
		P value	0.640	0.361	0.206	0.009
		n	6	6	7	7
	PPE	r	0.800**	0.795**	0.897**	0.962**
		P value	0.001	0.001	<0.001	<0.001
		n	13	13	16	16

*Note: PPE—Personal protective equipment; RH—Relative humidity; r: Pearson correlation coefficient; NIPSI: Non-invasive physiological strain index; $NIPSI_{33}$: Non-invasive physiological strain index with fixed initial temperature to 33 °C. $^{*}P < 0.05$, $^{**}P < 0.001$.

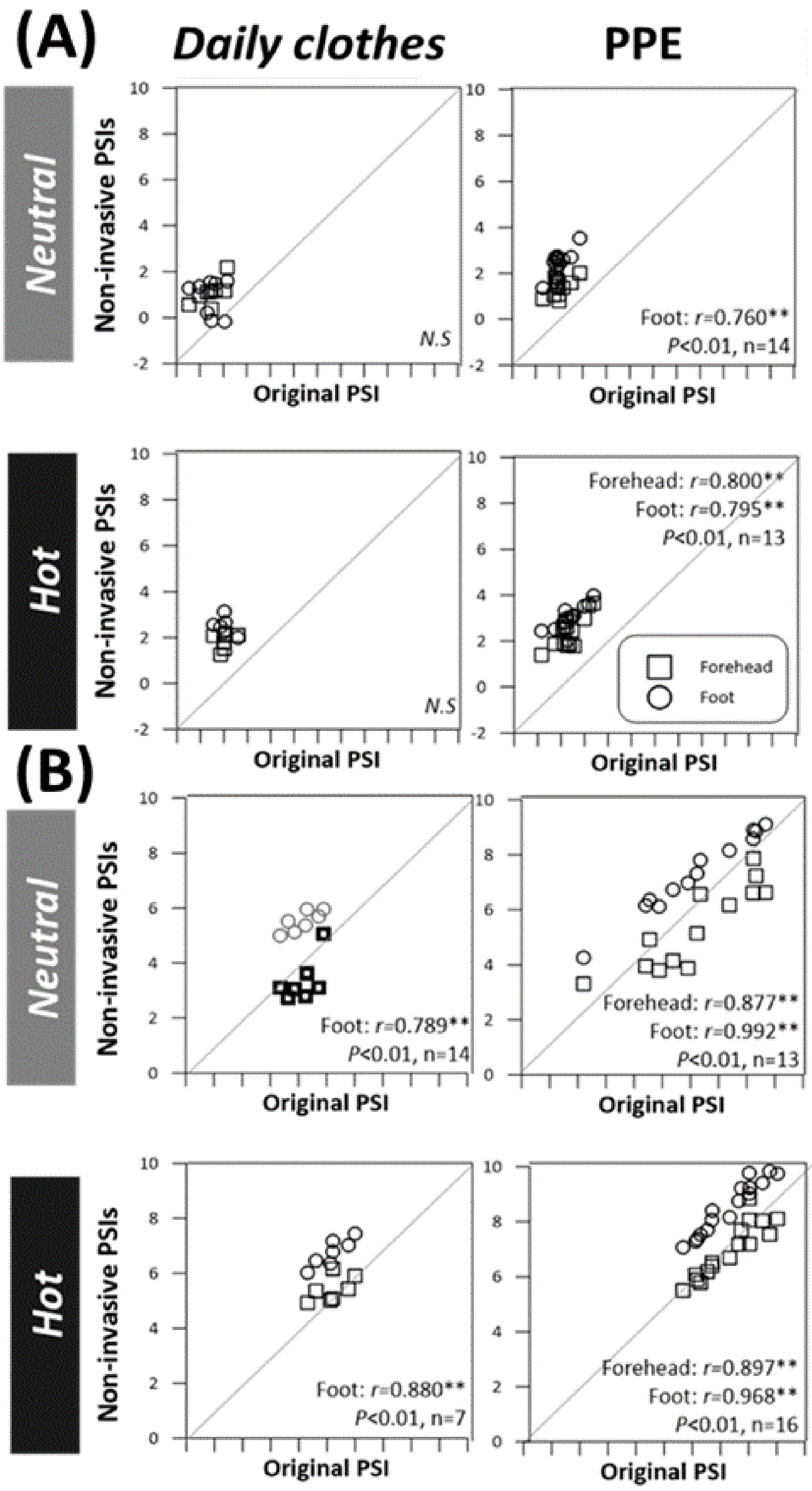

Figure 22. Correlation analysis of the original PSI with $NIPSI_{33}$ using forehead, foot skin temperature between different environment, different clothing, and different activity from Experiment C in rest (A) and exercise (B) conditions.

4.2.4 Summary

The validity test of the $NIPSI_{33}$ when wearing PPE during heat exposure was examined using data from ten experiments (Experiments C, D, F, G, I, J, K, l, M, and O) except conditions 4, 10 in Exp. C and condition 1 in Exp. K (see Table 11). The results revealed that the $NIPSI_{33}$ from ten experiments significantly correlated with the original PSI (r = 0.418–0.982, $P < 0.05$, $P < 0.01$, Table 17). Particularly, a higher correlation coefficient in the foot region (foot and/or toe) was observed in Experiments C, D, G, I, J, K, L, and O in the range from 0.800 to 0.995. Based on the findings of this study for the $NIPSI_{33}$, the foot temperature would be more suitable than the forehead temperature as a substitute for the rectal temperature. Additionally, it was confirmed that the non-invasive $NIPSI_{33}$ using the foot region (foot or toe) would be more applicable for the evaluation of the physiological strain during exercise than during rest and was also more suitable for wearing full-body PPE than basic cotton clothing (daily clothes) condition under heat stress (Figure 22).

Table 17. Correlation coefficients of non-invasive PSI_{33} with forehead, foot, and/or toe skin temperature under heat stress (air temperature: 30–33 °C)

	C (32 °C)		D (32 °C)			F (32 °C)			G (32 °C)		I (33 °C)		
Experiment	Forehead	Foot	Forehead	Foot	Toe	Forehead	Foot	Toe	Forehead	Foot	Forehead	Foot	Toe
r	0.982**	0.995**	0.902**	0.948**	0.939**	0.725**	0.669**	0.735**	0.812**	0.919**	0.866*	0.965**	0.957**
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.012	<0.001	0.001
n	29	29	31	31	31	50	49	52	24	24	7	7	7

Experiment	J (32 °C)			K (32 °C)		L (32 °C)		M (30 °C)		O (33 °C)	
	Forehead	Foot	Toe	Forehead	Foot	Forehead	Foot	Forehead	Foot	Forehead	Toe
r	0.895**	0.907**	0.902**	0.788**	0.878**	0.546*	0.800**	0.529**	0.418*	0.911**	0.965**
P value	<0.001	<0.001	<0.001	<0.001	<0.001	0.044	0.001	0.003	0.021	<0.001	<0.001
n	11	10	11	43	44	14	13	29	30	46	46

*Note: PPE, Personal protective equipment; RH, Relative humidity; *r*, Pearson correlation coefficient; NIPSI, Non-invasive physiological strain index; $NIPSI_{33}$, Non-invasive physiological strain index with fixed initial temperature to 33 °C. $^{*}P$<0.05, $^{**}P$<0.001.

Therefore, to summarize Part 2, a regression analysis was performed. Each region of frequency, standardization residuals, and regression line of the original PSI with non-invasive PSI_{33} presents in Figure 23. The non-invasive PSI_{33} on the toe exhibited the highest explanatory power of 0.864 and is the most reasonable index (Figure 23C).

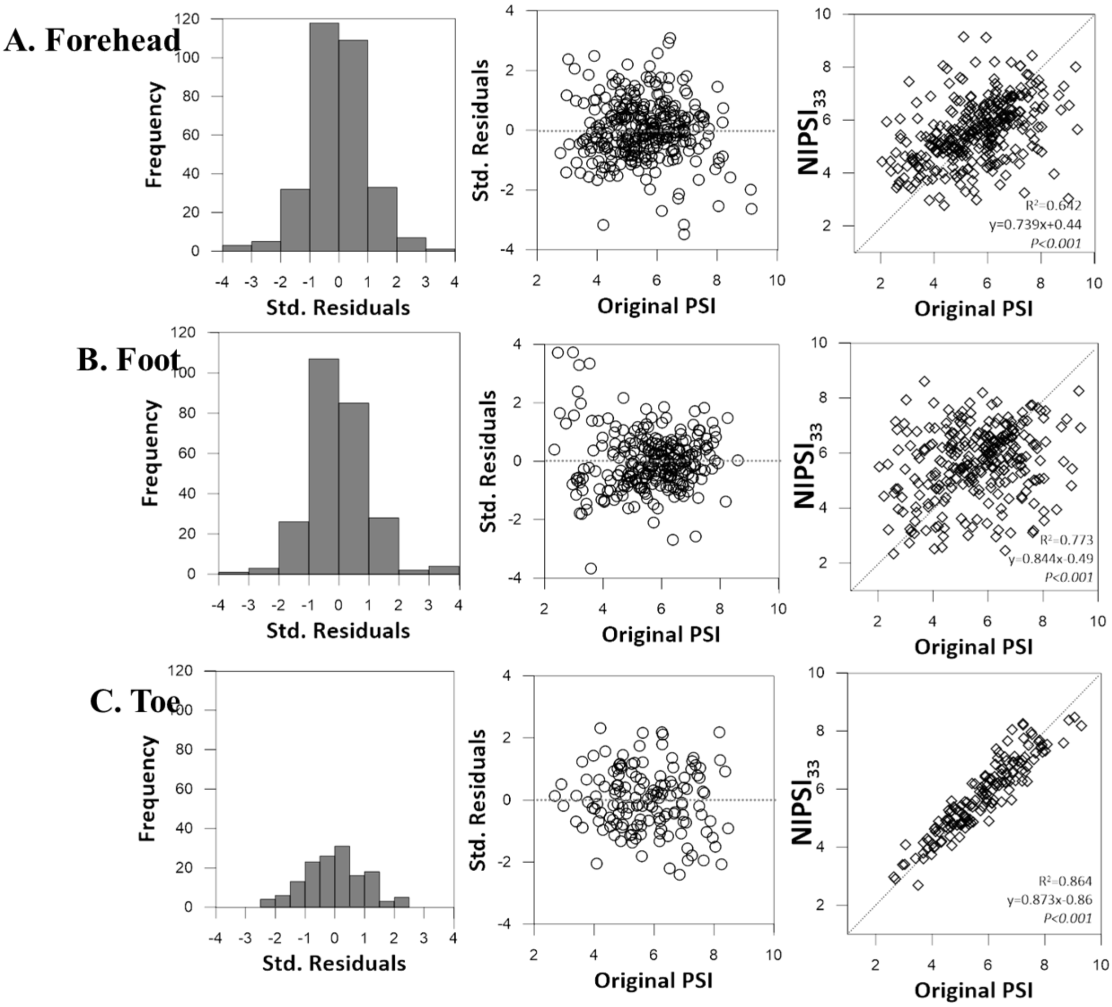

Figure 23. Residual analyses of the $NIPSI_{33}$ using forehead (A), foot (B), and toe (C) and the goodness of fit plot presenting the original PSI and non-invasive PSIs when wearing PPE during heat exposure.

Chapter 5. Summary and Conclusions

This study attempted to develop a non-invasive PSI to predict the heat strain during exercise when wearing full-body PPE under heat stress. To predict heat strain, Moran et al. (1998) developed the PSI, which can include both cardiovascular and thermoregulation response, and has been widely employed by several previous researchers. In addition, it has been used as an index for evaluating heat strain in the laboratory to date. However, despite the increasing importance of the real-time monitoring of individual workers, the invasiveness of the measurement of the rectal measurement has limited the further application of this method. In addition, it cannot be easily applied on the field despite the tremendous progress on the development of non-invasive measurement devices for core temperature. Therefore, this study explored a region of the non-invasive parameters in Part 1. The results revealed that the foot or toe temperature could be the most reliable parameter for rectal temperature replacement. particularly, the toe temperature was confirmed to be most consistent with the absolute value of rectal temperature. It seems most applicable to the foot area because when wearing PPE, the foot area is formed by shoes in a well-insulated environment like a core temperature environment. In addition, it is believed that the foot part is free from external inhibitory factors, such as sweat, and airflow experienced in the forehead part when wearing PPE.

The simplicity of the index was examined using the initial rectal temperature originally used in PSI, which was fixed to 33 °C based on the mean skin temperature in NIPSI using skin temperature and 37 °C based on the mean core temperature. The results revealed that the original PSI was most reasonably reflected in the index fixed to 33 °C rather than using the initial temperature.

■ Model 2 ($NIPSI_{33}$): Non-invasive PSI using 33 °C as the initial temperature

$$= 5\,(T_{sk}t - 33)\cdot(39.5 - 33)^{-1} + 5\,(HRt - HR0)\cdot(180 - HR0)^{-1} \quad \text{(Eq. 8)}$$

*$T_{sk}t$: the maximal value of skin temperature at time t period when is before 3 min from the time t

*HRt: the maximal value of heart rate at time t same, HR0: the initial value of heart rate

In Part 2, Model 2 with the foot, toe, and forehead verified the validity and reliability. First, among the skin temperature measurement regions, the toe temperature was the most reliable for replacing rectal temperature in the $NIPSI_{33}$. This study proposed the following equation as a NIPSI when wearing PPE under thermal stress.

■ Model 2 with the toe temperature ($NIPSI_{33\_toe}$)

$$= 5\ (T_{toe}t - 33)\cdot(39.5 - 33)^{-1} + 5\ (HRt - HR0)\cdot(180 - HR0)^{-1} \qquad \text{(Eq. 9)}$$

*$T_{toe}t$: the maximal value of skin temperature at time t period when is before 3 min at the end of exercise or recovery
*HRt: the maximal value of heart rate at t period same as skin temperature, HR0: the initial value of heart rate

This index is more valid when wearing protective clothing in hot environments and is less valid in daily wear and neutral or comfortable environments. Third, as this index was developed to estimate heat strain, such as hyperthermia, and as the initial temperature value is fixed, it is believed that it would not be suitable for early work or exercise. This is to estimate before reaching the rectal temperature risk level after a particular working time. Thus, this will be more reasonable in environments above 38.0 °C of the rectal temperature.

In conclusion, among the three regions (the forehead, foot, and toe), it was considered that the use of the temperature of the foot or toe is the most appropriate for the estimation of a workers heat strain. However, there are limitations on the conditions which can be applied to the $NIPSI_{33}$: 1) the environment temperature must be over 30 °C, 2) the environment wearing personal protective equipment, and 3) a state in which work or exercise over a certain period has been performed. This study is expected to contribute to the development of PPE, such as smart boots or wearable smart socks with sensors, that can be applied to smart wearable protection equipment in the future.

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초 록

서열 환경에서 개인보호복 착용 작업자의 서열부담 추정을 위한 비침습적 항목 탐색과 지표의 타당성 평가

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본 연구는 더운 환경에서 개인보호장비(Personal Protective Equipment: PPE)를 착용한 작업자를 대상으로 실시간 모니터링 시스템에서 활용할 수 있는 비침습적 생리학적 지표의 타당성을 탐색하고 평가하는 것을 목적으로 하였다. Moran et al. (1998)은 직장 온도(T_{re})와 심박수(HR)를 기반으로 생리적부담지수[Physiological Strain Index: PSI = 5 · ($T_{re}t$ - $T_{re}0$) · (39.5 - $T_{re}0)^{-1}$ + 5 · (HRt - HR0) · (180 - HR0)$^{-1}$] 처음 개발하였으며, 작업자의 서열부담 추정과 주로 실험실 환경에서 개별적 서열부담을 평가하는데 널리 사용되었다. 그러나, 직장온도 측정은 실제 작업현장에서 측정하기 쉽지 않으며, 작업자가 직접 센서를 삽입해야 한다는 단점이 있다. 이에 비침습적 측정을 통한 심부온 추정 방법이 많은 연구에서 제안되고 있다. 그러나 여전히 작업현장에서 활용되기엔 몇몇 기술적 한계가 존재한다. 따라서 이러한 한계점을 고려하여 본 연구에서는 보다 실용적이고 비침습적 생리부담 지표를 제시하는 것을 목표로 하였다. 본 연구는 두 부분으로 구성되었다. Part 1에서는 고온 환경에서 PPE를 착용 시 발생하는 서열부담을 평가하기 위해 실험[A(2018), B(2019)]를 각각 수행하였다. 실험 A는 9명 피험자가 기온 28 °C, 33 °C, 38 °C 및 상대습도 70%인 3가지 환경조건에서 일상복과 전신보호복(Level D, Tyvek)인 2가지 의복조건에 참여하였다. 실험A는 총 80분간 (10분 휴식-60분 운동-10분 회복)으로 구성되었다. 실험 B는 7명의 피험자가 기온 33 °C 및 상대습도70% 환경에서 4가지 다른 보호 수준의 PPE조건에 참여하였다. 실험B는 10분간 안정 후 직장온도 39 °C에 도달할 때까지 운동을 지속하였다. 실험 A와 B의 결과를 바탕으로 기존 PSI식의 직장온도를 대체할 비침습적 항목을 선정하였으며, 총

3가지의 비침습적 PSI식으로 수정되었다. 비침습적 식의 타당성 검사를 위해 기존 PSI식과 새로 수정된 비침습적 추정식을 비교하여 상관관계 및 일관성 분석을 수행하였다. Part 1의 결과, 직장온도를 대체할 수 있는 비침습적 측정항목으로 이마, 발 또는 발가락으로 나타났다. 비침습적 식 중 Model 2 ($NIPSI_{33}$)가 기존 PSI와 가장 높은 상관관계와 일관성을 보였다. 또한 Model1 (NIPSI)도 함께 분석하여 Model 2 ($NIPSI_{33}$)를 사용하는 것보다 더 정확한 개별 모니터링이 가능한지 확인하였다.

$$\text{Model 1 (NIPSI)} = 5\,(T_{sk}t - T_{sk}0)\cdot(39.5 - T_{sk}0)^{-1} + 5\,(HRt - HR0)\cdot(180 - HR0)^{-1}$$

*$T_{re}t$는 $T_{forehead}$, T_{foot}, 또는 T_{toe}로 대체되며, $T_{re}0$ 은 초기 피부온도인 $T_{sk}0$로 대체됨.

$$\text{Model 2 } (NIPSI_{33}) = 5\,(T_{sk}t - 33)\cdot(39.5 - 33)^{-1} + 5\,(HRt - HR0)\cdot(180 - HR0)^{-1}$$

*$T_{re}t$는 $T_{forehead}$, T_{foot}, 또는 T_{toe}로 대체되며, $T_{re}0$ 은 33 ˚C로 초기온도를 고정함.

Part 2는 실험 A 및 B와 겹치지 않는 새로운 13개 실험의 데이터 세트를 수집하여 분석에 사용하였고, Part 1에서 도출된 비침습적 추정식의 타당성을 검증하였다. 총 123명의 피험자에게서 얻어진 직장온도, 피부온도, 심박수를 사용하여 기존 PSI와 Model 1, Model 2를 비교하였다. Part 2의 결과, Model 1 (NIPSI)보다 Model 2 ($NIPSI_{33}$)가 기존 PSI와 더 높은 상관을 보였다. 발 또는 발가락 온도를 사용한 대부분의 비침습적 추정식이 이마보다 더 큰 타당성을 보였다. 따라서 본 연구는 세 부위(이마, 발, 발가락) 중에서 발 또는 발가락 온도를 이용하는 것이 작업자의 서열부담을 추정하는데 가장 적합할 것으로 사료된다. 다만, Model 2 ($NIPSI_{33\_\ 발가락/발등}$)에 적용할 수 있는 조건에는 한계가 존재하며, 1) 환경온도 30 °C 이상의 환경조건 시, 2) 개인보호구 착용 시, 그리고 3) 일정 시간에 걸쳐 작업 또는 운동이 수행된 경우, 본 연구에서 도출된 비침습적 추정식이 적용될 수 있음을 확인하였다. 본 연구논문은 고온환경에서 전신보호복을 착용하는 작업자들의 서열부담을 추정하여 열 질환을 예방할 수 있는 실시간 서열부담 모니터링 시스템의 개발에 도움이 될 수 있을 것이다.

주요어: 서열부담, 전신 보호복, 생리부담지수, 비침습적, 피부온, 심박수