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Evaluation of Effectiveness of a Water-perfused Suit as an Alternative Heat Acclimation Strategy

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고 예 린

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이 논문을 생활과학석사 학위논문으로 제출함

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서울대학교 대학원

의류학과

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고예린의 생활과학석사 학위논문을 인준함

2020 년 1 월

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Abstract

Heat acclimation (HA) refers to physiological and behavioral changes that can help increase heat tolerance so that the human body can more effectively dissipate heat to the environment. While active HA strategies have been robustly explored, not many studies highlighted passive HA strategies. The purpose of the present study was to evaluate the effects of 10-day passive and post-exercise heat acclimation strategies through directly heating the skin with a water-perfused suit for 10 days. A low-intensity exercise-intervention was included as a control condition. Nineteen young males were divided into three experimental groups: (1) Exercise condition (control) ($N = 6$, HA_{EXE}, 1-h exercise at 6 km·h^{-1} followed by 1-h rest in a sitting position), (2) Exercise & Passive heating condition ($N = 6$, $HA_{EXE+SUIT}$, 1-h exercise at 6 km·h^{-1} followed by 1-h passive heating in a sitting position), and (3) Passive heating condition ($N = 7$, HA_{SUIT}, 2-h passive heating in a sitting position). All heating programs were conducted for 10 consecutive days in a climatic chamber maintained at an air temperature of 33°C with 60% relative humidity. The passive heating was conducted using a newly-developed water perfused suit with 44°C water. A heat tolerance test before (PRE) and after (POST) the 10-day training consisted of a leg immersion in 42°C water for 60 min. The results showed that the suit-wearing for 10 days as passive and post-exercise HA strategies effectively induced adaptive changes in rectal temperature ($P < 0.05$), mean skin temperature ($P < 0.05$), sweat responses ($P < 0.05$), and cardiovascular responses ($P < 0.05$). Interestingly, increase in back sweat rate and rectal temperature reduction were only found in the passive-heating condition ($P < 0.05$) after the 10-day training. There were differences in the passive and the post-exercise strategies in inducing HA, in terms of the induction timing during the protocols and the number of training days needed. These results indicate that this novel means of heat acclimation, donning a skin-heating water-perfused suit, can generate thermoregulatory benefits. The passive HA intervention could be applied to individuals for whom doing exercise regularly is not feasible.

Keywords: Heat acclimation, Water-perfused suit, Passive heat acclimation strategy, Post-exercise heat acclimation strategy

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List of Abbreviations

BP	Blood pressure
DBP	Diastolic blood pressure
HA	Heat acclimation
HA_{EXE}	Active heat acclimation strategy
$HA_{EXE+SUIT}$	Post-exercise heat acclimation strategy
HA_{SUIT}	Passive heat acclimation strategy
HF	Heat flux
HR	Heart rate
PSI	Physiological strain index
RH	Relative humidity
RPE	Rating of perceived exertion
T_{air}	Air temperature
T_{re}	Rectal temperature
$\bar{T}_{sk}$	Mean skin temperature
T_{wi}	Water inflow temperature
T_{wo}	Water outflow temperature
VO_{2max}	Maximal oxygen consumption

Chapter 1. Introduction

Thermal strain on the human body can accumulate through physiological and perceptual stress in hot environments, in which the body temperature has to be effectively regulated. Among various countermeasures to lessen physiological strain in such environments, heat acclimation (HA) training has been highlighted as the most significant (Racinais et al. 2015; Tyler et al. 2016). Heat acclimation refers to physiological and behavioral changes that can help increase heat tolerance so that the human body can more effectively dissipate heat to the environment. Heat adaptations in the central and peripheral levels include the following physiological and perceptual hallmarks: earlier sweating onset, higher sweat output, lower body core temperature, lower heart rate, or alleviated perceptual strain (Daanen et al. 2018; Tyler et al. 2016). Obtaining these responses is especially desirable for athletes or workers who have to perform tasks in heat (Casadio et al. 2017; Périard et al. 2015), but not only to them; it may be a matter of great importance to other ordinary people as well whose heat tolerance should be improved due the climate emergency.

To induce heat adaptation, sufficient thermal stress exceeding an adaptation threshold, should be elicited; methods of producing thermal stress are classified into endogenous (active HA strategies) and exogenous thermal loads (passive HA strategies). Most studies on heat acclimation have been geared toward exercise-based active strategies, which conventionally consist of a daily bout of exercise increasing body core temperature for 1–2 h in an artificially hot environment (Garrett et al. 2009; Nadel et al. 1974). It seems reasonable to say that the effectiveness of active heat acclimation strategies for athletes has already solidly been proven, and research on heat acclimation has now been moving toward developing optimal models for active heat adaptation. This research focuses on the effects of varying duration (Kirby et al.

2019), frequency (Willmott et al. 2016), exercise intensity (Houmard et al. 1990; Schmit et al. 2018; Wingfield et al. 2016), climatic conditions (Griefahn 1997), and population (Best et al. 2014).

While active HA strategies have been widely used and extensively documented, relatively limited data are available on passive HA strategies. Studies advocating passive HA strategies, subjecting individuals to heat stress without any exercise mainly by hot water immersion (Shin et al. 2013), entering a heat chamber (Pallubinsky et al. 2017), or sauna (Stanley et al. 2015), reported physiological and perceptual changes similar to those actively induced. These studies suggested that active strategies are not necessary to induce HA, as the main stimulus for heat adaptation is simply a repeated rise in body core temperature (Heathcote et al. 2018), showing that non-exercise-based heat adaptation training may be a practical and effective alternative to traditional regimens (Heathcote et al. 2018). Passive heat exposure is also recommended to be used post-exercise as a way of maintaining or slightly elevating body core temperature that was increased during exercise (Scoon et al. 2007; Stanley et al. 2015; Zurawlew et al. 2016), so that actively-induced HA responses can be augmented. Casadio et al. (2016) mentioned that passive heat exposure post-exercise can be a more practical HA strategy for elite athletes who have difficulties in inducing HA by applying active HA strategies only. However, whether HA elicited by post-exercise passive heating corresponds to the one actively induced are yet to be further demonstrated (Daanen et al. 2018).

Even though the aforementioned studies have helped direct attention to passive HA strategies, this has been a relatively neglected area of research, and there have been limited efforts to diversify the methods of exogenous thermal stimulation. In the present study, we propose directly heating the skin using a water-perfused suit

as another passive heat acclimation strategy, in addition to existing passive methods (hot water immersion or environmental heat exposure). A water-perfused suit refers to a garment having tubes inside in which hot or cold water circulates, so that the garment can heat or cool the skin. Previous investigations on the thermo-physiological effects of water-perfused suits included focuses on age-related differences in cardiac functions (Wilson et al. 2010), thermosensitivity of the peripheral skin sites (Filingeri et al. 2017), vascular responses (Yamazaki and Sone 2006), and metabolic responses (Rowell et al. 1969).

Despite its extensive use in manipulating skin and body core temperatures, to the best of our knowledge, there is little research highlighting the potential benefits of utilizing a water-perfused suit as a heat acclimation (HA) strategy. Therefore, whether wearing the suit can be an alternative method to induce heat acclimation is not known, which motivated the present study. One might address that utilizing a water-perfused suit may be less practical than the established passive HA strategies. However, we believe that heat acclimation induction using clothing may have the following advantages, whose effectiveness thus is worthy to be examined: site-specific heating, easiness of temperature control, availability of double heating during exercise, and applicability to smart clothing. Last but not least, the fact that it is possible to estimate heat flow through the suit during passive heating can be another notable advantage, as it can be compared to heat production by exercise. This kind of comparison is not available in the existing methods to produce passive heat exposure. Finally, expanding possible options for passive heat exposure to induce HA can also be beneficial to those whose HA should be induced by low-intensity exercise or no exercise in the heat, such as the old and the disabled.

In the present study, two possible applications for the novel means of inducing HA were considered: skin-heating with the suit only (a passive strategy) and wearing the suit after exercise (a post-exercise strategy). The current study therefore aimed to evaluate how effective skin-heating using a water-perfused suit is in inducing heat acclimation when applied passively and after exercise. Whether it can be an alternative heat acclimation strategy was examined compared to a control intervention, which was a low-intensity exercise without suit-wearing after exercise. The effectiveness of the suit as HA strategies was investigated by comparing physiological and perceptual responses before and after 10-day heat acclimation training (pre- and post- heat tolerance tests), and by exploring heat adaptive changes in those responses during the 10-day intervention. The present study hypothesized that (1) heat acclimation will be obtained after 10 days of skin-heating passive heat acclimation training using a water perfused suit, (2) heat acclimation will be further acquired from an additional session of suit-wearing after exercise, and (3) the passive heat acclimation strategy using the suit will be less beneficial than the post-exercise strategy, and (4) differential effects of heat acclimation induction between the passive and post-exercise strategies would exist.

Chapter 2. Methods

2.1. Subjects

A total of 19 non heat-acclimatized young males participated in this study. All of them were Korean and lived in Seoul. Subjects were randomly assigned to one of three experimental groups: a control group who exercised followed by rest (HA_{EXE}: $N = 6$); a post-exercise HA group who wore water-perfused suits sitting down after exercise ($HA_{EXE+SUIT}$: $N = 6$); a passive HA group who wore a skin-heating water-perfused suit without any exercise (HA_{SUIT}: $N = 7$). The three groups were matched for age, height, body weight, body surface area, self-identified heat tolerance, and maximal oxygen consumption (Table 1). The matching was conducted using one-way ANOVA in SPSS, to make no statistical differences in these characteristics between the groups. In the recruiting process, subjects with cardiovascular, respiratory, or heat-related illnesses or symptoms were pre-screened. All subjects were required to abstain from strenuous exercise, alcohol and caffeine consumption 24-h before and eating food 3-h before each visit to the laboratory.

Table 1 Characteristics of subjects in each experimental group

	HA_{EXE} ($N = 6$)	$HA_{EXE+SUIT}$ ($N = 6$)	HA_{SUIT} ($N = 7$)	*P*-value
Age (yr)	22 ± 2	22 ± 2	24 ± 2	N.S.
Height (cm)	172.4 ± 2.2	174.8 ± 5.0	175.7 ± 6.0	N.S.
Body weight (kg)	69.5 ± 7.9	69.1 ± 10.2	71.7 ± 10.4	N.S.
Body surface area (m^2)	1.9 ± 0.1	1.9 ± 0.1	1.9 ± 0.1	N.S.
Self-identified heat tolerance	3 ± 2	3 ± 2	4 ± 1	N.S.
$\dot{V}O_{2max}$ ($mL \cdot min \cdot kg^{-1}$)	47.5 ± 9.1	46.6 ± 6.8	47.5 ± 1.5	N.S.

Note: All data are expressed as mean ± SD (standard deviation).

Self-identified heat tolerance was obtained using a seven-point scale (1: I am very susceptible to heat; 2: I am susceptible to heat; 3: I am a little susceptible to heat; 4: I am neither susceptible nor tolerant to heat; 5: I am a little tolerant to heat; 6: I am tolerant to heat; 7: I am very tolerant to heat). Body surface area was estimated by using the equation from Lee et al. (2008). Explanation of the aims, procedures, discomforts and risks of the current study was provided, and signed prior informed consent was obtained from each subject. All procedures of the present study were approved by the Institute Review Board of Seoul National University (IRB No. 1905/003-008).

2.2. Newly-developed water-perfused suit

Water-perfused suits were developed for the present experiments. The suit consisted of a detachable inner layer of nylon-spandex mesh (Nylon 85% and Polyurethane 15%) and a flexible polyester outer layer (Polyester 92% and Polyurethane 8%) (Fig. A1). After drawing the sections on the inner layer of the suit, a total of 30.9 m of PVC tubing (inner diameter 4 mm and outer diameter 6 mm) was inserted into the small holes of the inner mesh layer (Fig. A2). Four sets of couplings (PMCD 1702 and PMCD 2202, Colder Products Company, USA) were then positioned, to connect and disconnect the suit and the bath pump (① Inflow, suit and pump; ② Inflow, jacket and pants; ③ Outflow, jacket and pants; ④ Outflow, suit and pump) (Fig. A2). We adopted a spiral structure as a heating element (Fig. A3), which made it possible to assign one bath pump to each person. The water-perfused suit heated the chest (contact area: 436.3 cm^2), abdomen (350.9 cm^2), upper and lower back (970.2 cm^2), front and back thighs (1098.6 cm^2) (Fig. 1A). Peripheral body sites (hands, arms, legs and feet) were not heated in order to optimize the rate of water circulation.

To circulate warm water throughout the suit (water inflow temperature (T_{wi}) of 44.2°C; water flow rate of 37.3 ± 0.9 L·h^{-1}), a heated bath pump was connected and utilized (Fig. 1B) (RW-0525G, Jeio tech, Korea, a resolution of 0.1°C).

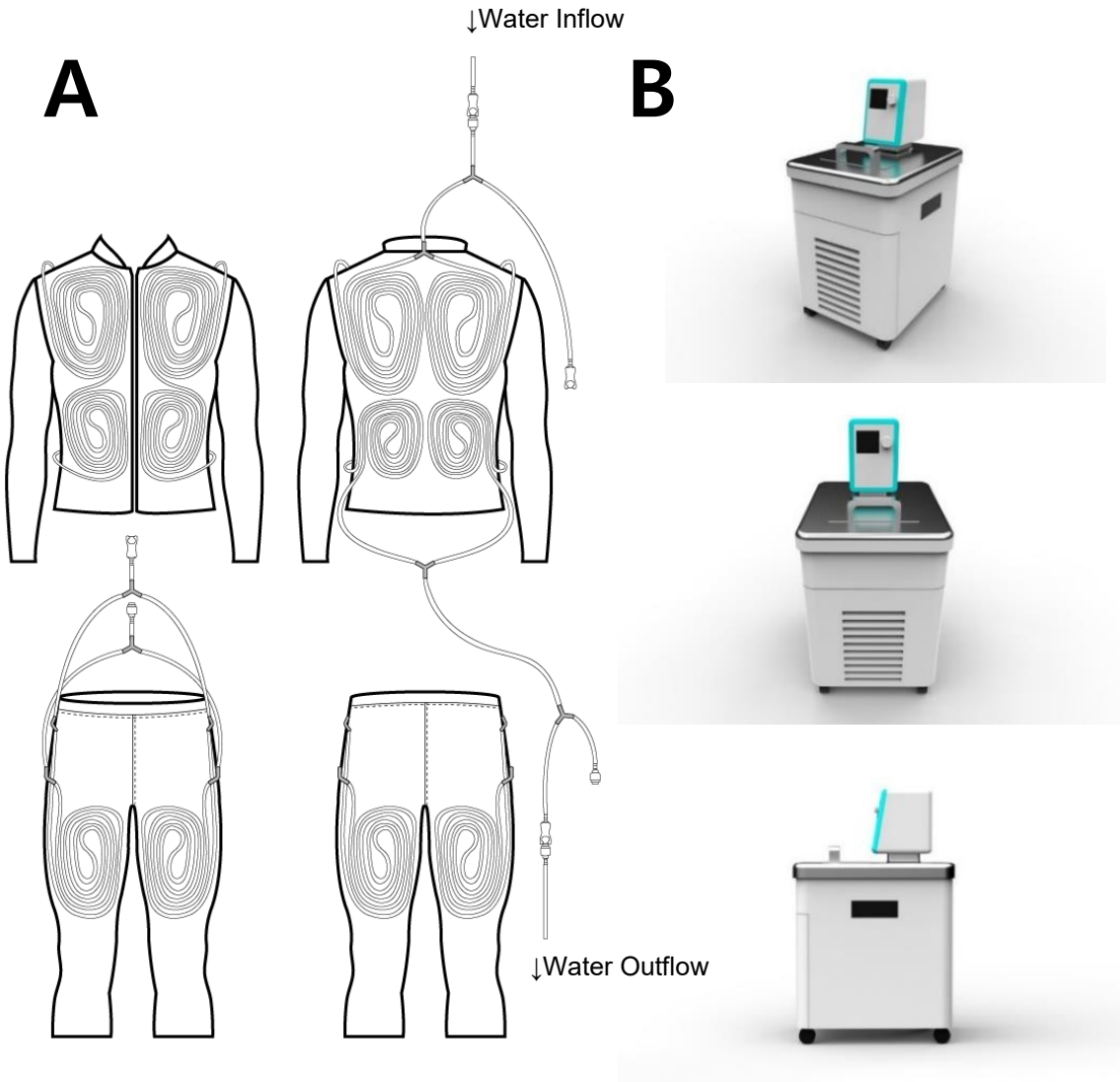

Fig. 1 Structure of a developed water-perfused suit (A) and a bath pump (B).

The donning process included the following steps: Firstly, after wearing the jacket and the cropped pants of the suit (Fig. A4A), subjects wore knee-length socks to cover their calves (Fig. A4B). Secondly, to enhance the efficiency of heat transfer from the circulating water to the skin, the flexible outer layer of the jacket was pinned before each trial so that the suit can tightly fit to each subject's body (Fig. A4C). Thirdly, two elastic bands (one around the chest and the other around the waist) were worn on the jacket to press the tubing against the skin (Fig. A4C). Next, a vapor-impermeable insulating jacket and pants (Polyester 100%, PVC coating) were donned over the suit (Fig. A4D) to minimize evaporative and radiant heat loss from the body. Finally, the suit was connected to a water pump bath (Fig. A4E).

2.3. 10-day heat acclimation training programs

2.3.1. Experimental procedures

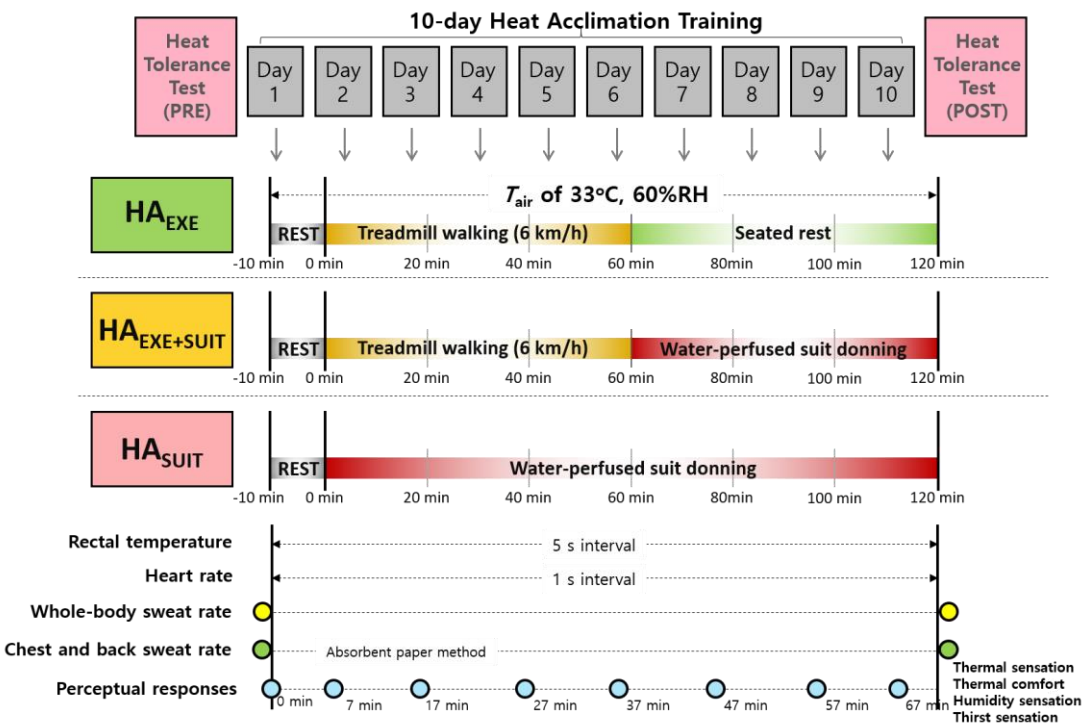

Fig. 2 Experimental protocols of each 10-day program and measurements.

All subjects participated in an HA training program for 10 consecutive days (Fig. 2) (Fig. A5). Each subject was trained for his assigned 2-h heat exposure protocol (HA_{EXE} or $HA_{EXE+SUIT}$ or HA_{SUIT}) which they followed for the 10-day HA intervention. Upon arriving at the laboratory in the morning, each subject was provided with 300 mL water and took a rest after wearing appropriately sized identical undershorts, shorts and socks. They were instructed to bring their own running shoes every day. Subjects in HA_{EXE} and $HA_{EXE+SUIT}$ waited in the preparation room wearing the set of experimental clothing before beginning their trials. Approximately 10 min before starting a trial, HA_{SUIT} took off the shorts and changed into water-perfused suits in a preparation room. For each trial, baseline rectal temperature and heart rate were checked to make sure the values were within normal ranges before entering the climatic chamber (maintained at 33°C with 60% relative humidity) (Fig. 2).

For the first one hour of the intervention subjects in HA_{EXE} and $HA_{EXE+SUIT}$ walked on a treadmill at 6 $km \cdot h^{-1}$ with 0% grade (2 repetitions of 25-min walking and 5-min break). During the first break they took a seated rest on a stool (Fig. A6A). After finishing the second walking session, during the second 5-min break $HA_{EXE+SUIT}$ changed into a water-perfused suit, while HA_{EXE} maintained a standing posture before starting a seated rest for the rest of the one hour. As subjects in HA_{EXE} were in the heat chamber during the 1-h rest period, they were passively heated too, after exercise. However, in this paper, "passive heating" only refers to 'skin-heating using a water-perfused suit' to avoid confusion. $HA_{EXE+SUIT}$'s post-exercise passive heating session lasted for the second one hour of the program (2 repetitions of 25-min heating and 5-min break) and was initiated by connecting the bath pump to the suit to allow inflow of warm water. Subjects in HA_{SUIT} were passively heated using

a water-perfused suit for two hours (4 repetitions of 25-min heating and 5-min break). Under the passive heating condition, a 5-min break was given by disconnecting the suit from the water pump and by instructing the subjects to unzip the insulating jacket (Fig. A6B).

The intensity of exercise (6 $km \cdot h^{-1}$) and the water inflow temperature of the suit (44.2°C) were decided based on the preliminary tests: (1) T_{wi} of 44.2°C increased rectal temperature by approximately 0.5°C for 1 h and by 1.5°C for 2 h, respectively; (2) 1-h walking at 6 $km \cdot h^{-1}$ which elevated rectal temperature by 1.0°C was thus chosen as the exercise intensity for the control group, to make rectal temperature increment of $HA_{EXE+SUIT}$ and HA_{SUIT} equivalent for the 2-h exposures. Subjects drank a total of 600 ml water *ad libitum* during the HA program. Only after completing the 2-h HA protocols all subjects exited the climatic chamber.

2.3.2. Measurements and calculations

During the 10-day HA program, rectal temperature (T_{re}) was measured every 5 s using a rectal probe (LT ST08-11, Gram Corporation, Japan) which was inserted 16 cm beyond the anal sphincter and recorded by a data logger (LT-8A, Gram Corporation, Japan). Heart rate (HR) was monitored every 1 s using a polar electrode with a chest belt (RC3 GPS, Polar Electro, Finland) and the data were sorted out at the interval of 5 s. Whole-body sweat rate was estimated using a change in total body mass which was measured in a semi-nude state on a calibrated scale (ID2, Mettler-Toledo, Germany: resolution of 1 g) before and after the experiment. The body mass loss due to respiratory water loss was not considered significant. Chest and back sweat rate were estimated by the change in the weight of thirty sheets of moisture absorbent papers (4 cm × 4 cm) applied to those areas. Before and after each trial,

the absorbent papers were weighed on an electronic scale (ENTRIS 224i-1S, Sartorius, Japan). The bottom of the papers was directly applied to the skin but the top was covered with vinyl film secured with surgical tapes to minimize sweat evaporation during the experiment.

Perceptual responses were obtained every 10 min using the following scales: nine-point thermal sensation (4: very hot, 3: hot, 2: warm, 1: slightly warm, 0: neutral, -1: slightly cool, -2: cool, -3: cold, and -4: very cold); seven-point humidity sensation (3: very wet, 2: wet, 1: a little wet, 0: not both, -1: a little dry, -2: dry, -3: very dry); seven-point thirst sensation (3: very thirsty, 2.5, 2: thirsty, 1.5, 1: a little thirsty, 0.5, 0: not thirsty at all). Rating of perceived exertion (RPE) was obtained according to the Borg scale (Borg, 1982). Physiological strain index (PSI) was calculated using the equation from Moran et al. (1998) <Eq. 1>. Peak PSI was calculated averaging the previous 5-min data at the time the maximum appeared. Heat flow (HF) through the water-perfused suit during the passive heating session was calculated using the following heat flow equation <Eq. 2>. Heat flow was then converted to watts (1 $kcal \cdot h^{-1}$ = 1.163 watts).

Physiological strain index (PSI)

$$= 5(T_{ret} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \quad \cdots\cdots\cdots \quad \text{<Eq. 1>}$$

where T_{ret}: rectal temperature at time t (°C); T_{re0}: rectal temperature at 0 min (°C); HR_t: heart rate at time t (bpm); HR_0: heart rate at 0 min (bpm).

$$\text{Heat flow (HF) } (kcal \cdot h^{-1}) = h_w \cdot C_w \cdot (T_{wi} - T_{wo}) \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad \text{<Eq. 2>}$$

where h_w: water flow rate of the suit ($L \cdot h^{-1}$);
C_w: water specific heat = 1 $kcal \cdot kg^{-1} \cdot {}^{o}C^{-1}$;
T_{wi}: water inflow temperature (°C); T_{wo}: water outflow temperature (°C).

2.4. Heat tolerance pre- and post-tests

2.4.1. Experimental procedures

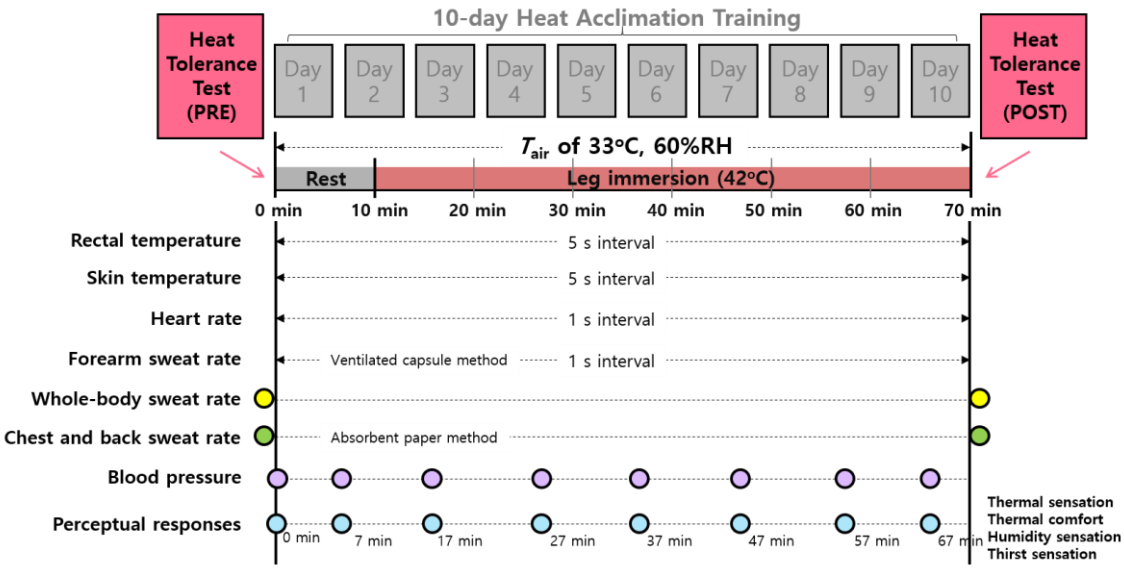

Fig. 3 Experimental protocol of the pre- and post- heat tolerance tests and measurements.

One day before (PRE) and one day after (POST) the 10-day HA program, all subjects participated in an identical heat tolerance test in the morning (Fig. 3) (Fig. A7). When arriving at the laboratory, subjects were provided with 300 mL of water and took a rest in a preparation room. To check hydration, a urine sample was obtained and the specific gravity was analyzed. Subjects were all dressed in appropriately-sized shorts, undershorts (all cotton 100%, 0.21 estimated clo) and backless slippers. After instrumentation for physiological measurements, they moved into a climatic chamber maintained at 33°C and 60% relative humidity (Fig. 3). Hot water leg immersion method was used as the heat tolerance test (Wijayanto et al. 2011), which consisted of a 10-min seated rest on a stool followed by a 60-min leg immersion in 42°C water (Fig. 3). All experiments were conducted between February 2019 and March 2019, which corresponds to late winter and early spring in Korea, to minimize

natural summer heat acclimatization. The average outside air temperature in Seoul was 4.1 ± 4.5°C with 48.2 ± 14.8%RH during the experimental period.

2.4.2. Measurements and calculations

While subjects were immersing both legs into a circulating bath, T_{re}, skin temperatures, heart rate, and forearm sweat rate were continuously monitored (Fig. 3). Rectal temperature was measured using the same probe used in the HA program inserted 16 cm. Skin temperatures on the seven sites (the forehead, abdomen, forearm, hand, thigh, calf, and foot) were measured every 5 s by thermistor probes (LT ST08-12, Gram Corporation, Japan). Rectal and skin temperature were recorded with the same data logger utilized in the HA program. Mean skin temperature (T_{sk}) was calculated using the Hardy and Dubois' equation (Hardy et al. 1938). Heart rate was monitored every 1 s using the same sensor and the receiver used in the 10-day intervention (Fig. 3). Forearm sweat rate was continuously monitored every 1 s using perspiration meters with ventilated capsules having a 0.25 cm^2 surface area (SKN-2000 perspiration meter, SKINOS, Japan) (Fig. 3). Whole-body sweat rate and local sweat rate on the chest and the back were estimated using the same methods as 10-day heat acclimation training. Systolic and diastolic blood pressure were measured at the 10-min interval using an automatic sphygmomanometer (JPN 1, Omron Corporation, Ltd., Japan). Perceptual responses (nine-point thermal sensation, seven-point humidity sensation, seven-point thirst sensation) were obtained at the 10-min interval.

2.5. Data analyses

For analytical and graphical purposes, all temperature, heart rate, and forearm sweat rate data were averaged into 5 min. For example, 5th min T_{re} represents average T_{re} from the 0th to 5th min. PRE and POST stand for the pre- and post- heat tolerance test, respectively. All the statistical analyses were conducted using SPSS statistics 25.0 with a significance level of $P < 0.05$. Prior to performing further statistical analyses, all data were assessed for normality and sphericity. Differences in heat flow through the suit and T_{re} increases between the experimental conditions on the days of 1, 4, 7, and 10 during the HA training were analyzed using two-factor mixed ANOVA with the tukey test as a post hoc. Data from HA training on the days of 1, 5, and 10 in each experimental condition were analyzed by using either a one-way repeated measures ANOVA or Friedman test for comparisons of the physiological and perceptual responses, across the training days. As a post-hoc test, pair-wise comparisons with FDR correction were used when needed. To check if there were differences between HA_{EXE}, $HA_{EXE+SUIT}$, and HA_{SUIT} in baseline T_{re}, $\bar{T}_{sk}$ and heart rate in the pre- heat tolerance test, one-way ANOVA was used because all data were proved to be normally distributed. Either paired t-test for parametric data or Wilcoxon signed-rank test for non-parametric data was undertaken to compare the values in the PRE and POST tests for each HA condition. Interaction effect (group: HA_{EXE}, $HA_{EXE+SUIT}$, HA_{SUIT} × time: PRE, POST) was determined by two-factor mixed ANOVA with the tukey test as a post hoc. All data were expressed as mean ± standard deviation (SD).

Chapter 3. Results

3.1. Heat flow through the suit and increase in rectal temperature during the 10-day heat acclimation training

Table 2 Heat flow through the water-perfused suits and increase in rectal temperature during the heat acclimation training

	Day 1	Day 4	Day 7	Day 10	Main effect of group
Heat insertion by the circulating water inside the water-perfused suit					
During the first 1-h of the suit donning (W)					
HA_{SUIT}	101 ± 12	103 ± 15	100 ± 11	100 ± 16	
Main effect of day	$P = 0.957$				
During the second 1-h of the suit donning (W)					
$HA_{EXE+SUIT}$	94 ± 16	100 ± 18	100 ± 13	104 ± 12	$P = 0.965$
HA_{SUIT}	97 ± 16	101 ± 17	99 ± 13	100 ± 16	
Main effect of day	$P = 0.629$				
Change in rectal temperature during the first 1-h of the heat acclimation training (°C)					
HA_{EXE}	1.06 ± 0.37	1.11 ± 0.14	1.22 ± 0.21	1.16 ± 0.17	$P < 0.001$: HA_{EXE}^{a}; $HA_{EXE+SUIT}^{a}$; HA_{SUIT}^{b}
$HA_{EXE+SUIT}$	1.01 ± 0.29	1.12 ± 0.19	1.15 ± 0.29	1.00 ± 0.15	
HA_{SUIT}	0.47 ± 0.29	0.38 ± 0.24	0.59 ± 0.33	0.46 ± 0.18	
Main effect of day	$P = 0.041$				
Change in rectal temperature during the first 2-h of the heat acclimation training (°C)					
HA_{EXE}	-0.37 ± 0.23	-0.53 ± 0.11	-0.54 ± 0.07	-0.50 ± 0.10	$P < 0.001$: HA_{EXE}^{c}; $HA_{EXE+SUIT}^{b}$; HA_{SUIT}^{a}
$HA_{EXE+SUIT}$	0.47 ± 0.31	0.54 ± 0.17	0.54 ± 0.20	0.54 ± 0.20	
HA_{SUIT}	1.06 ± 0.12	1.11 ± 0.15	1.07 ± 0.13	1.00 ± 0.06	
Main effect of day	$P = 0.836$				
Total change in rectal temperature during the 2-h of the heat acclimation training (°C)					
HA_{EXE}	0.70 ± 0.25	0.59 ± 0.15	0.68 ± 0.19	0.65 ± 0.17	$P < 0.001$: HA_{EXE}^{b}; $HA_{EXE+SUIT}^{a}$; HA_{SUIT}^{a}
$HA_{EXE+SUIT}$	1.48 ± 0.28	1.66 ± 0.19	1.70 ± 0.23	1.54 ± 0.21	
HA_{SUIT}	1.53 ± 0.34	1.48 ± 0.30	1.66 ± 0.31	1.45 ± 0.20	
Main effect of day	$P = 0.062$				

Note: All data are expressed as mean ± SD;
[a, b, c] represent significantly identical groups among the experimental conditions distinguished by a post hoc test.

All subjects in HA_{EXE}, $HA_{EXE+SUIT}$ and HA_{SUIT} completed the HA program on the 10 consecutive days. Table 2 shows the heat flow through the suit and the increase in T_{re} during the three HA programs. During the first one hour of the passive heating, heat flow through the water perfused suit in HA_{SUIT} was 102 ± 8 watts on average. The 10-day average heat flow calculated during the second one hour was 101 ± 9 watts and 102 ± 7 watts for $HA_{EXE+SUIT}$ and HA_{SUIT}, respectively. Rectal temperature increased by 0.70 ± 0.14°C on average for HA_{EXE} in the 2-h training during the 10 days, while those in $HA_{EXE+SUIT}$ and HA_{SUIT} rose by 1.62 ± 0.15°C and 1.50 ± 0.22°C, respectively. Results showed that the HA intervention was successfully conducted (Table 2): (1) no difference in ΔT_{re} during the first 1-h session of HA training but significant difference during the second 1-h between HA_{EXE} and $HA_{EXE+SUIT}$; (2) no difference in ΔT_{re} during the 2-h of training between $HA_{EXE+SUIT}$ and HA_{SUIT}; (3) systematic difference in ΔT_{re} during the 2-h of training between HA_{EXE} and $HA_{EXE+SUIT}$ or HA_{SUIT}.

3.2. Physiological and perceptual responses during the heat tolerance tests

3.2.1. Rectal and mean skin temperature during the heat tolerance tests

No significant differences in the baseline T_{re} between HA_{EXE}, $HA_{EXE+SUIT}$ and HA_{SUIT} were found in PRE (5th min: $P = 0.217$; 10th min: $P = 0.201$). Rectal temperature significantly decreased only in HA_{SUIT} after the 10-day heat acclimation program ($P < 0.05$) (Fig. 4A). Significant interaction (group × time) appeared in rectal temperature (at 20th min: $P = 0.036$; 25th min: $P = 0.025$; 30th min: $P = 0.025$; and 35th min: $P = 0.032$).

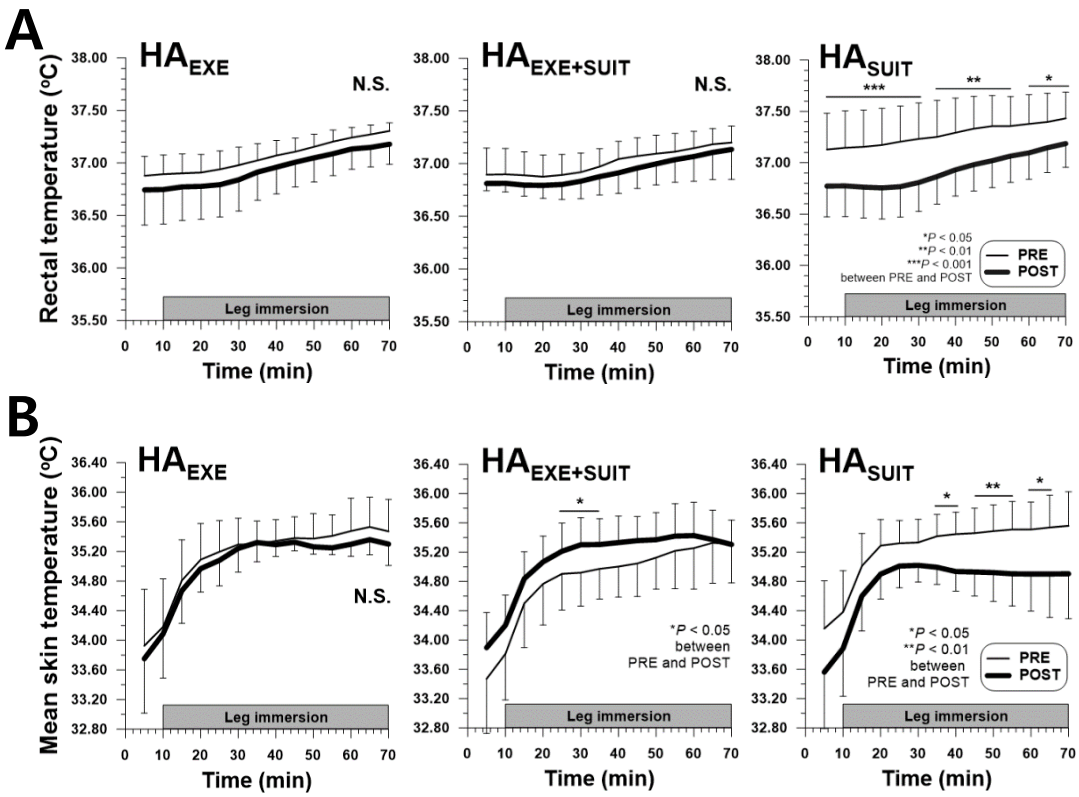

Fig. 4 Time courses of rectal (A) and mean skin temperature (B) during the pre- and post-heat tolerance tests.

Each HA program induced all different changes in mean skin temperature (Fig. 4B). The baseline $\bar{T}_{sk}$ did not differ between the three groups in PRE (5th min: $P = 0.178$; 10th min: $P = 0.185$). The HA_{EXE} showed no difference between PRE and POST in $\bar{T}_{sk}$ (Fig. 4B). The $HA_{EXE+SUIT}$, however, showed higher $\bar{T}_{sk}$ from 25th to 35th min in POST ($P < 0.05$) (Fig. 4B). Mean skin temperature observed in POST for HA_{SUIT}, on the contrary, was significantly lower than that in PRE (Fig. 4B). There were significant interaction effects (group × time) in $\bar{T}_{sk}$ (at 30th min: $P = 0.018$; 35th min: $P = 0.002$; 40th min: $P = 0.001$; 45th min: $P < 0.001$; 50th min: $P = 0.002$; 55th min: $P = 0.006$; and 60th min: $P = 0.028$).

3.2.2. Whole-body and local sweat rates during the heat tolerance tests

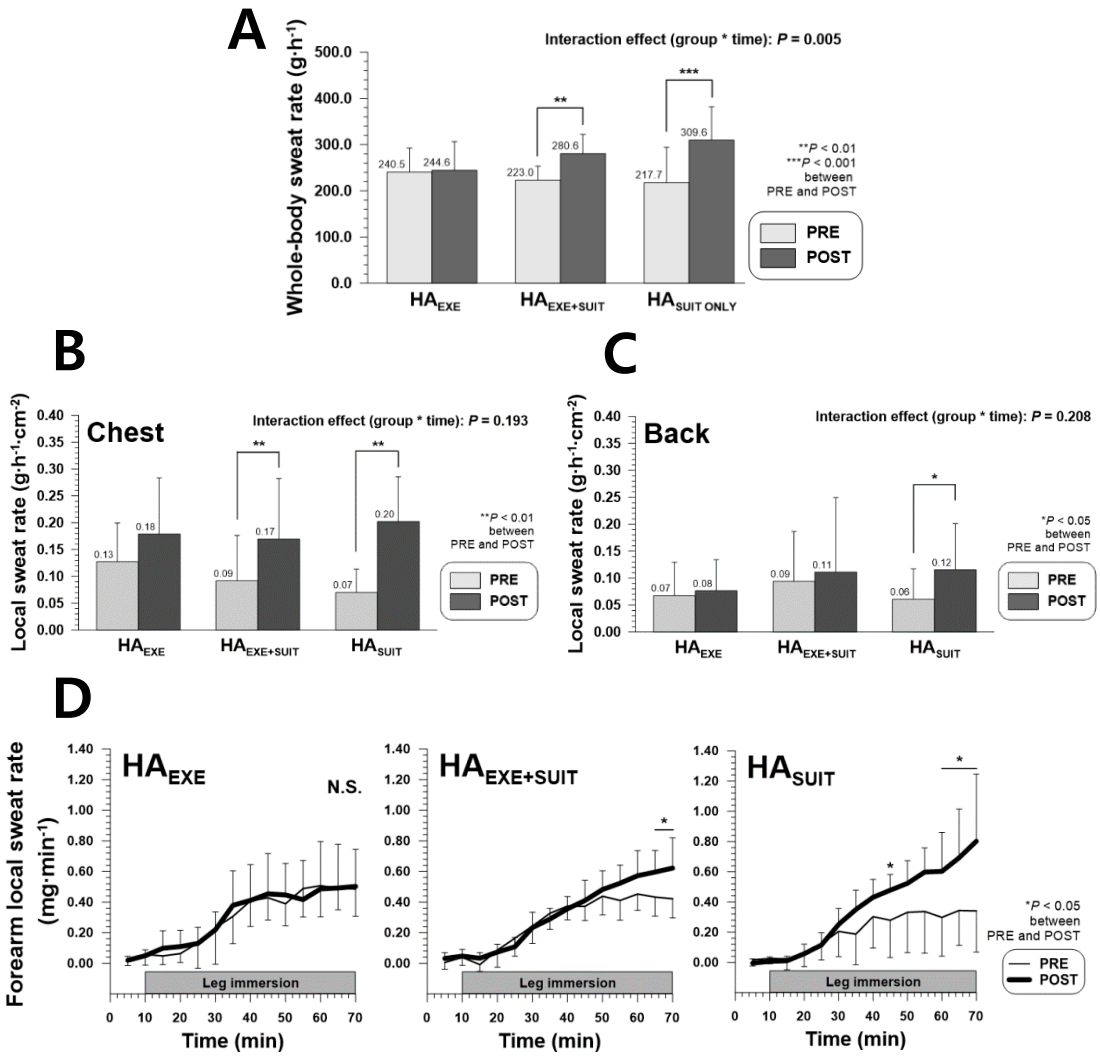

Fig. 5 Whole-body (A), chest (B), and back sweat rates (C), and time courses of forearm sweat rate (D) in the pre- and post- heat tolerance tests.

Both $HA_{EXE+SUIT}$ and HA_{SUIT} obtained 57.6 g·h^{-1} and 91.9 g·h^{-1} greater whole-body sweat rates in POST, respectively, (P = 0.001 and P < 0.001, respectively), but no change in whole-body sweat rate was found for HA_{EXE} (Fig. 5A). While HA_{SUIT} displayed significant increase both in chest and back sweat rates in POST (P = 0.001

and $P = 0.043$, respectively), $HA_{EXE+SUIT}$ acquired significantly greater local sweat rate on the chest in POST ($P = 0.009$) (Fig. 5B and 5C). HA_{EXE} did not show any differences between PRE and POST in both local sweat rates (Fig. 5B and 5C). Forearm sweat rate did not change in POST compared to PRE during the 70-min continuous measurement for HA_{EXE} (Fig. 5D). In $HA_{EXE+SUIT}$, however, increases in forearm sweat rate were found at the end of the post- heat tolerance test ($P < 0.05$) (Fig. 5D). In HA_{SUIT}, greater forearm sweat rate was seen in POST ($P < 0.05$) (Fig. 5D). No significant interaction effect was observed in forearm sweat rate.

3.2.3. Heart rate and blood pressure during the heat tolerance tests

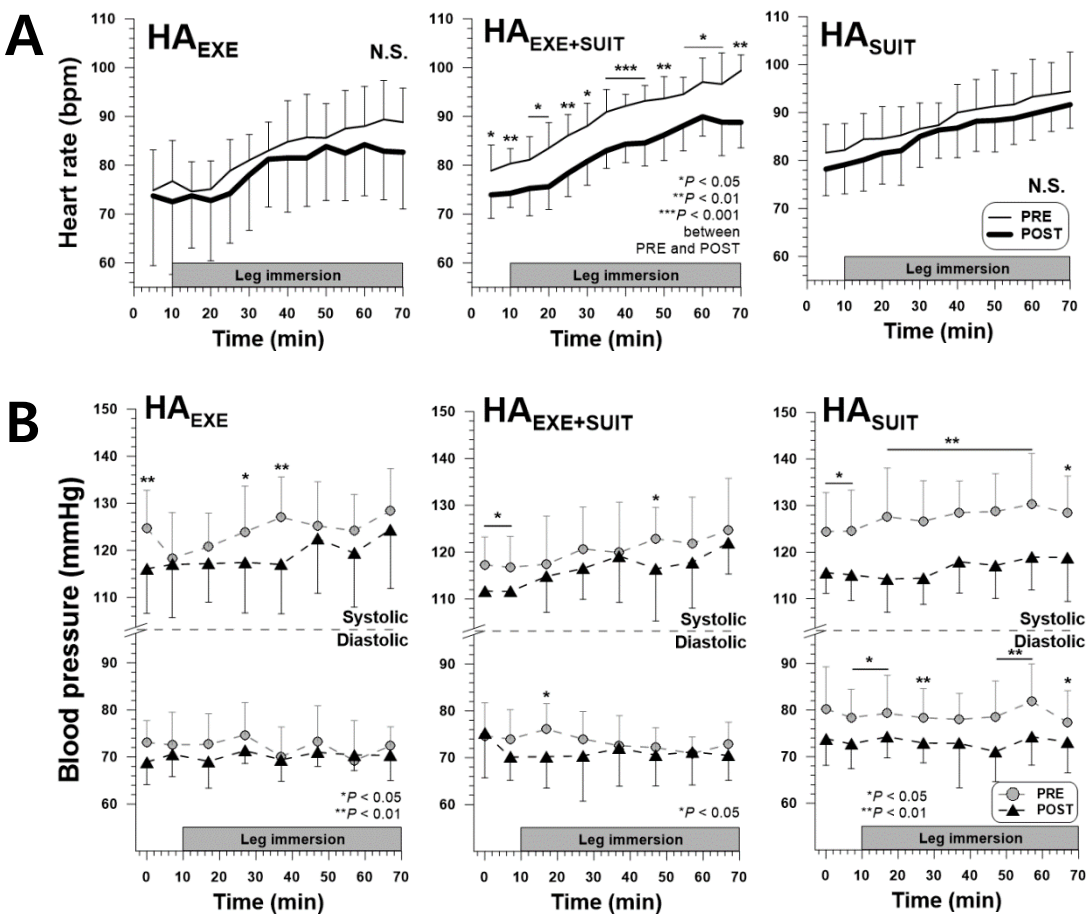

Fig. 6 Time courses of heart rate (A) and blood pressure (B) in the pre- and post- heat tolerance tests.

There were no significant differences in the baseline heart rate between the three groups in PRE (5th min: $P = 0.208$; 10th min: $P = 0.284$). Heart rate during the heat tolerance test after the 10-day intervention significantly dropped only for $HA_{EXE+SUIT}$ ($P < 0.05$) (Fig. 6A). Interaction effect was not significant in heart rate throughout the heat tolerance test. While $HA_{EXE+SUIT}$ and HA_{SUIT} displayed lower values in POST for both systolic and diastolic blood pressure, HA_{EXE} acquired lower systolic but not diastolic blood pressure (Fig. 6B). Significant interaction effects (group × time) were found in systolic blood pressure (at 17th min: $P = 0.042$; 37th min: $P = 0.028$; 47th min: $P = 0.022$) and diastolic blood pressure (at 57th min: $P = 0.019$).

3.2.4. Perceptual responses during the heat tolerance tests

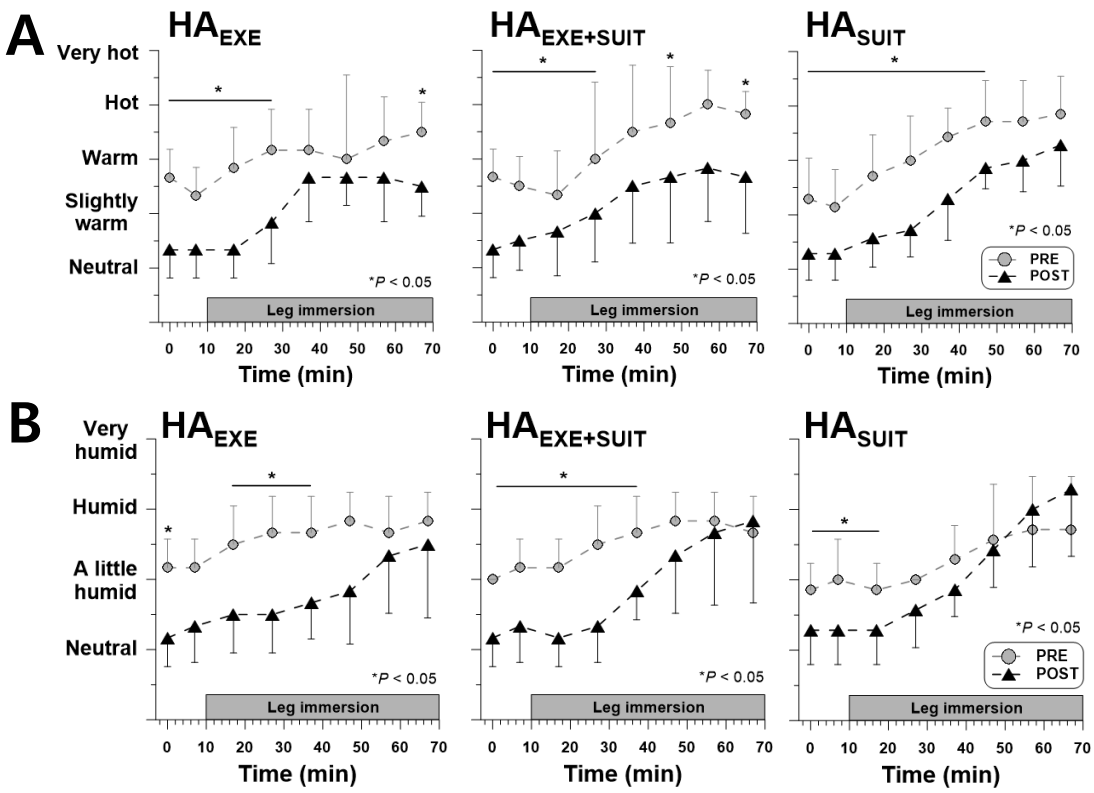

Fig. 7 Thermal sensation (A) and humidity sensation (B) during the pre- and post- heat tolerance tests.

Subjects in HA_{EXE}, $HA_{EXE+SUIT}$ and HA_{SUIT} felt less warm under the identical heat tolerance test after the 10-day (Fig. 7A). Humidity sensation also diminished in POST for all three conditions (Fig. 7B). In terms of thirst sensation, HA_{EXE} and $HA_{EXE+SUIT}$ did not show any significant adaptive changes in POST. The HA_{SUIT}, however, experienced alleviated thirst sensation in POST (PRE 7th: 0.6 ± 0.4; POST 7th: 0.1 ± 0.2, P = 0.034; PRE 27th: 0.6 ± 0.2; POST 27th: 0.2 ± 0.4, P = 0.025; PRE 47th: 0.9 ± 0.4; POST 47th: 0.4 ± 0.4, P = 0.045). No significant interaction (group × time) was found in perceptual responses.

3.3. Physiological and perceptual changes during the 10-day training

3.3.1. Changes in whole-body and local sweat rates during the 10-day training

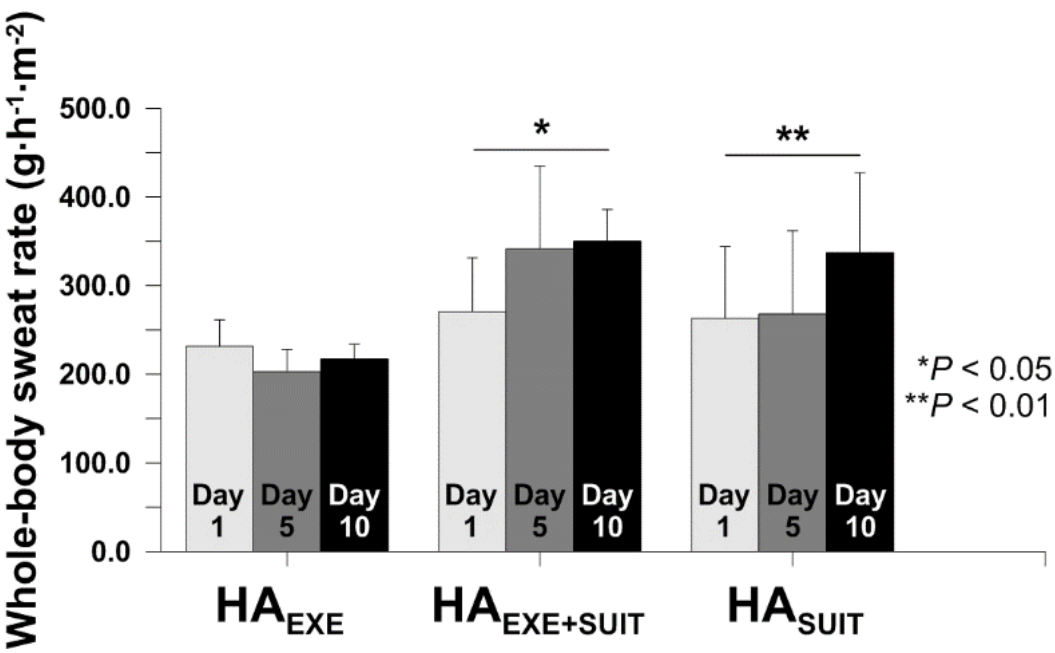

Fig. 8 Whole-body sweat rate on the day 1, 5, and 10 of the training.

Whereas HA_{EXE} did not show any differences in whole-body sweat rate across the training days, $HA_{EXE+SUIT}$ and HA_{SUIT} displayed higher whole-body sweat rate on day 5 and/or day 10 ($P = 0.013$ and $P = 0.003$, respectively) (Fig. 8). Compared to the first day of training, whole-body sweat rate in $HA_{EXE+SUIT}$ on day 5 increased by 71.1 ± 51.5 $g \cdot h^{-1} \cdot m^{-2}$ ($P = 0.006$) and on day 10 by 79.4 ± 44.5 $g \cdot h^{-1} \cdot m^{-2}$ ($P = 0.011$) (Fig. 8). For HA_{SUIT}, whole-body sweat rate increased on day 10: compared to day 1 it increased by 74.0 ± 51.7 $g \cdot h^{-1} \cdot m^{-2}$ ($P = 0.014$) and to day 5 it was elevated by 69.2 ± 45.3 $g \cdot h^{-1} \cdot m^{-2}$ ($P = 0.021$).

Chest sweat rate did not change during the training for all conditions, HA_{EXE} (day 1: 0.22 ± 0.05 $g \cdot h^{-1} \cdot cm^{-2}$; day 5: 0.21 ± 0.04 $g \cdot h^{-1} \cdot cm^{-2}$; day 10: 0.23 ± 0.04 $g \cdot h^{-1} \cdot cm^{-2}$), $HA_{EXE+SUIT}$ (day 1: 0.21 ± 0.07 $g \cdot h^{-1} \cdot cm^{-2}$; day 5: 0.21 ± 0.06 $g \cdot h^{-1} \cdot cm^{-2}$; day 10: 0.21 ± 0.07 $g \cdot h^{-1} \cdot cm^{-2}$) and HA_{SUIT} (day 1: 0.22 ± 0.04 $g \cdot h^{-1} \cdot cm^{-2}$; day 5: 0.21 ± 0.03 $g \cdot h^{-1} \cdot cm^{-2}$; day 10: 0.24 ± 0.02 $g \cdot h^{-1} \cdot cm^{-2}$). Similarly, back sweat rate showed no differences between the HA days for HA_{EXE} (day 1: 0.11 ± 0.05 $g \cdot h^{-1} \cdot cm^{-2}$; day 5: 0.16 ± 0.08 $g \cdot h^{-1} \cdot cm^{-2}$; day 10: 0.14 ± 0.08 $g \cdot h^{-1} \cdot cm^{-2}$), $HA_{EXE+SUIT}$ (day 1: 0.15 ± 0.06 $g \cdot h^{-1} \cdot cm^{-2}$; day 5: 0.11 ± 0.05 $g \cdot h^{-1} \cdot cm^{-2}$; day 10: 0.15 ± 0.07 $g \cdot h^{-1} \cdot cm^{-2}$) and HA_{SUIT} (day 1: 0.14 ± 0.08 $g \cdot h^{-1} \cdot cm^{-2}$; day 5: 0.10 ± 0.08 $g \cdot h^{-1} \cdot cm^{-2}$; day 10: 0.13 ± 0.07 $g \cdot h^{-1} \cdot cm^{-2}$).

3.3.2. Changes in perceptual responses during the 10-day training

The HA_{EXE} training adversely affected thermal sensation at the end of the seated rest, displaying lowest thermal sensation on the first day ($P < 0.05$) (Fig. 9A). In $HA_{EXE+SUIT}$ and HA_{SUIT}, on the contrary, subjects perceived themselves as being less hot after the 10-day HA training ($P < 0.05$) (Fig. 9A). Pairwise-comparison with FDR correction showed that thermal sensation in HA_{SUIT} on day 10 was significantly

lower than that of the first day (27th min, $P = 0.035$; 47th min, $P = 0.042$). Thirst sensation did not change in HA_{EXE} but decreased on day 5 and/or day 10 compared to day 1 in $HA_{EXE+SUIT}$ and HA_{SUIT} ($P < 0.05$) (Fig. 9B).

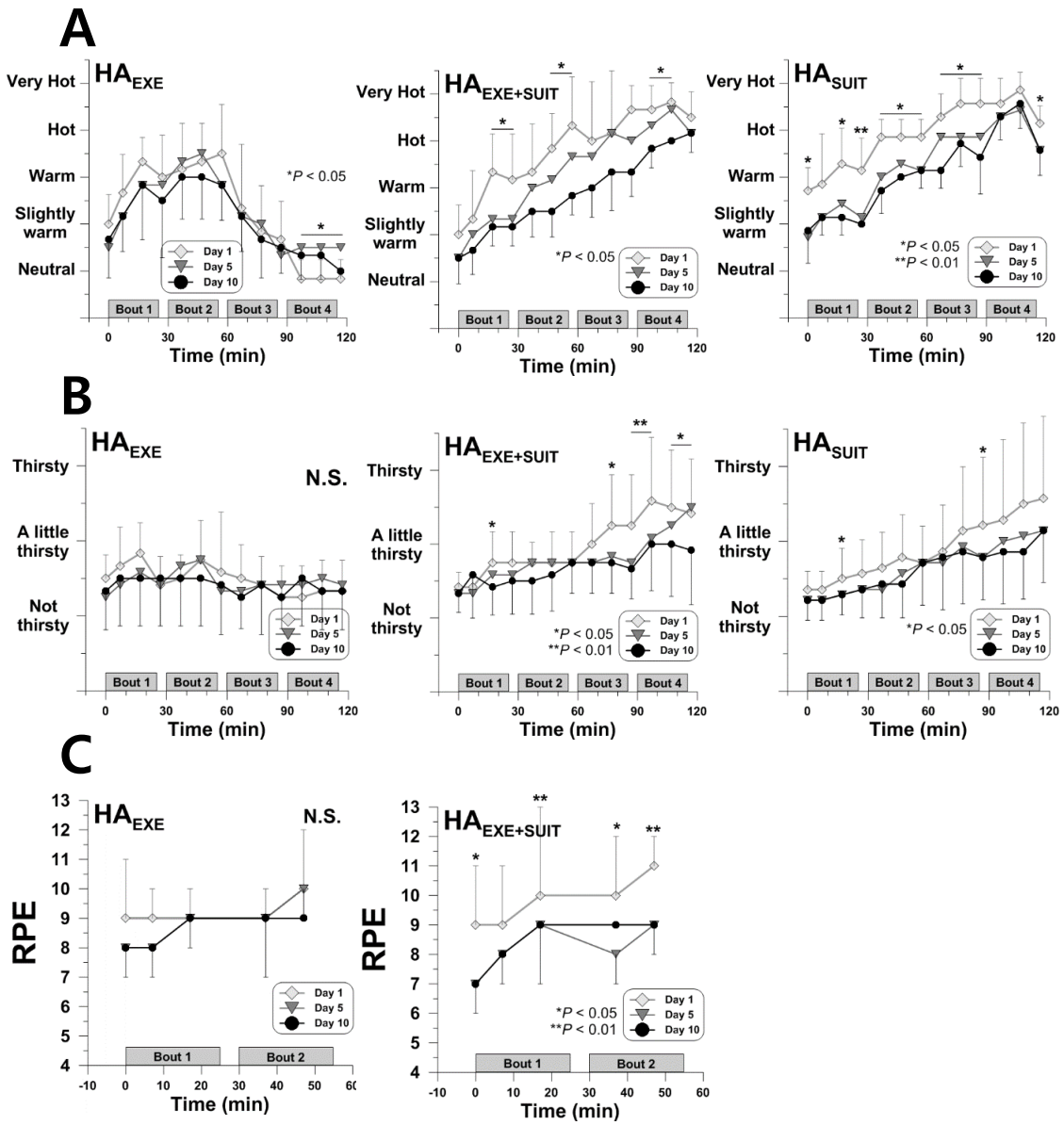

Fig. 9 Thermal sensation (A), thirst sensation (B), and rating of perceived exertion (RPE) (C) on the day 1, 5, and 10 of the training.

Rating of perceived exertion (RPE) showed no differences after the 10-day training in HA_{EXE}. Subjects in $HA_{EXE+SUIT}$, however, reported lower RPE on day 5 and/or day 10 during the exercise ($P < 0.05$) (Fig. 9C). Pair-wise comparisons with FDR correction showed that both on day 5 and 10, RPE at 47th min for $HA_{EXE+SUIT}$ significantly dropped from day 1 ($P = 0.021$ and $P = 0.030$, respectively). Humidity sensation decreased on the day 5 and 10 at 0th min in HA_{EXE} (day 1: 1.0 ± 0.0, day 5: 0.5 ± 0.5, day 10: 0.3 ± 0.5, $P = 0.039$) and $HA_{EXE+SUIT}$ (day 1: 1.0 ± 0.9, day 5: 0.2 ± 0.4, day 10: 0.2 ± 0.4, $P = 0.032$); but not in HA_{SUIT} (day 1: 0.4 ± 0.5, day 5: 0.3 ± 0.5, day 10: 0.3 ± 0.5).

3.3.3. Changes in rectal temperature during the 10-day training

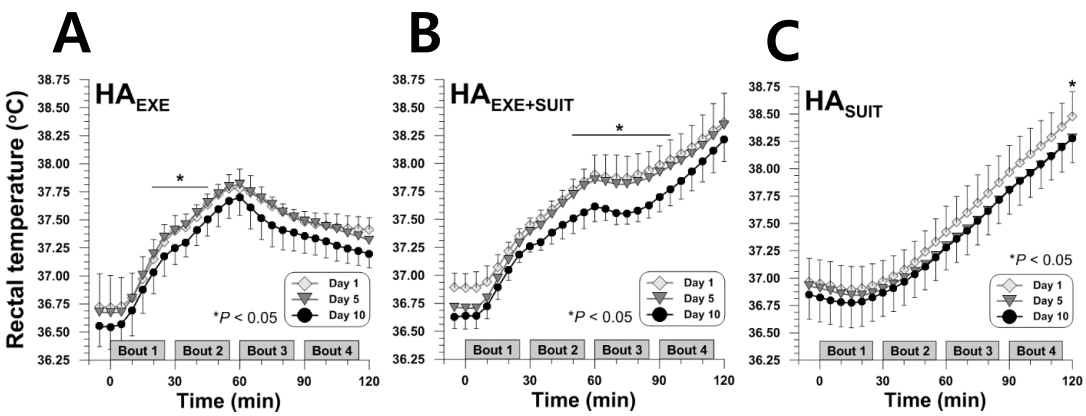

Fig. 10 Time courses of rectal temperature during heat acclimation training on the day 1, 5, and 10 for HA_{EXE} (A), $HA_{EXE+SUIT}$ (B), and HA_{SUIT} (C).

Lowest T_{re} appeared on day 5 or day 10 in the different stages of the training protocols for HA_{EXE}, $HA_{EXE+SUIT}$ and HA_{SUIT} (Fig. 10A, 10B, and 10C). The active strategy-based control group HA_{EXE} displayed lower rectal temperature on day 10 during the mid to last stage of exercise ($P < 0.05$) (Fig. 10A). Pairwise comparison with FDR correction revealed that in HA_{EXE}, T_{re} of day 10 was lower than the values

of day 1 (at 35th min, $P = 0.038$) and lower than those of day 5 (25th to 35th min, $P < 0.05$), respectively. For $HA_{EXE+SUIT}$, significant differences across the days in T_{re} were present from the end of the exercise to the mid stage of post-exercise suit donning ($P < 0.05$) (Fig. 10B). The HA_{SUIT} showed the lowest T_{re} at the end of the training ($P < 0.05$) (Fig. 10C).

3.3.4. Changes in heart rate during the 10-day training

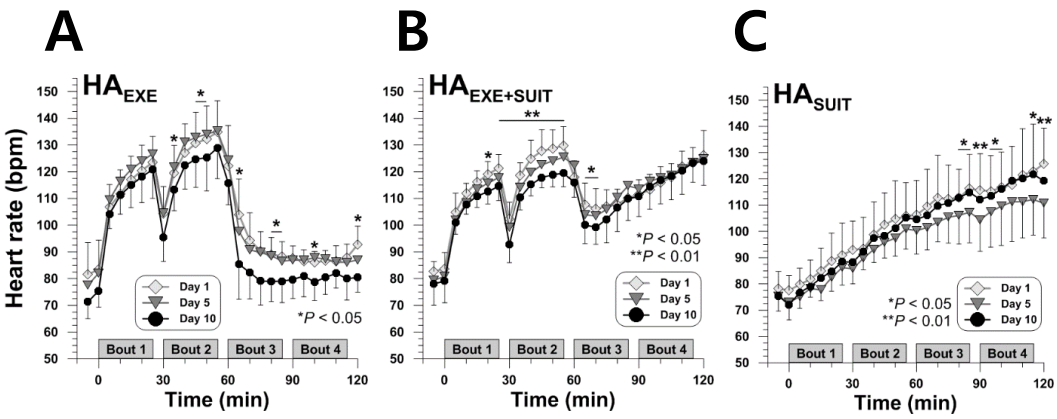

Fig. 11 Time courses of heart rate during heat acclimation training on the day 1, 5, and 10 for HA_{EXE} (A), $HA_{EXE+SUIT}$ (B), and HA_{SUIT} (C).

Heart rate on day 10 for HA_{EXE} was significantly lower than day 1 and day 5 primarily during the seated-rest period ($P < 0.05$) (Fig. 5A). According to the pair-wise comparisons, heart rate for HA_{EXE} on day 10 was lower than on day 1 (at 50th, 65th, 80th, 100th and 120th min, $P < 0.05$); it was also lower than heart rate on day 5 (at 100th min, $P = 0.044$). When passive skin-heating was added post-exercise ($HA_{EXE+SUIT}$), heart rate on day 10 displayed lower values from the mid-stage of the exercise session to the earlier stage of passive HA session ($P < 0.05$) (Fig. 5B). The results from the post-hoc test showed that heart rate for $HA_{EXE+SUIT}$ on day 10 significantly decreased from day 1 (20th to 55th and 70th min; $P < 0.05$). There were

also significant differences in heart rate for $HA_{EXE+SUIT}$ between day 1 and day 5 (40th and 45th min, $P < 0.05$). Unlike the other two HA strategies, HA_{SUIT} induced lower heart rate on day 5 at the later stage of skin-heating ($P < 0.05$) (Fig. 5C). Pair-wise comparison with FDR correction indicated that on day 5 heart rate for HA_{SUIT} significantly dropped from day 1 (90th and 120th min, $P < 0.05$), and from day 10 (85th, 115th and 120th min, $P < 0.05$).

3.3.5. Changes in physiological strain index (PSI) during the 10-day training

Significant differences between the heat acclimation training days in peak and mean PSI were found only for HA_{SUIT} (Fig. 12A and 12B). Peak PSI for HA_{SUIT} on day 5 was the lowest ($P < 0.001$), showing significant differences from the values on day 1 ($P = 0.001$) and on day 10 ($P = 0.018$) (Fig. 12A). Compared to the other two days, mean PSI also displayed the lowest value on day 5 ($P = 0.027$) (Fig. 12B).

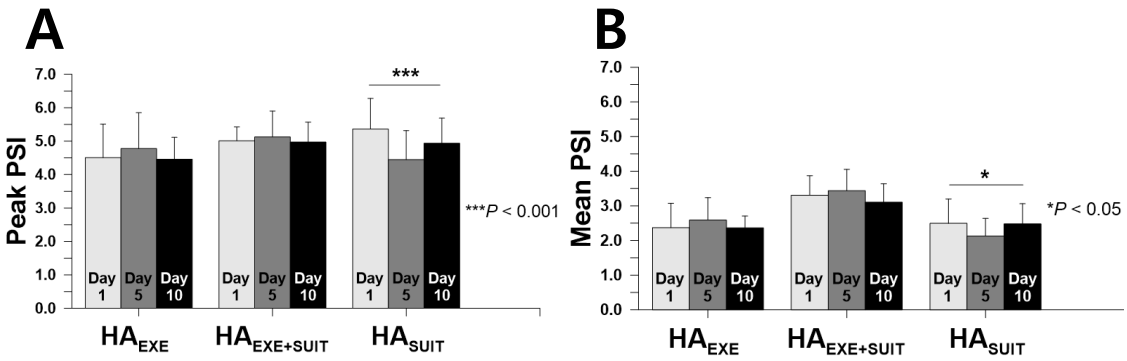

Fig. 12 Peak (A) and mean physiological index (PSI) (B) on the day 1, 5, and 10 of the training.

Chapter 4. Discussion

The present study explored whether a skin-heating garment could be an effective method of heat acclimation strategy in a hot-humid environment: (1) as a passive HA strategy with no exercise, and (2) as a post-exercise HA strategy to extend actively-induced HA. In order to prove the efficacy of this novel method, a mild-exercise HA strategy was included as a control intervention. To the best of our knowledge, the current study is the first attempt to utilize a skin-heating water-perfused suit to attain HA comparing it to an actively induced HA. Three principal findings are worthy to note in the present study. Firstly, wearing a water-perfused suit for 10 days as both passive and post-exercise heat acclimation strategies was effective to induce heat acclimation. Secondly, the passive skin-heating strategy was superior to the other partially active strategy in obtaining heat acclimation in some physiological responses. Finally, the two HA strategies differed in terms of the timing during the HA protocols and training days at which the HA responses appeared.

4.1. Effectiveness of a water-perfused suit as a passive heat acclimation strategy: HA_{SUIT} vs. HA_{EXE}

The ongoing debates on HA strategies have established that repeated bouts of exercises in heat on consecutive days are optimal (Tyler et al. 2016). Not underestimating the significance of active HA strategies, we additionally propose that skin-heating using a water-perfused suit can be an effective alternative for HA. The effectiveness of this suit as a passive HA strategy can be seen from its ability to induce typical adaptive changes more readily than the control did, which only elicited lower systolic blood pressure and alleviated perceptual strain in the post-heat tolerance test. Inclusion of the control (HA_{EXE}) which experienced mild-active

HA training, provides confidence that the more conspicuous adaptations found in HA_{SUIT} during the heat tolerance tests did not naturally occur but were experimentally induced. However, since the T_{re} increase in HA_{SUIT} during the HA training was significantly greater than that of HA_{EXE}, the effectiveness of donning the suit for HA should be carefully interpreted: it is not better than all exercise protocols, but is than the mild one only.

One of the most intriguing observations of the present study is that the exogenous heat stimulus provided by wearing a water-perfused suit was strong enough to induce HA, contrary to the common consensus (Tyler et al. 2016). According to Taylor et al. (2014), some previous studies have pointed out that passive heating for HA is less recommended because it may only cause "a slight-moderate homeostatic disturbance", producing smaller cumulative adaptation stimulus. However, the passive heat exposure using the suit led to the following responses similar to those actively induced that have been demonstrated in previous research. First of all, reduction in T_{re} was found throughout the post- passive heat tolerance test and at the end of the training protocol, which is in accordance with previous studies (Neal et al. 2016). Secondly, the passive skin-heating strategy improved sudomotor functions displayed as seen by increased whole-body sweat rate during the post- heat tolerance test and across the training days; elevated local sweat rates on the chest, back and forearm during the heat tolerance tests which are the hallmarks of HA responses helping the body to dissipate heat more effectively (Périard et al. 2015). It is also noteworthy that enhanced sweating functions on the forearm appeared in HA_{SUIT} even though the forearm was not directly heated by the suit. Such finding might suggest the efficiency of local skin-heating by donning a water-perfused suit, in terms of triggering beneficial sweating activities of body

regions with larger areas than the heated areas by the suit. In line with previous investigations, additionally, advantageous changes in diastolic blood pressure (Armstrong et al. 2005) as well as thirst sensation were found in the heat tolerance tests only in the passive HA training group, whereas such changes were not present in the control group.

It has been well known that not only the elevation of temperature of the body core but also that of the skin is important to optimize heat acclimation. While the former activates deep-body sensors that can affect the organs involved in heat dissipation, the latter causes increase in thermal sensory input from the skin, which is very crucial under some conditions (Taylor et al. 2014). There can be two positive effects of elevating skin temperatures on HA. First of all, blood volume can expand mainly within the plasma compartment, due to the combined actions of increased plasma colloid and crystalloid osmotic pressure (Taylor et al. 2014). Plasma volume expansion is associated with facilitation of vascular filling contributing to improved cardiovascular stabilities (Périard et al. 2015), which is likely to account for the reduction in blood pressure observed in the present study. In addition, the intravascular enlargement was also reported to be linked with enhanced sudomotor sensitivity (Goto et al. 2010), which might be related with the greater sweat rates after the training using a water-perfused suit. Secondly, cutaneous blood flow can rise. This can drive heat delivery from the core to the skin faster and also facilitate sweat evaporation, by elevating cutaneous water vapor pressure (Taylor et al. 2014). Coupled with more profuse sweating found on the whole body, chest, back, and forearm in the present study, decrease in T_{re} and $\bar{T}_{sk,}$ induced by skin-heating using the suit may thus be explained by this.

4.2. Effectiveness of a water-perfused suit as a post-exercise heat acclimation strategy: $HA_{EXE+SUIT}$ vs. HA_{EXE}

In the present study, wearing a water-perfused suit after daily exercise augmented HA responses which were not observed in the low-intensity exercise-only group, underpinning our hypothesis: (1) whole-body sweat rate increased in the post- heat tolerance test and during the 10-day training; (2) chest sweat rate was also elevated in the post- heat tolerance test; (3) sweating function of the forearm was enhanced at the end of the heat tolerance test; (4) heart rate declined throughout the heat tolerance test and during the 10-day training. The present findings advance those previous studies which revealed that maintaining and further elevating T_{re} through applying an exogenous stimulus, which was already increased by a pre-session of exercise, can intensify HA. For example, Stanley et al. (2015) reported that post-exercise sauna bathing was effective in reducing resting heart rate under heat stress. Zurawlew et al. (2016) who compared 40ºC hot water immersion intervention after exercise with an exercise-only control condition also reported lower heart rate only for the post-exercise passive-heating condition. They found decreases in resting and end T_{re}, but no change in sweat rate in the post-exercise hot water immersion group contrary to the present findings. The inconsistency might indicate that forming a warm microclimate using a skin-heating suit after exercise is helpful in stimulating sweat glands at the peripheral level not affecting the central thermoregulatory regulation. Taken together, the results of the present study can support the notion that while HA rely upon how much body core temperature increases during the training, elevation in skin temperatures has significance for full development of HA (Fox et al. 1964).

It is also worthy to note that, during the 10-day training, the post-exercise

strategy using a water-perfused suit was effective in alleviating perceptual thermal strain not only during the passive heating but also during exercise. Perceptual adaptations during exercise under heat stress are particularly important because those changes can relieve premature fatigue and exert positive influences on endurance performance (Armada-da-Silva et al. 2004; Cheuvront et al. 2010; Steven et al. 2018). In addition, heart rate for $HA_{EXE+SUIT}$ was reduced after HA training primarily during exercise, while heart rate for HA_{EXE} decreased mainly during the recovery. These adaptations found in $HA_{EXE+SUIT}$ during exercise may suggest the effectiveness of passive heating using a water-perfused suit for improving aerobic capacity in heat.

4.3. Comparisons between the passive and post-exercise heat acclimation strategies: HA_{SUIT} vs. $HA_{EXE+SUIT}$

Beyond our expectation, the skin-heating passive HA strategy outperformed the post-exercise one, in changes in T_{re} and back sweat rate. Alleviation of thirst sensation in the post- heat tolerance test was only observed in HA_{SUIT} even though whole-body sweat rates increased in both conditions. In light of the equivalent 2-h T_{re} increases between the two different strategies during the 10-day training, the present findings are surprising, because a passive HA strategy alone is less recommended than a passive strategy combined with exercise (Heathcote et al. 2018). At least in a water-perfused suit-based HA protocol, notably, passive skin-heating seems more effective than in conjunction with mild-exercise bouts at a given T_{re} increase if the aforementioned changes are desired. Benefits of longer direct skin-heating in eliciting more profuse sweating can be associated with the relationship between skin temperatures and sweating rates explored in the previous studies (Davies 1979; Van Beaumont and Bullard 1965): higher than 33°C skin temperatures

evidently influence sweating, stimulating the eccrine sweat glands. Decrease in T_{re} observed in HA_{SUIT} but not in $HA_{EXE+SUIT}$ may as well be coupled with accelerating sweat onset, which is achieved by activation of the central sudomotor mechanism lowering the body temperature threshold for sweating (Hori 1995). When decrease in heart rate is a priority to be achieved, however, physical training followed by wearing a water-perfused suit may be preferred over a passive HA strategy alone.

Another interesting observation is that, in $\bar{T}_{sk}$, contrary changes were induced by the passive and the post-exercise HA strategies. Such variability indeed supports the fact that no established hallmarks exist for heat adaptation in $\bar{T}_{sk}$ to date; it has been documented to remain unchanged (Chen et al. 2013), to increase (Petersen et al. 2010) and to decrease (Zurawlew et al. 2016; Neal et al. 2016) from study to study. Though conflicting, HA protocols consisting of more than eight heat exposures were reported to induce a fall in $\bar{T}_{sk}$ as reviewed by Chalmers et al. (2014); this is caused by advanced evaporative skin cooling due to sweat rate increases (Hori 1995). On the basis of the most profound increase in sweat rates observed in HA_{SUIT}, therefore, decrement in $\bar{T}_{sk}$ found in the passive strategy provides clear evidence of HA. Meanwhile, elevated $\bar{T}_{sk}$ is associated with increase in skin blood flow. Tyler et al. (2016) suggested that skin blood flow increase commences earlier than HA, readily delivering heat to the periphery. When this blood flow redistribution is later coupled with improvements in heat loss pathways such as sweating, effective heat dissipation occurs once the heat has reached the skin. Increase in $\bar{T}_{sk}$ found in $HA_{EXE+SUIT}$, therefore, may indicate an intermediate stage of adaptive changes in skin temperatures toward decrement as observed in HA_{SUIT}, but this interpretation is speculative.

4.4. Differential effects of the passive and post-exercise heat acclimation strategies during the 10-day training

The two strategies heating the skin either after exercise or throughout the training induced HA responses at different times during the protocols and on different training days. In the post-exercise HA condition, T_{re} and heart rate decreased mainly in the middle of the training while in the passive HA condition those values decreased at the end. Adaptive changes appearing later in the protocol for HA_{SUIT} are indeed not surprising considering that the increase in T_{re} for HA_{SUIT} during the first 1-h was only approximately 0.5°C but it was accelerated during the second 1-h reaching 1.0°C. When utilizing only a skin-heating suit, "sufficiently overloading thermal impulses" that exceed an adaptation threshold, which is known to be the requirement for HA (Taylor et al. 2011) seem to be achieved by two hours but not by one hour.

Comparisons of the timing of HA induction in terms of T_{re} and heart rate during the protocol for $HA_{EXE+SUIT}$ with those found in HA_{EXE} and HA_{SUIT} make it more reasonable to interpret that, the changes are due to the combined effects of the exercise and passive heating: it appeared from the end of exercise to the early stage of passive heating. During exercise, HA_{EXE} also elicited lower T_{re} and heart rate, as well known but it did not last (T_{re}) or only intermittently appeared after exercise stopped (heart rate). Therefore, it is more likely that the post-exercise passive heating 'extended' actively induced HA responses as previously suggested (Daanen et al. 2018; Zuralew et al. 2016). In addition, the decreases during the early phase of suit donning are less likely to be solely caused by the skin-heating because sufficiently long periods seem needed for heat accumulation on the body for the passive HA strategy.

Another point to bear in mind is that HA_{SUIT} showed adaptations earlier than $HA_{EXE+SUIT}$ did except for the sweat responses. This might suggest that forming warm-humid microclimate on the skin using the passive heat exposure may be a more efficient strategy than an exercise-combined one, in inducing some adaptive changes to humid heat, which deserves further demonstration. On day 5, HA_{SUIT} already showed reduction in T_{re} and heart rate contributing to reduction in PSI, in accordance with the findings of previous studies suggesting that less than seven days of training are enough for core temperature reduction (Tyler et al. 2016; Robinson et al. 1943); decrease in heart rate appears within the first 4-5 days (Périard et al. 2015).

The later expression of elevated whole-body sweat rate for HA_{SUIT} might be explicable by the warm-humid microclimate formed inside the suit. When sweat adaptations occur at a peripheral level, it is seldom related to the number of activated eccrine glands but due to higher efficiency and larger sizes of sweat glands (Hori 1995). In a hot and humid environment, sweating adaptations are largely associated with hidromeiosis, which decreases the mean output of each sweat gland of wetted skin. Fox et al. (1964) demonstrated that higher whole-body sweat rate induced in humid-heat acclimation is linked with reduction in hidromeiosis. Candas et al. (1980) also suggested that delay in the occurrence of sweat reduction takes place in acclimated individuals. Therefore, it is probable that in the more poorly ventilated condition (HA_{SUIT}) due to the longer duration of suit donning, the eccrine glands had to develop not only morphological and functional changes but also greater resistance to hidromeiosis, in order to show more profuse sweating. The different tendencies in T_{re} or heart rate (earlier in HA_{SUIT}) and sweat response (later in HA_{SUIT}) may be accounted for by the consensus, that hidromeiosis and its adaptive changes are peripheral phenomenon rather than being related to central factors (Candas et al.

1980; Ogawa et al. 1982). Finally, 10-day is not a surprisingly long period for achieving an elevation in sweat rate as longer term HA interventions (at least 14 days were recommended by Tyler et al. (2016) have been shown to be appropriate for achieving sweat adaptations.

Chapter 5. Practical Applications, Suggestions, and Limitations

5.1. Practical applications

Although exercise in heat has been robustly examined to be the optimal way to induce heat acclimation, there still can be other population facing difficulties in adopting such active method. Donning a skin-heating water-perfused suit can be an alternative heat acclimation strategy to those people, whose heat tolerance should also be enhanced in this hotter world. The old or the disabled can be those who may benefit from utilizing the suit to induce heat acclimation, as they are likely to be able to exercise in heat for a limited time or not to exercise at all. Eliciting heat acclimation of a disabled person with a water-perfused suit can be particularly relevant, in view of the availability of site-specific heating within the suit.

Secondly, suit donning as a passive or post-exercise heat acclimation strategy may be introduced as one of the training programs to improve occupational health of the workers in hot environments, such as soldiers, firefighters, and outdoor workers. Wearing a water-perfused suit might be more beneficial than existing methods for heat acclimation, because it would not require environmental facilities that can maintain hot room temperatures, which are costly. In addition, it can be more feasible training method within a limited space. Last but not least, wearing a water-perfused suit after exercise can be applied to extremely well-trained athletes as a post-exercise heat acclimation strategy, who need additional stimulus in addition to exercise, as their bodies are already used to exercise.

5.2. Suggestions

Based on the efficacy of skin-heating using the water-perfused suit for inducing HA, the following considerations can be taken into account when further elaborating passive HA protocols. In order to produce sufficient thermal impulses exceeding an adaptation threshold needed to induce HA (Heathcote et al. 2018) by the passive

strategy, at least 2-h heating seems needed under an T_{wi} of 44.2ºC. In addition, inserting a 5-min break every 25 min is recommended to make it more tolerable without compromising elevation of rectal temperature.

When combining with an active strategy, we recommend donning a water-perfused suit post-exercise rather than pre-exercise, contrary to sauna-based HA which has proven effective in accelerating or extending HA when applied both before (Mee et al. 2018) and after exercise (Stanley et al. 2015). This is because sufficient time seems needed to form a microclimate between the skin and the clothing warm enough to elevate body core temperature. Minimal transition time between exercise and passive skin-heating is critical to optimize thermoregulatory-adaptive changes in a post-exercise HA (Heathcote et al. 2018). The 5-min delay in the present study, which is longer than 2–3 min of transition achieved by Zurawlew et al. (2016) in hot water immersion, did not hinder HA. Target changing time therefore can be set to less than five minutes.

5.3. Limitations

First of all, the type of heat tolerance test used can be an issue. We chose a passive heat tolerance test using leg immersion that provided mild heat stress. The tests were conducted only passively, which might be, at least partially, responsible for the most notable effects of the passive HA strategy. But the results might differ for an active heat tolerance test (exercise test). Evaluating advantages of water-perfused suit-based HA strategies in running heat tolerance tests (Mee et al. 2015) will may provide an opportunity to advance its utility. Secondly, one might address that 2-h exercise should have been compared to the 2-h passive heating with the suit, to examine the effectiveness of it as an 'alternative' heat acclimation strategy to a

traditional one. This is why we emphasized the exercise condition in the present study as a control group and mentioned that the effectiveness of the suit in inducing HA should not be interpreted as 'being more advantageous than an active strategy'. Comparisons of exercise and the passive strategy using the suit during the same time period or given the same amount of rectal temperature increase, should be further explored.

Finally, the present findings may be only applicable to a warm (hot) and humid environment. One of the practical advantages of passive HA strategies is that it does not necessarily require a hot environment (Zurawlew et al. 2016; Zurawlew et al. 2018). Therefore, further assessment proving benefits of donning a water-perfused suit in a cooler climate to attain HA, may suggest broader application of the passive HA strategy proposed in the present study, though 33°C is already somewhat temperate considering that 40°C is typically set for environmental temperature for HA training (Tyler et al. 2016). Despite the aforementioned limiting factors, we believe that the first tried investigation on assessing the use of a water-perfused suit as a new HA strategy can add to the previous attempts.

Chapter 6. Conclusions

We explored the effects of passive heating using a water-perfused suit on inducing heat acclimations for 10 days. The novel finding of the present study is that the passive and post-exercise strategies that heated the skin using the suit (water inflow temperature 44.2ºC) were proven to be effective for heat acclimation. The passive strategy using the suit elicited reduction in rectal temperature and increase in back sweat rate in the post- heat tolerance test, whereas the other strategies did not. In this regard, we can recommend that especially the elderly or the disabled, who are not able to exercise in hot environments, utilize a water-perfused suit for at least 2 h-daily for ~10 days to induce heat acclimation. Elite athletes who want intensified heat acclimation could also incorporate this novel method into their training programs. When choosing between the passive and post-exercise heat acclimation strategies using a water-perfused suit, optimal heat acclimation responses for the specific training period and training duration will should have to be considered.

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Appendix

Fig. A1 Outer layer (A) and inner layer (B) of the suit and detachable layers (C).

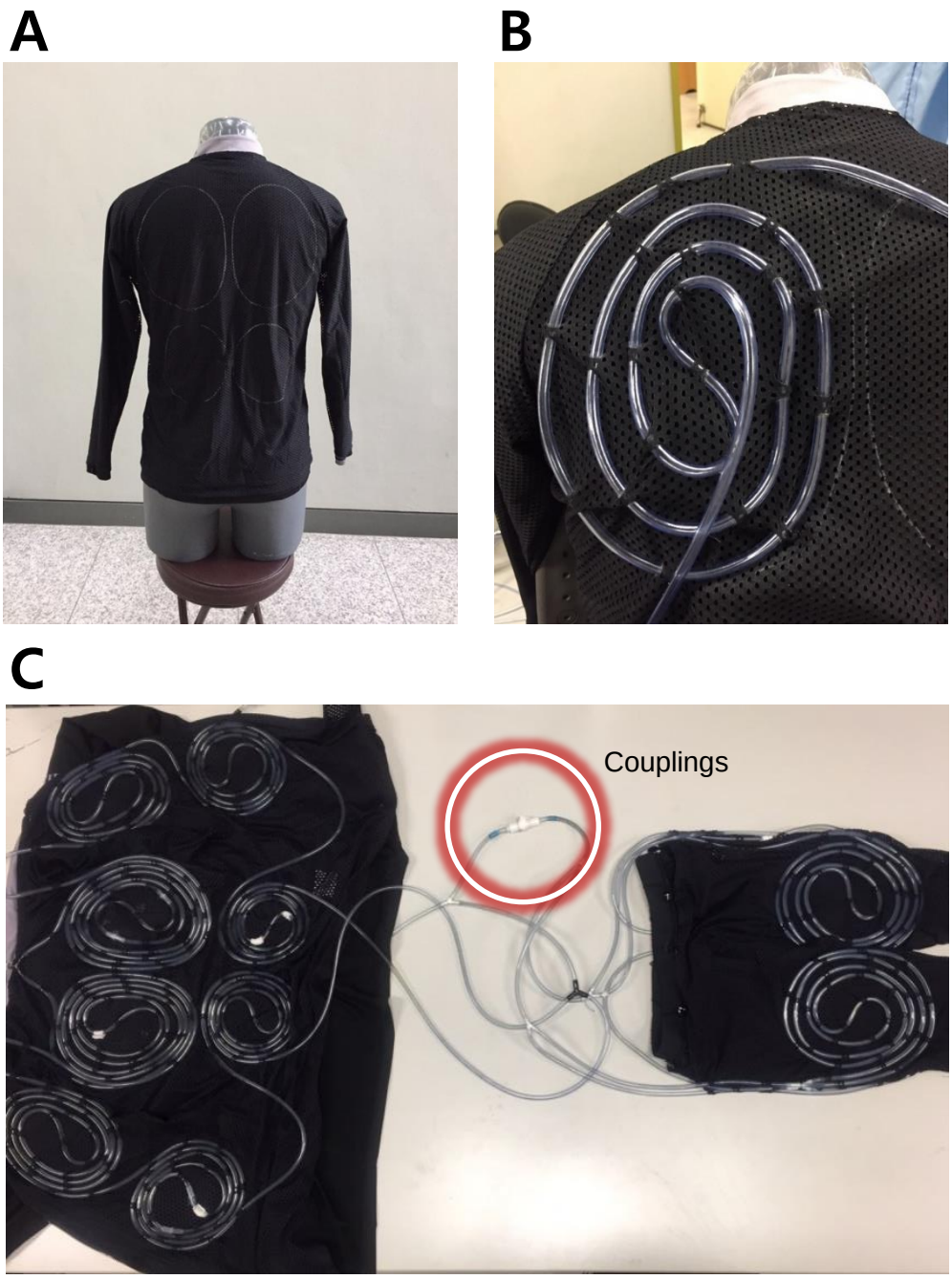

Fig. A2 Making process of a water-perfused suit: section drawing (A), tubing insertion (B), and couplings positioning (C).

Fig. A3 Pictures of a spirally-structured water-perfused suit.

Fig. A4 Donning process of a water-perfused suit: suit wearing (A), socks wearing (B), fitting and elastic bands donning (C), insulation clothing donning (D), and connection to the bath (E).

Fig. A5 Experimental photos during the 10-day heat acclimation training.

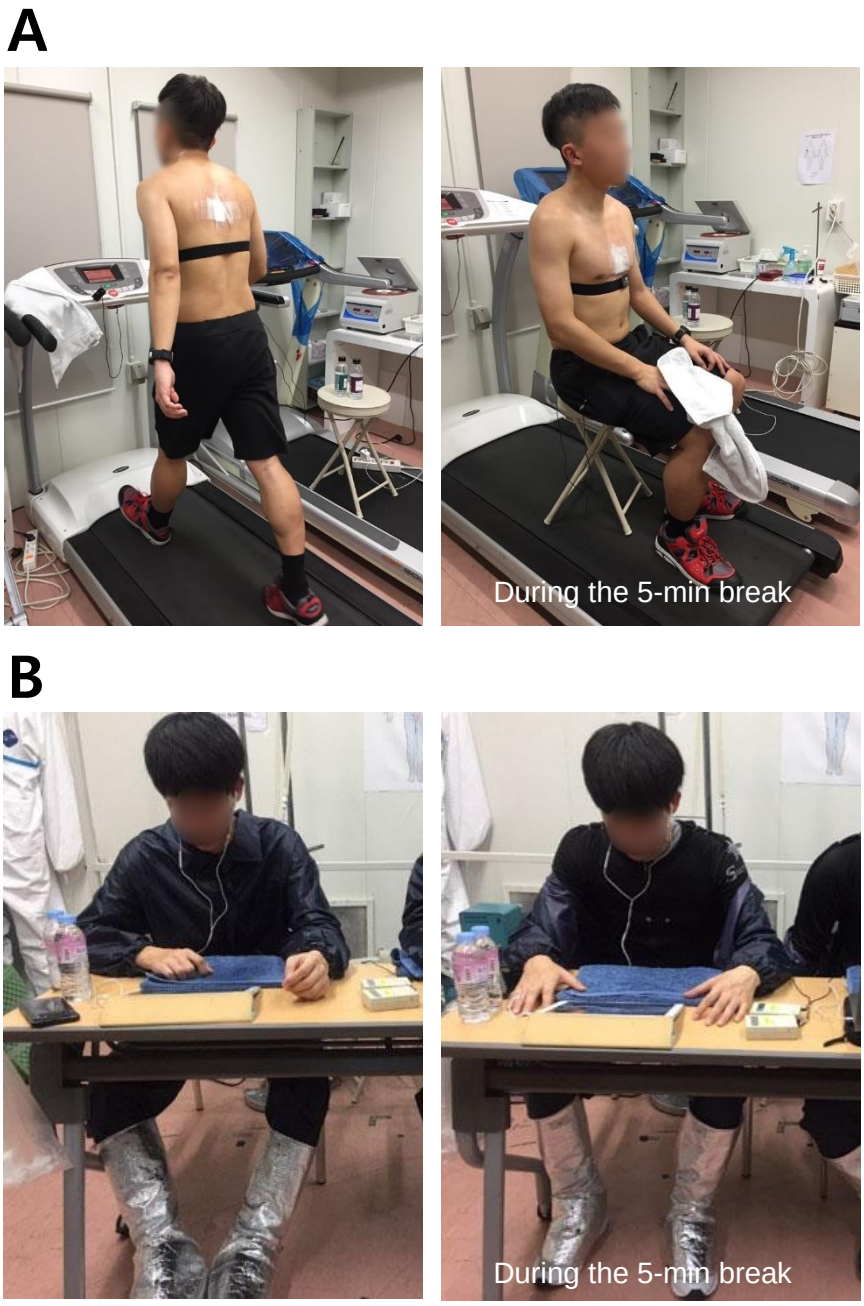

Fig. A6 Five-min break during the exercise (A) and during the passive heating using the suit (B).

Fig. A7 Experimental photos during the pre- and post- heat tolerance tests.

국문 초록

단기 열 적응이란 더운 환경에서 방열 반응이 효과적으로 일어날 수 있게 하는 생리적 및 행동적 변화를 통해 인체의 내열성을 항진시키는 것을 의미한다. 액티브 단기 열 적응 전략인, 운동을 통해 열 적응을 일으키는 방법에 대한 연구는 활발하게 진행되어 온 반면 운동 없이 외부에서의 열 자극을 통해 열 적응을 일으키는 패시브 단기 열 적응 전략에 대한 연구는 매우 미비하다. 본 연구는 피부를 가온하는 물 순환 수트를 이용한 10일 간의 패시브 전략 및 운동 후 착용 전략의 열 적응 유도 효과를 살펴보는 것을 목적으로 하였다. 저강도 운동의 액티브 열 적응 전략이 대조군으로 도입되었다. 열아홉 명의 젊은 남성들은 세 가지 열 적응 프로그램 중 하나에 랜덤으로 배치되었다: (1) '운동 조건' (여섯 명, $HA_{EXE,}$ 한 시간 동안 6 $km{\cdot}h^{-1}$ 로 트레드밀 운동 후 한 시간 앉아서 휴식, (2) '운동 후 착용 조건' (여섯 명, $HA_{EXE+SUIT}$, 한 시간 동안 6 $km{\cdot}h^{-1}$ 로 트레드밀 운동 후 한 시간 동안 물 순환 수트 착용, (3) '수트' 조건 (일곱 명, 두 시간 동안 물 순환 수트 착용). 모든 열 적응 프로그램은 기온 33°C와 상대습도 60%로 유지되는 인공 기후실에서 10일 연속으로 오전에 진행되었다. 패시브 가온은 본 연구에서 새롭게 개발한 물 순환 수트를 이용하였고, 유입 물 온도는 44°C 였다. 10일 훈련 전후로 진행한 내열성 테스트는 42°C 물에 60분 간 다리를 침지하여 진행하였다. 패시브 및 운동 후 착용 전략으로써의 10일 간의 물 순환 수트 착용은 직장온 감소 ($P < 0.05$), 평균피부온 감소 혹은 증가 ($P < 0.05$), 발한 반응 항진 ($P < 0.05$), 심혈관계 반응 항진 ($P < 0.05$)을 유도하였다. 10일 훈련 후 등 발한량과 직장온 하강은 패시브 전략에서만 나타났다 ($P < 0.05$). 패시브 및 운동 후 착용 전략은, 훈련 프로토콜 중 열 적응 발현 시점과 반응 극대화 훈련 일수에서 차이를 나타냈다. 본 연구의 결과는 기존에 시도되지 않았던, 단기 열 적응 전략으로써의 물 순환 수트 착용은 체온 조절 측면에서 이점을 가져다 줄 수 있음을 시사한다. 따라서 물 순환 수트를 이용한 패시브 가온은 더운 환경에서 운동하는 것이 힘든 개인들을 위한 열 적응 전략으로 활용될 수 있을 것으로 기대한다.

주요어: 단기 열 적응, 물 순환 수트, 패시브 열 적응 전략, 운동 후 착용 열 적응 전략

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