의류학석사 학위논문

Firefighters' cardiovascular and immune-inflammatory responses in a hot and humid environment: Effects of personal protective equipment (PPE) and age

고온 다습 환경 하 소방관의 심혈관계 및 면역·염증 반응: 개인보호복과 연령의 영향

2023 년 02 월

서울대학교 대학원
의류학과
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Firefighters' cardiovascular and immune-inflammatory responses in a hot and humid environment: Effects of personal protective equipment (PPE) and age

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Submitting a master's thesis of
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October 2022

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Abstract

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The purpose of this study was as follows: (1) First, examine the immune-inflammatory, cardiovascular and thermal strains caused by wearing Full PPE in a hot and humid environment. (2) Second, the entropy-TOPSIS model was used to calculate each firefighter's level of psycho-physiological strain and identify the individual characteristic that influenced that. (3) Third, by dividing groups based on the individual characteristic, physiological and psychological measures were to be checked in detail. A total of 28 current firefighters participated in two experimental conditions (condition 1: SU; condition 2: Full PPE). After a 10-minute rest in the climate chamber with a temperature of 30°C and a humidity of 61% RH, exercise and recovery were repeated. The results were (1) firstly, under the Full PPE condition, some immune-inflammatory responses, heart rate, rectal temperature, skin temperature, thermal sensation, and ratings of perceived exertion were significantly higher, and heart rate variability was lower than SU (all $P<0.05$). That meant the psychological-physiological strain increased by wearing Full PPE. (2) Second, as a result of deriving each firefighter's relative psycho-physiological strain level using the entropy-TOPSIS model, it was confirmed that the psycho-physiological strain level also increased with age. (3) Third, as a result of confirming the correlation between age and time point measurements, positive correlations were confirmed in some inflammatory responses and subjective perceptions, and negative correlation in heart rate variability of the time domain. In addition, middle-aged firefighters (Older-FF) in their 40s and 50s increased significantly in immune and inflammatory reactions than young-aged firefighters (Young-FF) in their 20s and 30s. At the same time, the two groups were stressed at a similar level since there was no significant difference in the degree of decrease in HRV and increase in thermal sensation and ratings of perceived exertion as the protocol progressed. These results showed that wearing personal protective equipment in a hot and humid environment increased not only total sweat rate and core temperature but also immune-inflammatory responses. In addition, the comparative analysis results of Older-FF and Young-FF suggested that the age of firefighters should be considered when constructing work-rest time or repetitive work during fire suppression or rescue operations in summer. This study confirmed that when firefighters wore Full PPE in summer, immune-inflammatory responses, cardiovascular and thermal strain increased significantly. In addition, each firefighter's physiological and psychological strain was derived, and it was confirmed that middle-aged firefighters could be more dangerous during summer fire suppression, rescue, and first aid work than young firefighters. The results of this study can be used to improve turnout gear to reduce the physiological and psychological strain on firefighters in summer. Furthermore, the results of comparing Young-FF and Older-FF can be applied to develop firefighting work guidelines for the health and safety of middle-aged firefighters.

Keywords: Firefighter, Personal Protective Equipment, psycho-physiological strain, immune-inflammatory response, cardiovascular strain, thermal strain, age, Entropy-TOPSIS model

Student Number: 2021-21114

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List of Abbreviations

SU	Station uniform
Full PPE	Full personal protective equipment
Young-FF	Young firefighter
Older-FF	Older firefighter
PRE	Right before entering the climatic chamber
EXE1	The phase of the first exercise
RCV1	The phase of the first recovery
EXE2	The phase of the second exercise
RCV2	The phase of the second recovery
HR	Heart rate
HRV	Heart rate variability
CRP	C-reactive protein
IL-6	Interluekin-6
TNF- α	Tumor necrosis factor α
T_{re}	Rectal temperature
T_{sk}	Skin temperature
$\overline{T}_{sk}$	Mean skin temperature
TSR	Total sweat rate
VO_{2max}	Maximal volume of oxygen consumed during graded exercise test
BMI	Body mass index
%BF	Total body fat

Chapter 1. Introduction

Firefighters should perform the work repeatedly in hot and humid environments, wearing impermeable and heavy personal protective equipment. It is well documented that this increases the cardiovascular, thermal and immune-inflammatory strain. Responses related to cardiovascular strain can be expressed in heart rate and heart rate variability. Heart rate reached the maximum age prediction during a live-fire drill in hot environments (Smith et al., 2001). In addition, it reached a maximum of 194 bpm during repeated treadmill exercise in hot and humid summer environments (Chou, 2011). Heart rate variability (HRV) is an indicator that can confirm cardiovascular health and physiological stress by non-invasive evaluation of cardiac autonomic control. Simulated firefighting with heat loads disturbed HRV response (Marcel-Millet et al., 2018) and decreased some indicators (Gendron et al., 2022), which meant being under stress and less parasympathetic nerve reactivation. Next, increases in the thermal strain can be observed such as an increase of core temperature (Horn et al., 2013) and total sweet rate (Lee, 2014). Changes in thermoregulatory strain influence how permeable the gut's internal walls are, allowing endotoxins or lipopolysaccharides (LPS) to flow from the digestive system into the blood (Lambert et al. 2002) and possibly elicit an immunological response. These pro-inflammatory cytokines, produced in the early stages of the inflammatory response, can trigger the release of IL-6 and TNF-α (Main et al., 2020). Exercise in the heat also increases catecholamine and cytokine responses (Neil and Martin. 2006), as well as leukocytes and platelets of firefighters who are wearing Full

Personal Protective Equipment (Full PPE) in hot environments (Walker et al., 2015).

In conclusion, a combination of elements including hot and humid summer environments, repetitive metabolic work, and personal protective equipment cause cardiovascular, thermoregulatory, and immune-inflammatory responses. To examine the effect of wearing Full PPE among the three factors, it is required to compare with the control clothing condition. In general, firefighters wear station uniforms under Full PPE (Tochihara et al., 2022). However, in most studies so far, only full PPE wearing conditions were carried out without control conditions. Otherwise, control conditions are conducted as short-sleeved shorts (Lee et al., 2013) or station pants with a cotton short-sleeve shirt (McLellan and Selkirk, 2004). Therefore, this study attempts to widely confirm cardiovascular, thermoregulatory strain and immune-inflammatory response, including two clothing conditions: a station uniform (control condition) and Full PPE (experimental condition).

Next, the physiological and psychological responses of firefighters are affected by individual characteristics such as physical fitness level, age, body mass index (BMI), and % body fat (Kannel et al. 1985; Taylor et al. 2010; Wright-Beatty et al. 2014). For instance, firefighters with low fitness levels may have a higher strain at the same level of activity load than those who don't (Baur et al. 2012). Walker et al. (2017) also found that high body fat and low lean mass were related to elevated leukocyte values in the heat. Especially about age, when exercising in the heat, older male firefighters showed a more considerable decline in whole-body heat loss capacity than younger firefighters, indicating a greater risk of heat-related injuries (Kenny et al. 2015). On the other hand, there was no difference in the firefighter age group's thermal, cardiovascular, and perceptual responses while exercising in hot-humid or hot-dry environments (Wright et al. 2014).

However, in most studies, the relationship with individual risk factors was confirmed by focusing on only some measurements among various strain indicators. Through previous research, this study is novel to derive individual comprehensive psycho-physiological strain levels from cardiovascular, thermal, and immune-inflammatory measurements. For this purpose, weighing and comparing the individual measurements is necessary. It can be calculated by an Entropy-TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) model. Entropy means the degree of information uncertainty in information theory (Shannon, 1948), and entropy weighting is an objective technique for mathematically determining weights using only the measured data. Subsequently, the TOPSIS technique is used to prioritize optimal alternatives from finite measurements (Hwang and Yoon, 1981). Based on this, this study aims to determine the physiological and psychological strain experienced by a firefighter who wears full protective equipment (PPE) while repeatedly working in a hot and humid environment.

To sum up, the purpose of this study is as follows. (1) How much strain does Full PPE have on the cardiovascular, thermal and immune-inflammatory systems? (2) How much psycho-physiological strain is brought on firefighters by performing repetitive tasks and wearing Full PPE in a hot and humid environment? And also, which individual characteristics affect the derived psycho-physiological strain level? (3) For a significant individual characteristic, how do group differences appear for physiological and psychological responses in detail?

Chapter 2. Methods

2.1. Subjects

A total of 28 Korean professional male firefighters in charge of putting out fires or performing rescues participated in the study. Firefighters who only worked in emergency medical services or office work were excluded since they did not experience excessive thermal strain directly. They worked in one of the fire stations among Gangnam, Seocho, Gwanak, and Gwangjin. Duration of job, age, height, body weight, % body fat, body mass index, and VO2max were described in Table 2.1. With the Bruce protocol, a graded treadmill exercise test was used to determine VO2max. In addition, firefighters were self-reported to see if they had been diagnosed with diabetes, stroke, cardiovascular disease or hypertension in the past, or if they had it at the time of the investigation. For health habits such as frequency of smoking (No, <5, 5-10, 11-20, >20 in a day), alcohol drinking (No, ≤2, 3-5, ≥6 in a week) and exercising (No, ≤2, 3-5, ≥6 in a week) was also responded by self-reporting. Other demographic characteristics, self-identified heat tolerance, disease-related family history, and job-related characteristics are shown in the appendix (Table A). The subjects gave their prior informed consent after being informed of the study's purpose, procedures, discomforts, and risks. The Institute Review Board of Seoul National University approved this study (IRB No. 2209/004-014).

Table 2.1 Individual characteristics of total firefighters

ID	Sex	Duration of job	Age	Height	Body weight	Body fat(%)	BMI	VO_{2max}	Stroke*	Cardio-vascular disease*	Hyper-tension*	Diabetes*	Smoking	Alcohol drinking	Exercising
A	male	1	27	176.3	89.6	15.9	28.8	44.3	No	No	No	No	5-10	No	≥6
B	male	1	28	174.5	76.2	8.0	25	61.0	No	No	No	No	11-20	No	3-5
C	male	1	27	182.4	70.8	10.4	21.3	49.4	No	No	No	No	No	No	≥6
D	male	2	27	175.6	75.4	7.2	24.5	64.5	No	No	No	No	No	≤2	≥6
E	male	3	29	186.3	91.9	20.4	26.5	46.1	No	No	No	No	5-10	≤2	3-5
F	male	4	30	167.4	70.9	15.7	22.4	50.1	No	No	No	No	No	≤2	3-5
G	male	4	31	184.1	94.0	21.9	27.6	43.5	No	No	No	No	5-10	≤2	≤2
H	male	5	30	182.5	82.4	16.9	24.7	41.5	No	No	No	No	No	No	3-5
I	male	1	31	186.0	86.7	13.7	25.1	48.4	No	No	No	No	No	No	3-5
J	male	7	32	175.2	81.8	17.6	26.6	61.7	No	No	No	No	11-20	≤2	≥6
K	male	1	31	177.6	82.4	14.6	26.1	43.6	No	No	No	No	No	No	≥6
L	male	4	33	176.8	72.4	16.2	23.1	50.5	No	No	No	No	No	≤2	3-5
M	male	7	36	168.5	75.8	24.5	26.7	41.2	No	No	No	No	No	≤2	3-5
N	male	8	35	169.1	59.2	14.8	20.7	52.3	No	No	No	No	No	≤2	≤2

O	male	9	36	169.9	74.2	23.5	25.7	54.0	No	No	No	No	No	≤2	≥6
P	male	2	38	177.5	69.3	17.5	21.8	43.6	No	No	No	No	No	No	≤2
Q	male	13	42	182.8	75.3	12.3	22.5	42.2	No	No	No	No	11-20	≤2	≤2
R	male	10	42	176.3	66.5	17.8	21.4	45.2	No	No	No	No	11-20	3-5	≤2
S	male	19	45	170.9	76.3	26.9	26.1	42.4	No	No	No	No	No	No	3-5
T	male	14	44	187.1	104.1	31.9	29.7	33.8	No	No	Yes[P]	No	No	≤2	3-5
U	male	15	48	178.4	105.7	28.0	33.2	40.0	No	No	Yes*	No	11-20	≤2	≤2
V	male	21	47	170.3	60.8	11.6	20.6	53.2	No	No	No	No	11-20	3-5	≤2
W	male	16	48	166.5	69.1	17.9	24.6	39.5	No	No	No	No	No	≤2	3-5
X	male	21	44	174.6	70.2	16.8	23.0	40.1	No	No	No	No	No	No	3-5
Y	male	25	54	173.6	81.2	25.8	26.9	52.2	No	No	Yes*	No	No	≤2	3-5
Z	male	28	55	169.7	67.2	15.8	23.3	43.2	No	No	No	No	No	No	3-5
AA	male	30	58	178.0	92.3	25.9	29.2	33.9	No	No	No	Yes[P]	No	≤2	≤2
AB	male	23	50	177.2	79.6	21.8	25.4	42.5	No	No	No	No	5-10	≤2	≤2
Total	-	11 ± 9	39 ± 9	176.3 ± 11.6	78.6 ± 11.6	18.3 ± 6.1	25.1 ± 3.0	46.6 ± 7.6	-	-	-	-	-	-	-

Total data reported as mean±sd Yes*=Yes/Yes
Abbreviation: BMI Body mass index, VO_{2max} maximal volume of oxygen consumed during graded exercise test
Yes[P]: respondent had been diagnosed with disease in the past; Yes*: respondent had it at the time of the investigation but nor severe

2.2. Environmental and experimental clothing conditions

2.2.1 Environmental conditions

All trials were conducted in a climate chamber (FLC-5000S, Fuji Medical science, Japan) with a temperature of 30.1 ± 0.4°C and humidity of 61 ± 1 %RH. The environmental condition was based on the consideration of Asia's hot and humid summer climate. Additionally, the experimental environments of the previous study were taken into account that confirmed the physiological responses of firefighters when wearing personal protective equipment in hot and humid environments (Chou et al., 2008; Chou et al., 2011; and Lee et al., 2014).

2.2.2 Experimental clothing conditions

Two different clothing conditions were conducted in this experiment, all of which were undertaken in an identical environment: (1) Station Uniform condition (SU), (2) Full Personal Protective Equipment (Full PPE). SU condition consisted of undershorts, station uniform [short sleeve shirts and long pants], socks, and sneakers, and the total weight was 1.4 ± 0.1 kg. Full PPE consisted of undershorts, station uniform [short sleeve shirts and long pants], socks, turnout jacket and pants, fire hood, helmet, firefighting gloves, boots, and self-contained breathing apparatus [SCBA], the total weight was 17.2 ± 0.2 kg (Table 2.2). They were instructed to bring their uniforms according to the experimental clothing conditions, and the oxygen cylinder was maintained without oxygen inside.

Table 2.2 Experimental clothing conditions

	SU condition	Full PPE condition
Picture		
Ensemble	undershorts, station uniform [short sleeve shirts and long pants], socks, sneakers	undershorts, station uniform [short sleeve shirts and long pants], socks, turnout jacket and pants, fire hood, helmet, firefighting gloves, boots, and self-contained breathing apparatus [SCBA]
Total weight	1.4 ± 0.1 kg	17.2 ± 0.2 kg

Abbreviation: SU station uniform, Full PPE full personal protective equipment

2.3. Experimental procedures

All trials were conducted in the mornings to minimize the influence on circadian rhythms. Subjects visited an experimental laboratory for three separate times, including the VO_{2max} test and two experimental trials. They carried out one clothing condition on a visit. Each visit was separated by at least a two-day interval to reduce the impact of the previous experiment. The subjects drank 330 mL of water upon arrival. Then, before and after the trial, they weighed on a scale (Mettler-Toledo ID2, resolution of 1 g, Germany) in a semi-nude state. Subjects wore sensors and probes to measure their heart rates, rectal and skin temperatures. Baseline rectal temperatures were monitored at every trial to ensure the normal range of 37.0 ± 0.5°C. Subjects took a venous blood sample from their arm (blood sampling) and measured Heart Rate Variability (HRV) in the pre-room. If the clothing condition was Full PPE condition, the personal protective equipment was worn right before entering the climatic chamber. In the climatic chamber, they proceeded for a total of 110 minutes (Fig. 2.1). The protocol was determined based on Tochihara et al. (2022) which is the review for developing a test method of measuring the thermal strain of firefighters. First, Subjects rested on the stool for 10 minutes (REST). Next, after completing their first exercise (EXE1, walking on a treadmill at 5 $km \cdot h^{-1}$ with 1% grade), they quickly removed their turnout jacket, fire hood, helmet, firefighting gloves, SCBA and had a 20-minute recovery (RCV1, sitting on the chair). Blood sampling, 330mL of water intake, and HRV measuring were carried out consecutively during the recovery. They did one more exercise (EXE2, walking on a treadmill at 5.5 km.h-1 with a 1% grade) before another recovery (RCV2, sitting on the chair).

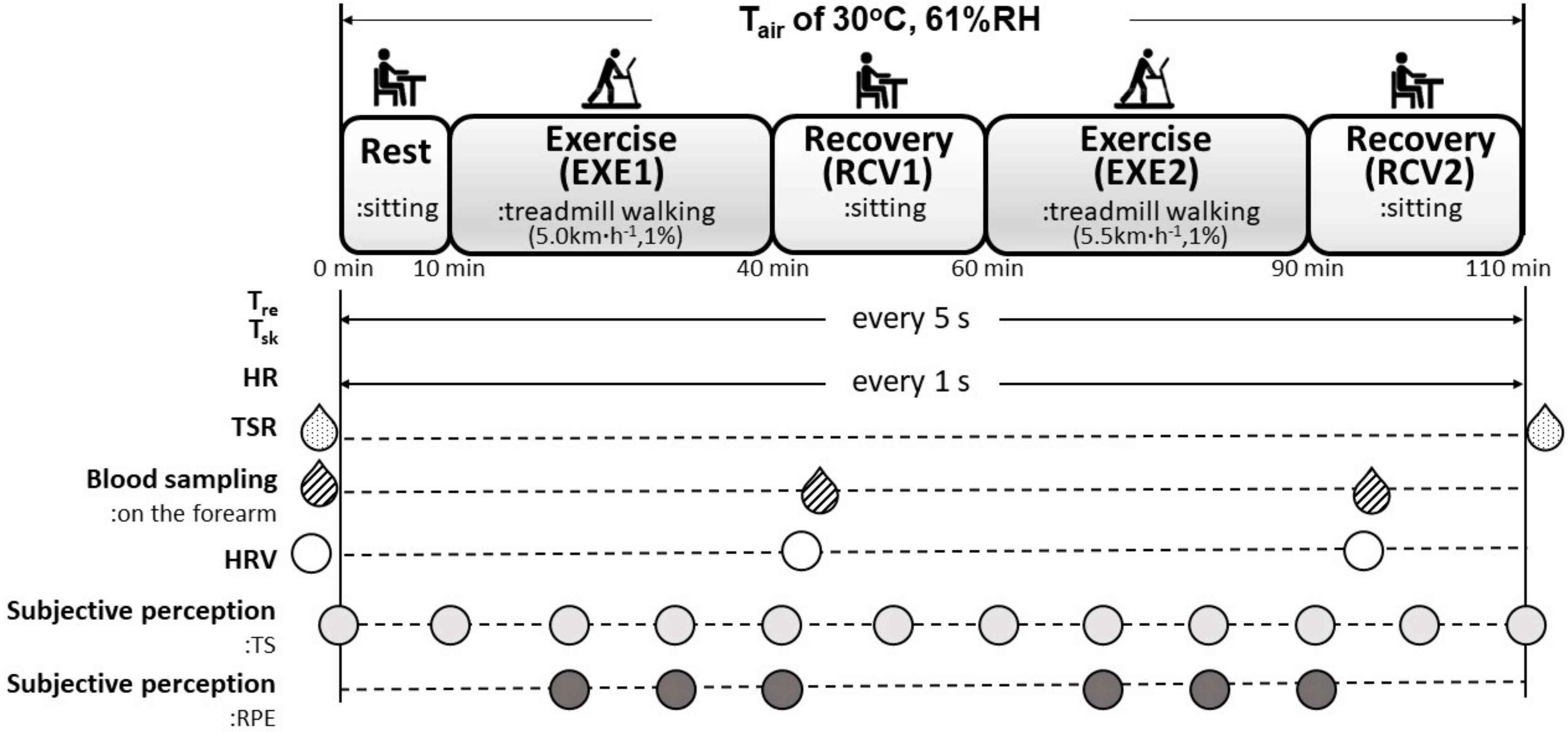


Fig. 2.1 Experimental protocol and measurements

Abbreviation: PRE right before entering the climatic chamber (EXE1 first exercise, RCV1 first recovery, EXE2 second exercise, RCV2 second recovery. T_{re} rectal temperature, T_{sk} skin temperature, HR heart rate, TSR total sweat rate, HRV heart rate variability, TS thermal sensation, RPE ratings of perceived exertion

2.4. Measurements and Calculations

The measurements were divided into three categories: (1) immune-inflammatory responses, (2) cardiovascular responses, (3) thermal responses. (1): Immune-inflammatory responses were all physiological measurements. (2): In cardiovascular responses, heart rate was measured as a physiological measurement, and heart rate variability was measured as a psycho-physiological response. (3): In thermal responses, rectal temperature, skin temperature, total sweat rate were physiological measurements, while thermal sensation and ratings of perceived exertion were psychological measurements (subjective perception).

2.4.1 Immune-Inflammatory responses

The immune-inflammatory responses were confirmed through blood sample component analysis. Three times during each trial, a pathologist and qualified nurse took venous blood samples.: (1) Pre; (2) RCV1; (3) RCV2. The venous blood was collected in two tubes (A and B) and evaluated; (A) 3.0 ml vacutainer tubes with tripotassium ethylenediaminetetraacetic acid (K3 EDTA) for CBC (Complete blood count) including leukocytes and platelets analysis. The tubes were inverted several times, maintained at 2-8oC, and analyzed within 24 hours after collection. The CBC analysis was performed using an automated analysis system (XN-1000, Sysmex, Japan) with flow-cytometry technology. (B) 5.0 ml serum separator tube (SST) for inflammatory markers including interleukin-6 (IL-6), tumor necrosis factor (TNF-α), and C-reactive protein (CRP). After being repeatedly inverted, the SST tube was coagulated for 30 minutes at room temperature and centrifuged for 10 minutes at

6,000 rpm. The separated serum was transferred into 2 ml microtubes frozen at -20ºC. The remaining SST tubes were stored refrigerated at 2-8°C. Enzyme-Linked Immunosorbent Assay (Versa Max, Molecular device, USA) was used to evaluate the IL-6 and TNF-α, while CRP was donned with Turbidimetric immunoassay (c501, Roche, Swiss).

2.4.2 Cardiovascular responses

A portable chest strap and a polar electrode were used to check heart rate every 5 seconds throughout the trial (RS400, Polar Electro Oy, Finland). Heart Rate Variability (HRV) was measured three times: (1) Rest; (2) RCV1; (3) RCV2. Each measurement was recorded continuously for 5 minutes and 30 seconds. Electrocardiogram (ECG) electrodes were affixed to both sides of the wrist and the left side of the ankle. They were connected to the BioAmp cable (Bio Amp, ADInstruments, Australia), and then the 2ch Data Acquisition system (PowerLab 2/26, ADInstruments, Australia). The data were calculated by HRV analysis software (LabChart, ADInstruments, Australia). The analysis of HRV included time domain analysis based on NN interval in electrocardiogram and frequency domain analysis that is useful for sympathetic-parasympathetic evaluation. RMSSD, SDNN, and nNN50 were the indicators in time domain analysis (Table 2.3). SDNN was used for evaluating overall HRV meanwhile RMSSD and pNN50 were used for short-term heart rate variability. In frequency range analysis, there are low frequencies (absolute power in the low-frequency [LF, 0.04 – 0.15 Hz]) and high frequencies (absolute power in the high-frequency range [HF, 0.15 – 0.4 Hz)]. The balance could be examined through LF/HF, which is the ratio of sympathetic to parasympathetic. In the situation of stress, indicator values tend to decrease except for LF/HF.

Table 2.3 Variables of HRV and tendency under the stress conditions

Domain	Variable	Unit	Description	During stress
Time	RMSSD	ms	The Root Mean Square of the Successive Differences	↓
	SDNN	ms	The Standard Deviation of all NN interval	↓
	nNN50	%	The percentage of intervals where the variation of consecutive NN intervals is more than 50 ms	↓
Frequency	LF/HF	-	The ratio between Low Frequency and High Frequency	↑(↓)

2.4.3 Thermal responses

T_{re} was measured at a depth of 16 cm from the anal sphincter every 5 s using the data logger (LT-8A, Gram Ltd, Japan). Tsk was monitored every 5 s on the following 7 regions of the left body except the forehead: the forehead (middle), chest, forearm, hand, thigh, calf, and foot using a data logger (LT-8A, Gram Ltd, Japan). Chest temperature was considered the representative trunk temperature following Lee et al. (2010). Mean skin temperature (T_{sk}) was calculated using a modified Hardy and DuBois' formula equation (Hardy and Dubois, 1938) [Eq. 2.1].

Mean skin temperature ($\overline{T}_{sk}$) (ºC)

$$= 0.07\ T_{forehead} + 0.35\ T_{chest} + 0.14\ T_{forearm} + 0.05\ T_{hand} + 0.19\ T_{thigh} + 0.13\ T_{calf} + 0.07\ T_{foot} \quad \text{[Eq. 2.1]}$$

TSR was calculated by subtracting the pre-weight from the post-weight. Psychological responses were recorded every 10 min using the following scales: nine-point TS (4: very hot, 3: hot, 2: warm, 1: slightly warm, 0: neutral, -1: slightly cool, -2: cool, -3: cold, and -4: very cold; ISO 10551, 1995); RPE was obtained during EXE1 and EXE2 according to the Borg scale (a scale of 6 (very, very light) to 20 (very, very hard); Borg, 1982)

2.5. Data analysis

Data analysis was divided into three processes according to the purpose of the study. First, it was confirmed for each measurement whether there was a difference according to clothing conditions. Second, the relative degree of strain induced under the Full PPE condition was calculated. In addition, identified which characteristics of the subject were associated with the degree of physiological-psychological strain. Finally, for meaningful personal characteristics, what differences appeared in what measurements. All data were reported as mean and standard deviation (mean ± SD). Entropy-TOPSIS was performed by MS Excel. Other statistics were analyzed with SPSS 27.0. The significance was accepted at $P < .05$, and trends were noted for $0.05<P\leq0.10$.

2.5.1 Immune-inflammatory, Cardiovascular and Thermal responses induced by Full PPE

To examine the strain caused by Full PPE when firefighters repeatedly exercised in a hot and humid environment, all measurements of the Full PPE were compared with the SU. In the physiological responses which were continuously measured, the last 5-min average (5th – 10th min for the Rest, Rest meant before entering the chamber in HRV and immune-inflammatory response; 35th – 40th for the EXE1; 55th – 60th for the RCV1; 85th – 90th for the EXE2; 105th – 110th for the RCV2) were selected to represent values of each period respectively. Two-way repeated measure ANOVA was conducted to determine the difference between the clothing and time factor. The psychological responses of TS and RPE were tested using the Mann-Whitney U Test.

2.5.2 The psycho-physiological strain of each firefighter and individual characteristics that affected

The following three processes were needed to identify individual characteristics that affect psychological and physiological (psycho-physiological) strain levels: (A) obtaining entropy weights of each measurement; (B) calculating the relative psycho-physiological strain of individual firefighters by TOPSIS; (C) evaluating the effects of individual characteristics.

(A): To comprehensively examine each firefighter's psycho-physiological strain level, it was necessary to weigh the measurements. The entropy weight was obtained by determining and calculating the measurements. Evaluation measurements were obtained based on previous studies of firefighters' cardiovascular responses in a hot and humid environment (Table 2.4). Skin temperature, TSR, and pNN50 were excluded that were not covered in most studies. Since the baseline values of subjects are different, the delta value (△RCV2-Rest) was used to derive the relative value. The measurements were designated as the change over time considering the individual baseline, calculated by subtracting a resting value from a second recovery value (△RCV2-Rest).

Table 2.4 Psycho-physiological strain measurements with previous studies

Index		Reference
Cardiovascular response	HR	Hostler et al. (2014); Smith et al. (2001); Smith et al. (2005); Smith et al. (2011); Walker et al. (2015a); Walker et al. (2015b); Wright-Beatty et al. (2014)
	SDNN	Narciso et al. (2020); Schwerdfeher et al. (2019)
	RMSSD	Jeklin et al. (2021); Narciso et al. (2020); Schwerdfeher et al. (2019)
	pNN50	Narciso et al. (2020)
	LF/HF	Narciso et al. (2020); Schwerdfeher et al. (2019)
Immune-inflammatory response	Platelet	Hostler et al. (2014); Smith et al. (2011); Walker et al. (2015a); Walker et al. (2015b); Walker et al. (2017)
	Leuko-cyte	Smith et al. (2011); Walker et al. (2015a); Walker et al. (2015b); Walker et al. (2017)
	Lympho-cyte	Smith et al. (2005); Smith et al. (2011); Walker et al (2015a)
	CRP	Walker et al (2015a); Walker et al. (2017); Wright-Beatty et al. (2014)
	IL-6	Main et al. (2020); Walker et al. (2015a); Wolkow et al. (2015); Wolkow et al. (2017); Wright-Beatty et al. (2014)
	TNF-α	Main et al. (2020); Walker et al (2015a); Walker et al. (2017); Wolkow et al. (2015); Wolkow et al. (2017); Wright-Beatty et al. (2014)
Thermal response	T_{re}	Hostler et al. (2014); Smith et al. (2005); Smith et al. (2011); Walker et al. (2015a); Walker et al. (2015b); Walker et al. (2017); Wright-Beatty et al. (2014)
	T_{sk}	Hostler et al. (2014)
	TSR	Walker et al (2015a)
	TS	Hostler et al. (2014); Smith et al. (2001); Smith et al. (2011)
	RPE	Hostler et al. (2014); Smith et al. (2001); Smith et al. (2005); Smith et al. (2011); Walker et al (2015)

Abbreviation: HR heart rate, CRP c-reactive protein, IL-6 interleukin-6, TNF- α tumor necrosis factor α, T_{re} rectal temperature, T_{sk} skin temperature, TSR total swat rate, HRV heart rate variability, TS thermal sensation, RPE ratings of perceived exertion.

The process of obtaining entropy weight was as follows. An evaluation matrix with I (=24) subjects and j (=13) measurements were set up as Eq. 2.2.

$$X_{m\times n} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_I \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_j \end{array} \\ \begin{bmatrix} X_1(1) & X_1(2) & \cdots & X_1(j) \\ X_2(1) & X_2(2) & \cdots & X_2(j) \\ \vdots & \vdots & & \vdots \\ X_i(1) & X_i(2) & \cdots & X_i(j) \end{bmatrix} \end{array}$$ ....[Eq. 2.2]

Since each measurement had a different unit, normalizing was required. Accordingly, the measurements were normalized, $\rho_i(j)$, through Eq. 2.3 when the psycho-physiological strain and measurement were proportional, and Eq. 2.4 when inversely proportional: was calculated by:

$$\rho_i(j) = \frac{X_i(j) - minX_i(j)}{maxX_i(j) - minX_i(j)}$$ ....[Eq. 2.3]

$$\rho_i(j) = \frac{maxX_i(j) - X_i(j)}{maxX_i(j) - minX_i(j)}$$ ....[Eq. 2.4]

The entropy value of each measurement was obtained through:

$$H_j = -\lambda \sum_{i=1}^{m} \rho_i(j) ln\rho_i(j) \ \forall j \ (\lambda = \frac{1}{lnm}, \ 0 \le H_j \le 1)$$ ....[Eq. 2.5]

The degree of information diversification $\overline{H_j}$ was calculated through:

$$\overline{H_j} = 1 - H_j$$ ....[Eq. 2.6]

The entropy weight (w_j) corresponding to each j index was derived through:

$$w_j = \frac{\bar{H}_j}{\sum_{j=1}^{n} \bar{H}_j} \quad (\sum_{j=1}^{n} w_j = 1) \text{ ...... [Eq. 2.7]}$$

(B): Through the TOPSIS model, the relative value of each subject's comprehensive psycho-physiological strain of each subject (Ci) was determined through the TOPSIS model. The closer C_i was to 1, the closer it was to the purpose. Considering the purpose of this study, the original "possible alternative" became "each subject", and the "optimal choice" became a "psycho-physiological strain". As a result, Ci, which was close to 1, meant that psycho-physiological tension was relatively high.

Suppose that there is an evaluation matrix as shown in [Eq. 2.2]. To eliminate the effect of measurement results of dimensions, the original matrix (R=$[r_i(\mathrm{j})]_{\mathrm{m \times n}}$) normalized:

$$r_i(j) = \frac{x_i(j)}{\sum_{j=1}^{m} x_i(j)^2} \quad (i= 1, 2,\cdots m; \quad j=1,2,\cdots n) \text{ ...... [Eq. 2.8]}$$

Then, the entropy weight was multiplied by a normalized metric to obtain a weighted measurement:

$$v_i(j) = w_j r_i(j), (i= 1, 2,\cdots m; \quad j=1,2,\cdots n) \text{ ...... [Eq. 2.9]}$$

To obtain the psycho-physiological strain, the optimal value V^+ and the worst value V^- was estimated by:

$$V^+ = (V_1^+, V_2^+, \ldots, V_m^+)$$

$$V^- = (V_1^-, V_2^-, \ldots, V_m^-)$$

$$V_j^+ = \begin{cases} \max v_i(j), \textit{the more the better} \\ \min v_i(j), \textit{the more the worse} \end{cases}$$

$$V_j^- = \begin{cases} \max v_i(j), \textit{the more the worse} \\ \min v_i(j), \textit{the more the better} \end{cases} \quad \text{[Eq. 2.10]}$$

The distance between the positive ideal subject value (S_i^+) and negative ideal subject value (S_i^-) was derived through [Eq. 2.11] for all experimental subjects:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_i(j) - V_j^+)^2}, (i = 1, 2, \ldots m; j = 1, 2, \ldots n)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_i(j) - V_j^-)^2}, (i = 1, 2, \ldots m; j = 1, 2, \ldots n) \quad \text{[Eq. 2.11]}$$

The relative degree of psycho-physiological strain (C_i) was calculated by:

$$C_i = \frac{S_i^+}{(S_i^+ + S_i^-)}, \ (0 \leq C_i \leq 1; i = 1, 2, \ldots m) \quad \text{[Eq. 2.12]}$$

(C): Multiple regression analysis was conducted to identify the effect of individual characteristics on C_i. In the analysis, Age, BMI, %BF, and VO_{2max} were independent variables, and C_i was the dependent variable.

2.5.3 Analysis of psycho-physiological strain by significant factor group

First, Pearson correlation analysis was conducted to confirm the relationship between the significant personal characteristic revealed through 2.5.2 and each measurement. Secondly, to check the difference according to time (Rest, RCV1, RCV2) and individual characteristics, the subjects were divided into two groups. However, in the immune-inflammatory response obtained through blood sampling and HRV, the value of Rest which corresponds to the baseline is obtained just before entering the chamber. Two-way repeated measure ANOVA was conducted to determine the difference between the group and time factor in immune-inflammatory, cardiovascular, and thermal responses. Thirdly, Increase or decrease values were calculated to check whether there was a difference in the degree of increase or decrease in physiological and psychological strain according to the individual characteristic group: △RCV1-Rest: subtracting a resting value from a first recovery value; ⊿RCV2- Rest: subtracting a resting value from a second recovery value. Two-way repeated measure ANOVA was also conducted. In addition, an independent T-test was examined to analyze whether there was a difference between groups at each point. The subjective responses of TS and RPE were confirmed differences between groups by Mann Whitney U Test.

Chapter 3. Results

3.1. Immune-Inflammatory, Cardiovascular and Thermal responses induced by Full PPE

3.1.1 Immune-inflammatory responses

Immune-inflammatory responses were physiological measurements. All values increased over time except the platelet value in RCV2 (P<0.001, CRP P-value: 0.007). In addition, leukocyte, lymphocyte, and IL-6 tended to differ depending on the clothing conditions (P<0.1). When examining the difference according to the clothing condition at each time, there was no difference at Rest and RCV1. However, RCV2, leukocyte (7.4 ± 2.5 $10^3 \cdot mL^{-1}$), lymphocyte (2.6 ± 0.8 $10^3 \cdot mL^{-1}$)values of the Full PPE condition were significantly higher than SU condition (6.1 ± 1.7 and 2.1 ± 0.7 $10^3 \cdot mL^{-1}$ respectively)(P<0.05). Furthermore, platelet (297.3 ± 42.6 and 263.5 ± 38.1 $10^3 \cdot mL^{-1}$ for Full PPE and SU respectively), and IL-6 (4.2 ± 3.5 and 1.6 ± 1.6 $pg \cdot mL^{-1}$ for Full PPE and SU respectively) showed statistical significance at P<0.01 (Table 3.1).

Table 3.1 Immune-inflammatory responses between SU and Full PPE

	Time	SU	Full PPE	Time *P*-value	Clothing *P*-value
Leukocyte	Rest	5.3 ± 1.1	5.7 ± 1.8	<0.001	0.084
(10^3·mL^{-1})	RCV1	5.6 ± 1.1	6.3 ± 1.9		
	RCV2	**6.1 ± 1.7**	**7.4 ± 2.5***		
Lymphocyte	Rest	1.9 ± 0.5	1.9 ± 0.5	<0.001	0.085
(10^3·mL^{-1})	RCV1	1.9 ± 0.5	2.2 ± 0.6		
	RCV2	**2.1 ± 0.7**	**2.6 ± 0.8***		
Platelet	Rest	256.5 ± 39.3	258.6 ± 39.7	<0.001	0.242
(10^3·mL^{-1})	RCV1	270.2 ± 48.5	280.3 ± 42.8		
	RCV2	**263.5 ± 38.1**	**297.3 ± 42.6****		
IL-6	Rest	1.4 ± 1.6	1.6 ± 2.3	<0.001	0.064
(pg·mL^{-1})	RCV1	1.6 ± 1.7	2.3 ± 2.5		
	RCV2	**1.6 ± 1.6**	**4.2 ± 3.5****		
TNF- α	Rest	0.65 ± 0.13	0.67 ± 0.21	<0.001	0.504
(pg·mL^{-1})	RCV1	0.68 ± 0.18	0.71 ± 0.25		
	RCV2	0.69 ± 0.21	0.77 ± 0.29		
CRP	Rest	0.73 ± 0.62	0.85 ± 1.00	0.007	0.542
(pg·L^{-1})	RCV1	0.71 ± 0.61	0.88 ± 1.05		
	RCV2	0.73 ± 0.65	0.91 ± 1.09		

All data reported as mean ± SD.
Abbreviation: RCV1 first recovery, RCV2 second recovery, SU station uniform, Full PPE full personal protective equipment CRP c-reactive protein, IL-6 interleukin-6, TNF- α tumor necrosis factor α. Bold expressions were significant clothing effects.
* and ** represent significant greater than SU condition at $P<0.05$ and $P<0.01$, respectively.

3.1.2 Cardiovascular responses

There was a significant difference in heart rate according to clothing conditions ($P<0.001$) and time conditions ($P<0.001$). The initial phase (Rest) values were similar, 73 in the SU and 76 bpm in Full PPE. However, there was a gap between exercise and recovery (Fig. 3.1). The heart rate under SU condition was 102 ± 15 bpm for EXE1, 74 ± 13 bpm for RCV1, 109 ± 17 bpm for EXE2, and 77 ± 14 bpm for RCV2. On the other hand, in Full PPE, a larger increase was shown according to the repetition of the bout. Full PPE recorded as 135 ± 18 bpm for EXE1, 95 ± 17 bpm for RCV1, 155 ± 20 bpm for EXE2, 113 ± 19 bpm for RCV2. In addition, the maximum heart rate of one firefighter was 194 bpm under the SU condition, while 218 bpm under the Full PPE condition. Except for this firefighter, the maximum value under SU condition was 141 bpm and 191 bpm in Full PPE.

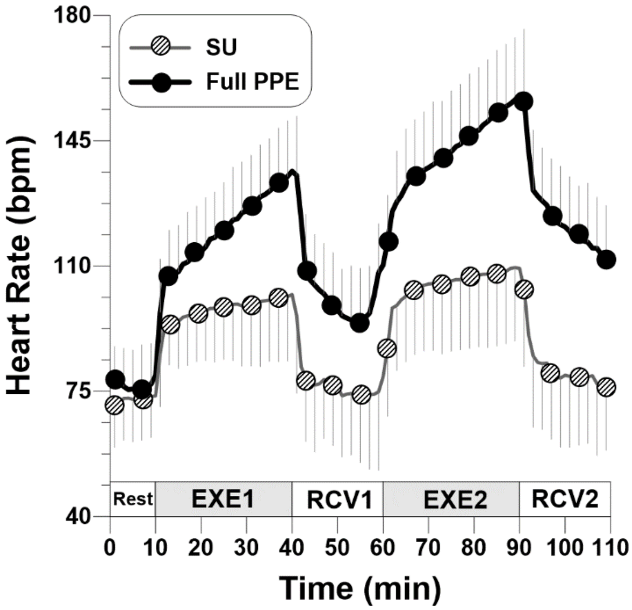


Fig. 3.1 Time course of heart rate between SU and Full PPE

Abbreviation: SU station uniform, Full PPE full personal protective equipment, EXE1 first exercise, RCV1 first recovery, EXE2 second exercise, RCV2 second recovery.

HRV was confirmed by SDNN, RMSSD, and LF/HF. Over time, SDNN and RMSSD showed a significant decrease, and LF/HF showed a significant increase (P<0.001). There was no difference at the Rest which was measured just before entering the chamber (SDNN: 59.9 ± 31.4 ms, 51.5 ± 25.2 ms; RMSSD: 57.9 ± 50.9 ms, 38.5 ± 25.6 ms; LF/HF: 1.7 ± 2.2 ms, 1.8 ± 1.2 ms for SU and Full PPE respectively). Significant differences in the clothing conditions during the first (RCV1) and second recovery (RCV2) were observed in SDNN (RCV1: 52.3 ± 21.9 ms, 20.3 ± 12.9 ms, RCV2: 53.9 ± 23.2 ms, 34.0 ± 18.9 ms for SU and Full PPE respectively) and RMSSD (RCV1: 42.6 ± 30.1 ms, 10.0 ± 16.8 ms; RCV2: 44.5 ± 35.3 ms, 21.7 ± 24.1 ms for SU and Full PPE). Although the Full PPE in RCV1 and RCV2 was slightly greater in LF/HF than in SU, this difference was not statistically significant (Fig. 3.2).

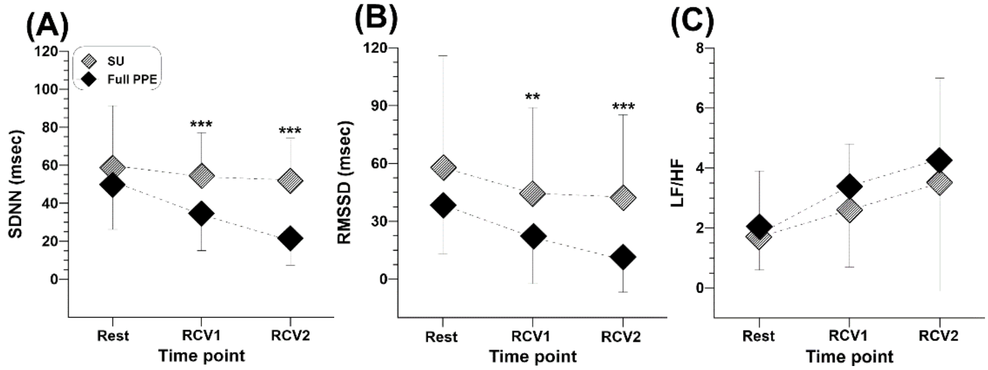


Fig. 3.2 Time courses of heart rate variability (A: SDNN; B: RMSSD; C: LF/HF) between SU and Full PPE condition

Abbreviation: SU station uniform, Full PPE full personal protective equipment. Rest right before entering the climatic chamber, RCV1 first recovery, RCV2 second recovery.
** and *** represent significant differences between two conditions at P<0.01 and P<0.001.

3.1.3 Thermal responses

Rectal and skin temperature increased during exercise and decreased during rest (*P*<0.001). The Full PPE increased much more than SU. (*P*<0.001; Fig. 3.3). T_{re} under SU started at 37.0°C in Rest and was maintained at 37.3, 37.3, 37.6, 37.5°C for EXE1, RCV1, EXE2, RCV2 respectively, not exceeding 38°C. T_{re} of Full PPE started at 37.0°C but increased continuously (37.6, 37.8, 38.5, 38.7°C for EXE1, RCV1, EXE2, RCV2, respectively). The peak value was 39.6°C during RCV2. Under the Full PPE, skin temperature increased by 3.3°C, compared to a 0.5°C increase under the SU.

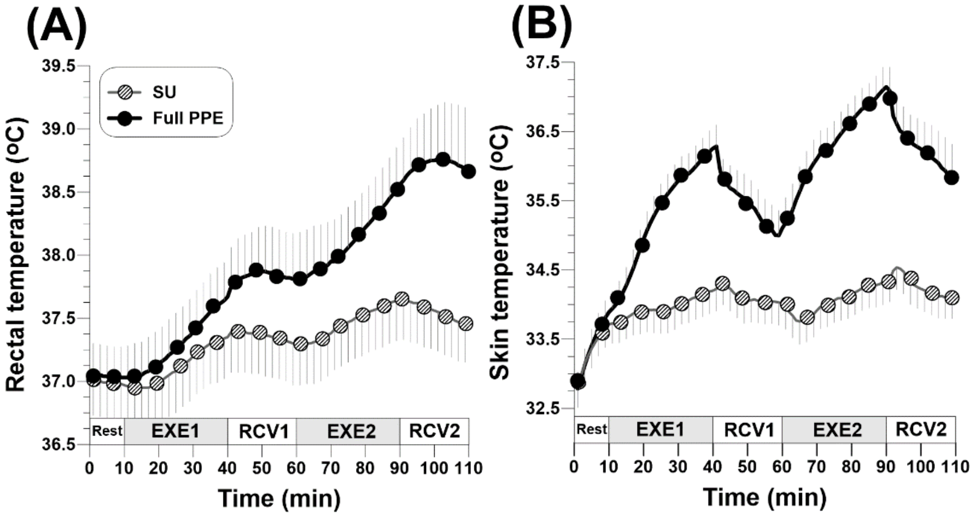


Figure. 3.3 Time courses of Rectal temperature (A) and Skin temperature (B) between SU and Full PPE

Abbreviation: SU station uniform, Full PPE full personal protective equipment, EXE1 first exercise, RCV1 first recovery, EXE2 second exercise, RCV2 second recovery.

TSR was 98 ± 23 $g \cdot trial^{-1}$ in SU and 194 ± 61 $g \cdot trial^{-1}$ in Full PPE (Fig. 3.4). In the psychological response, subjects answered hotter and harder when wearing Full PPE than SU (Fig. 3.5).

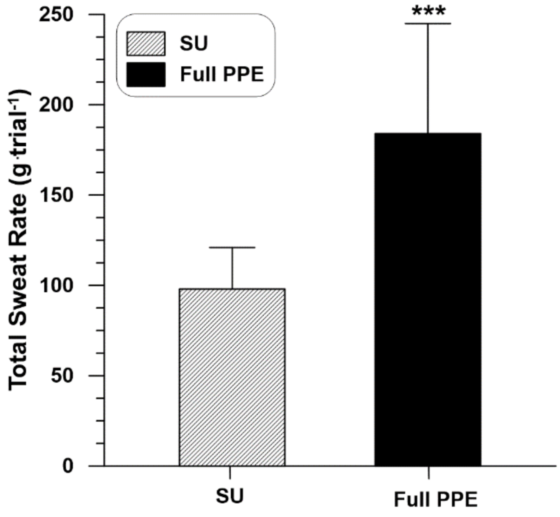


Figure. 3.4 Total sweat rate between SU and Full PPE

Abbreviation: SU station uniform, Full PPE full personal protective equipment.
*** represents significant differences between the two conditions at *P*<0.001.

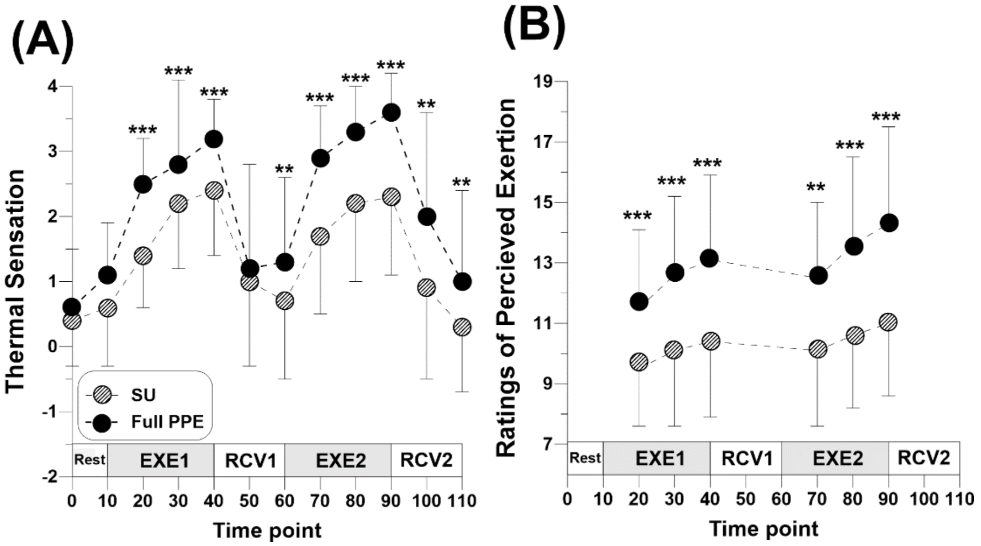


Fig. 3.5 Time courses of Thermal Sensation (A) and Ratings of Perceived Exertion (B) between SU and Full PPE

Abbreviation: SU station uniform, Full PPE full personal protective equipment
Thermal Sensation : -2: Cool; -1: Slightly cool; 0: Neutral; 1: Slightly warm; 2: Warm; 3: Hot; 4: Very hot. Ratings of Perceived Exertion (scale: 6~20): 7: Very, very light; 9: Very light; 11: Fairly light; 13: Somewhat hard; 15: Hard; 17: Very hard; 19: Very, very hard.
, * represents significant differences between the two conditions at *P*<0.01 and *P*<0.001.

3.2. The psycho-physiological strain level of each firefighter and individual characteristics that affected

3.2.1 The psycho-physiological strain level of each firefighter

Physiological and psychological values for measuring psycho-physiological strain were calculated according to Shannon's entropy method and weights from the 13 measurements selected based on previous studies. The index values with a large measurement variance had small entropy values and large weights. IL-6 and CRP were the highest, 0.154 and 0.146, respectively. The criteria with the low weights and high entropy were rectal temperature (0.030) and heart rate (0.043).

Table. 3.2 Entropy and weights of measurements

	Measurement	Entropy	Weight
Immune-inflammatory response	Platelet	0.950	0.045
	Leukocyte	0.911	0.081
	Lymphocyte	0.939	0.056
	CRP	0.839	0.146
	IL-6	0.830	0.154
	TNF-α	0.944	0.051
Cardiovascular response	HR	0.952	0.043
	SDNN	0.901	0.090
	RMSSD	0.917	0.075
	LF/HF	0.908	0.084
Thermal response	T_{re}	0.967	0.030
	TS	0.943	0.052
	RPE	0.897	0.094

Abbreviation: HR heart rate, CRP c-reactive protein, IL-6 interleukin-6, TNF- α tumor necrosis factor α, T_{re} rectal temperature, TS thermal sensation, RPE ratings of perceived exertion.

Next, the results of obtaining each subject's proximity coefficient (C_i, meaning psycho-physiological strain level of a firefighter in this study) through TOPSIS with the weight were shown in Table 3.3. The psycho-physiological strain increased with increasing Si+ and decreasing Si-. As a result, firefighter S showed the highest value of 0.516, showing the highest psycho-physiological strain level, and firefighter B showed the lowest value of 0.179, showing the lowest psycho-physiological strain level.

Table 3.3 Positive ideal subject value (Si^+), negative ideal subject value (Si^-), and the relative degree of psycho-physiological strain (C_i) through TOPSIS

Subject	Si^+	Si^-	C_i	Subject	Si^+	Si^-	C_i
A	0.146	0.061	0.297	M	0.146	0.041	0.221
B	0.154	0.034	0.179	N	0.145	0.046	0.240
C	0.148	0.052	0.261	O	0.140	0.057	0.292
D	0.154	0.064	0.294	P	0.115	0.089	0.435
E	0.132	0.064	0.327	Q	0.111	0.113	0.505
F	0.153	0.050	0.246	R	0.143	0.075	0.344
G	0.150	0.042	0.219	S	0.108	0.115	0.516
H	0.161	0.036	0.182	T	0.132	0.066	0.333
I	0.156	0.039	0.200	U	0.148	0.048	0.243
J	0.125	0.058	0.318	V	0.145	0.053	0.268
K	0.131	0.079	0.375	W	0.137	0.071	0.342
L	0.154	0.041	0.212	X	0.126	0.091	0.420

Abbreviation: Si^+ positive ideal solution, Si^- negative ideal solution, C_i the relative degree of approximation.

3.2.2 Individual characteristics that affected psycho-physiological strain

With the multiple regression analysis, the F statistic was 3.910 (*P*=0.018), and for the regression equation, the regression model showed an explanation of 45.1% (33.6% by the adjusted coefficient). Excluding physical fitness level (VO_{2max}), body mass index (BMI), and body fat weight, age was the only effective parameter on the overall and relative psycho-physiological strain level of an individual (C_i) (*P*= 0.022). Age had a significant positive effect on C_i, showing that as age increased, the C_i value increased, meaning that psycho-physiological strain increased (Table 3.4).

Table 3.4 Effect of individual characteristics on subjects' psycho-physiological strain (C_i)

Dependent variable	Independent variable	R^2	Adjusted R^2	F	β	t	*P*-value	VIF
Each subject's psycho-physiological strain (C_i)	Intercept					-0.844	0.409	
	Age	0.451	0.336	3.910*	0.522	2.493	0.022	1.518
	VO_{2max}				0.079	0.327	0.747	1.996
	BMI				0.253	1.019	0.321	2.137
	%BF				0.175	0.572	0.574	3.256

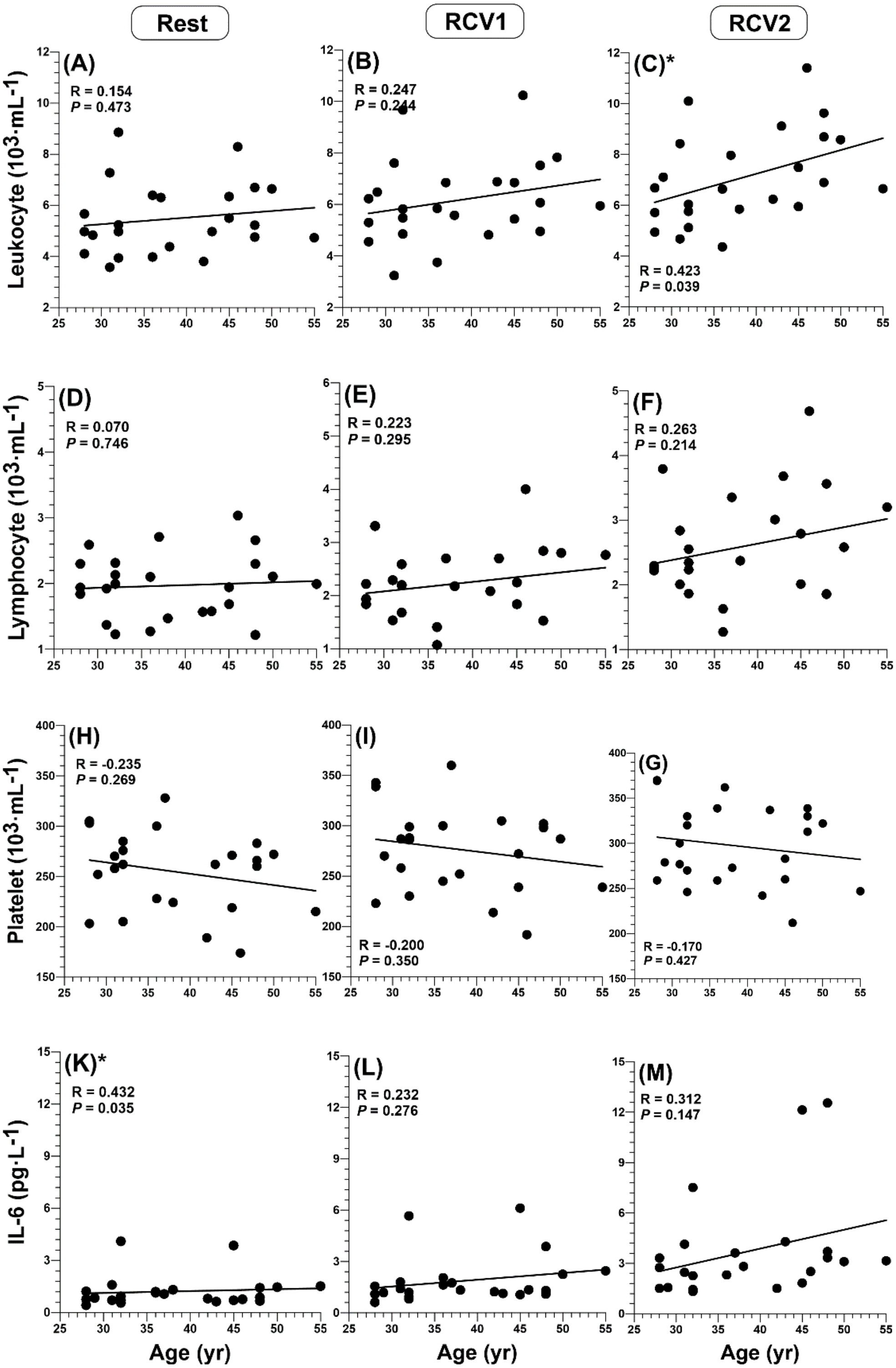
The total number of firefighters was 24.
Abbreviation: VO_{2max} maximal volume of oxygen consumed during the graded exercise test, BMI body mass index. %BF total body fat.

3.3. Immune-inflammatory, Cardiovascular and Thermal responses by age group

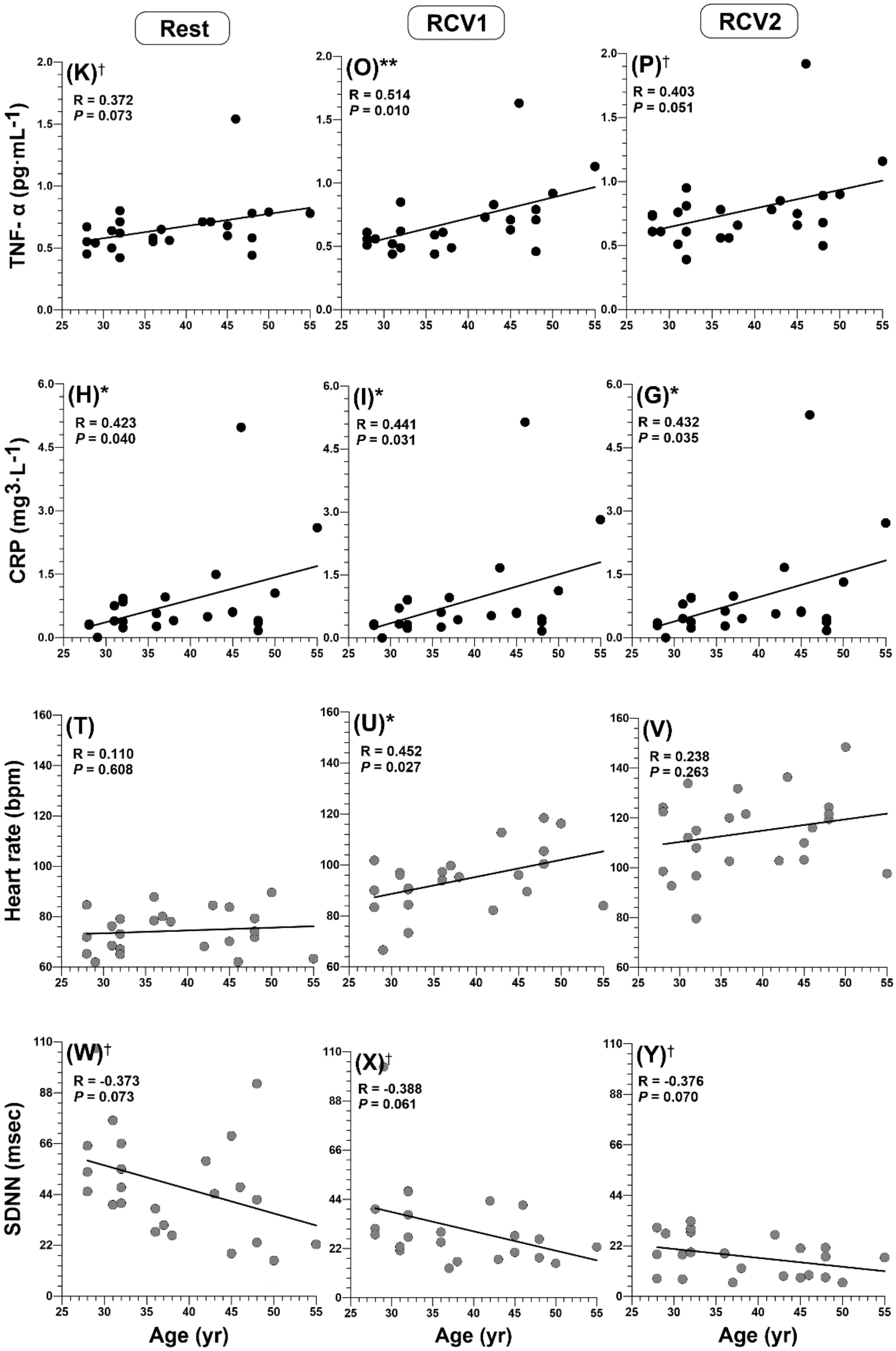
3.3.1 The correlation between age and immune-inflammatory, cardiovascular and thermal responses

As a result of examining the correlation between age and psycho-physiological responses, firstly, some inflammatory measurements showed significant correlations. IL-6 and CRP were significantly higher with age at Rest (Fig. 3.6 K, H), and TNF-α had an increasing tendency ($r = 0.372$, $P = 0.073$) (Fig. 3.6K). In RCV1, TNF-α and CRP showed significantly higher values with increasing age (Fig. 3.6O, I). In RCV2, leukocyte, and CRP showed a positive correlation with age (Fig. 3.6C), and TNF-α also showed a positive tendency (Fig. 3.6P).

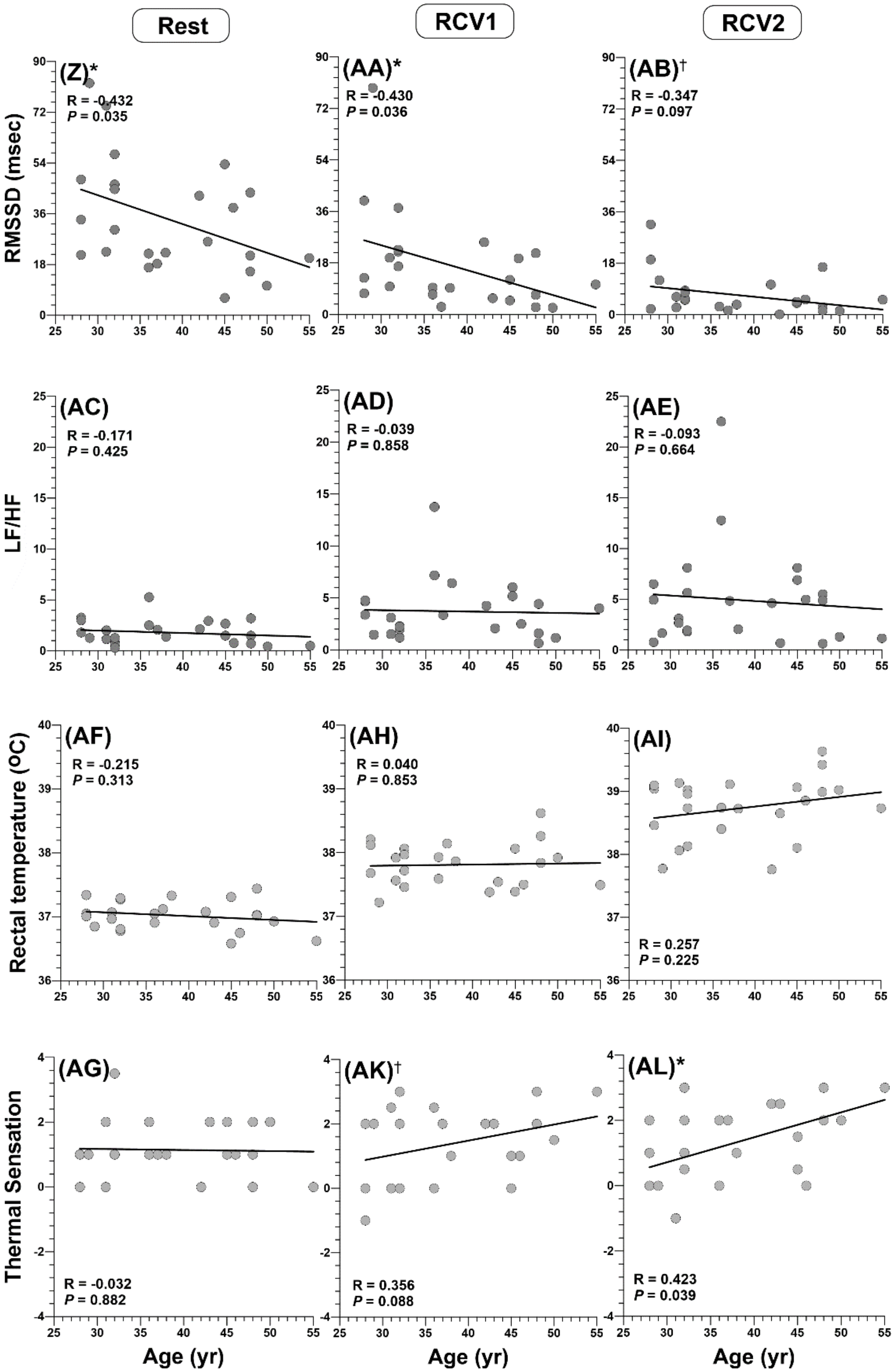
Secondly, among Cardiovascular responses, heart rate showed a significant positive correlation only in RCV1 (Fig. 3.6U). Next, SDNN, which were time domains in HRV, tended to decrease with age (Rest:r=-0.373, P=0.073; RCV1: r=-0.388, P=0.061; RCV2: r=-0.376, P=0.070). The relationship between age and RMSSD values also showed a negative correlation (Fig 3.6Z, AA, AB). On the other hand, no significant results were found in LF/HF which were the frequency domain. Thirdly, in thermal responses, rectal temperature had no relationship with age. However, TS showed no difference in the first 10 minutes during psychological measurements. However, as the protocol progressed, the older the subjects were, the hotter they felt. (Fig 3.6AK, AL). In addition, RPE showed age-specific differences only at the first measurement after the firefighters started working out.



Rest
RCV1
RCV2
(A)
R = 0.154
P = 0.473
(B)
R = 0.247
P = 0.244
(C)*
R = 0.423
P = 0.039
Leukocyte (10³·mL⁻¹)
(D)
R = 0.070
P = 0.746
(E)
R = 0.223
P = 0.295
(F)
R = 0.263
P = 0.214
Lymphocyte (10³·mL⁻¹)
(H)
R = -0.235
P = 0.269
(I)
R = -0.200
P = 0.350
(G)
R = -0.170
P = 0.427
Platelet (10³·mL⁻¹)
(K)*
R = 0.432
P = 0.035
(L)
R = 0.232
P = 0.276
(M)
R = 0.312
P = 0.147
IL-6 (pg·L⁻¹)
Age (yr)
Age (yr)
Age (yr)



Rest
RCV1
RCV2
(K)†
R = 0.372
P = 0.073
(O)**
R = 0.514
P = 0.010
(P)†
R = 0.403
P = 0.051
TNF- α (pg·mL-1)
(H)*
R = 0.423
P = 0.040
(I)*
R = 0.441
P = 0.031
(G)*
R = 0.432
P = 0.035
CRP (mg3·L-1)
(T)
R = 0.110
P = 0.608
(U)*
R = 0.452
P = 0.027
(V)
R = 0.238
P = 0.263
Heart rate (bpm)
(W)†
R = -0.373
P = 0.073
(X)†
R = -0.388
P = 0.061
(Y)†
R = -0.376
P = 0.070
SDNN (msec)
Age (yr)
Age (yr)
Age (yr)


Rest
RCV1
RCV2
RMSSD (msec)
(Z)*
R = -0.432
P = 0.035
(AA)*
R = -0.430
P = 0.036
(AB)†
R = -0.347
P = 0.097
LF/HF
(AC)
R = -0.171
P = 0.425
(AD)
R = -0.039
P = 0.858
(AE)
R = -0.093
P = 0.664
Rectal temperature (oC)
(AF)
R = -0.215
P = 0.313
(AH)
R = 0.040
P = 0.853
(AI)
R = 0.257
P = 0.225
Thermal Sensation
(AG)
R = -0.032
P = 0.882
(AK)†
R = 0.356
P = 0.088
(AL)*
R = 0.423
P = 0.039
Age (yr)
Age (yr)
Age (yr)

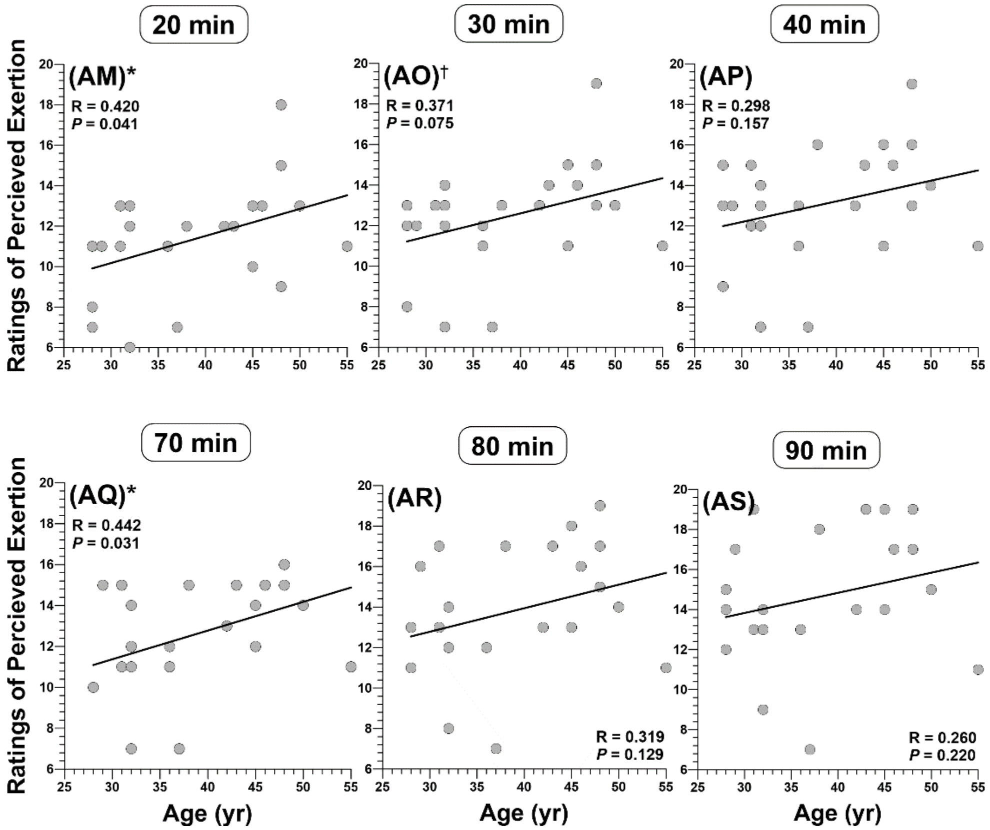


Fig. 3.6 Correlation between age and immune-inflammatory, cardiovascular, and thermal responses

Abbreviation: Rest first 10 minutes (before entering the chamber in immune-inflammatory and HRV responses), RCV1 first recovery, RCV2 second recovery.
*, ** represent statistically significant at $P<0.05$ and $P<0.01$ and † representing tendency at $0.05 \leq P < 0.1$.
Closed circles: the value of each subject in immune-inflammatory measurements, dark gray circles: the value of each subject in cardiovascular measurements, and light gray circles: the value of each subject in thermal measurements.
Thermal Sensation (scale: -4~4): -4: Very cold; -3: Cold; -2: Cool; -1: Slightly cool; 0: Neutral; 1: Slightly warm; 2: Warm; 3: Hot; 4: Very hot. Ratings of Perceived Exertion (scale: 6~20): 7: Very, very light; 9: Very light; 11: Fairly light; 13: Somewhat hard; 15: Hard; 17: Very hard; 19: Very, very hard. Because RPE was measured only during exercise periods, each value of 20, 30, 40, 70, 80 and 90 min was shown.

3.3.2 The groups of firefighters by age

To compare the differences based on time and age, the firefighters were divided into two age groups. The first group was the young firefighters (Young-FF; age: 32 ± 3 yr), and the second group was the older firefighters (Older-FF; age: 47 ± 4 yr). The characteristics of the two groups were shown in Table 3.5, and the values of VO_{2max} according to the group showed a significant difference (Young-FF: 50.1 ± 7.7; Older-FF: 42.2 ± 4.9; $P < 0.01$).

Table 3.5 Characteristics of the total, young, and older firefighters

	Total-FF (N=24)	Young-FF (N=14)	Older-FF (N=10)
Sex	Male	Male	Male
Duration of job (yr)	11	4	18
	(1 - 28)	(1 – 9)	(10 – 28)
Age (yr)	39	32	47
	(28 – 55)	(25 - 38)	(42 - 55)
Height (cm)	176.3	176.9	175.4
	(166.5 – 187.1)	(167.4 – 186.3)	(166.5 – 187.1)
Body weight (kg)	78.6	77.9	77.5
	(59.2 – 105.7)	(59.2 – 94.0)	(61.8 – 105.7)
Body fat (%)	18.3	16.2	20.9
	(7.2 – 31.9)	(7.2 – 24.5)	(11.6 – 31.9)
Body mass index ($kg \cdot m^{-2}$)	25.1	24.6	25.0
	(20.6 – 33.2)	(20.7 – 27.6)	(20.6 – 33.2)
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	46.6	50.1	42.2
	(33.8 – 64.5)	(41.2 – 64.5)	(33.8 – 42.2)

All data are reported as mean (min-max).
Abbreviation: Total-FF total firefighter, Young-FF young firefighter in their 20s and 30s, Older-FF middle-aged firefighters in their 40s and 50s, VO_{2max} maximal volume of oxygen consumed during the graded exercise test.

3.3.3 Immune-inflammatory responses

Leukocytes, lymphocytes, IL-6, TNF- α and CRP significantly increased over time (*P*<0.001). Older-FF had higher values of leukocyte at RCV2 (P<0.05). In addition, TNF- α (P<0.05) and CRP (P=0.054) had statistical differences, while values of Older-FF were higher than Young-FF at every time (Table 3.6).

Table 3.6 Immune-inflammatory responses between Young-FF and Older-FF

	Time	Young-FF (*N*=14)	Older-FF (*N*=10)	Time *P*-value	Age *P*-value
Leukocyte	Rest	5.4± 1.5	5.6 ± 1.3	<0.001	0.133
($10^3 \cdot mL^{-1}$)	RCV1	5.8 ± 1.7	6.6 ± 1.6		
	RCV2	**6.4 ± 7.9**	**7.9 ± 1.8***		
Lymphocyte	Rest	37.6 ± 8.0	35.3 ± 6.1	<0.001	0.683
($10^3 \cdot mL^{-1}$)	RCV1	36.4 ± 7.9	36.7 ± 5.9		
	RCV2	37.3 ± 8.5	36.8 ± 8.3		
Platelet	Rest	267.3 ± 35.8	239.5 ± 37.0	0.781	0.265
($10^3 \cdot mL^{-1}$)	RCV1	286.8 ± 42.5	263.5 ± 39.0		
	RCV2	306.2 ± 44.7	287.1 ± 43.8		
IL-6	Rest	1.2 ± 0.9	1.3 ± 0.9	<0.001	0.208
($pg \cdot mL^{-1}$)	RCV1	1.7 ± 1.3	2.1 ± 1.6		
	RCV2	2.9 ± 1.7	4.6 ± 3.9		
TNF- α	Rest	**0.6 ± 0.1**	**0.7 ± 0.3**†	<0.001	0.024
($pg \cdot mL^{-1}$)	RCV1	**0.6 ± 0.1**	**0.8 ± 0.3****		
	RCV2	**0.7 ± 0.1**	**0.9 ± 0.4***		
CRP	Rest	**0.5 ± 0.3**	**1.2 ± 1.4**†	<0.001	0.054
($pg \cdot L^{-1}$)	RCV1	**0.5 ± 0.3**	**1.3 ± 1.5***		
	RCV2	**0.5 ± 0.3**	**1.3 ± 1.5**†		

All data are expressed as mean ± SD. *, ** represent significant greater than Young-FF at *P*<0.05 and *P*<0.01 and † representing greater tendency than Young-FF at 0.05≤*P*<0.1.

Absolute changes in all immune-inflammatory responses had significant time differences ($P<0.001$; TNF- α $P = 0.013$; CRP $P = 0.020$). Besides, values of increase in leukocyte (P=0.003), TNF- α (P=0.033), and CRP (P=0.007) showed significant differences among groups (Fig. 3.8A, E, F). In particular, values of leukocyte were 0.5 ± 0.6 $10^3 \cdot mL^{-1}$ (Young-FF) and 1.0 ± 0.7 $10^3 \cdot mL^{-1}$ (Older-FF) at RCV1-Rest, while 1.1 ± 0.5 and 2.4 ± 1.1 at RCV2-Rest (Fig. 3.8A). The increase in TNF- α was 0.0 ± 0.1 $pg \cdot mL^{-1}$ for Young-FF and 0.1 ± 0.1 $pg \cdot mL^{-1}$ for Young-FF, while 0.1 ± 0.1 and 0.2 ± 0.1 $pg \cdot mL^{-1}$ at RCV2-Rest (Fig. 3.8E). Furthermore, Older-FF showed a huge increase in RCV2-rest (0.11 ± 0.11 $pg \cdot L^{-1}$ for Older-FF and 0.03 ± 0.03 $pg \cdot L^{-1}$ for Young-FF) (Fig. 3.8F). In particular, CRP values of 1.0 - 3.0 $pg \cdot L^{-1}$ mean moderate risk. Only 2 of 14 Young-FF showed a value of close to 1 (0.94 and 0.99 $pg \cdot L^{-1}$) in RCV2. However, in the case of Older-FF, 4 out of 10 people showed a value greater than 1 (1.05, 1.49, 1.05, and 2.60 $pg \cdot L^{-1}$, respectively).

Moreover, Older-FF tended to have higher values than Young-FF in Lymphocyte (P = 0.082) and IL-6 (P = 0.070). Differences tended to be greater in RCV2-Rest than in RCV1-Rest, with lymphocyte of 0.4 ± 0.5 and 0.9 ± 0.8 $10^3 \cdot mL^{-1}$ (Fig 3.8B), and IL-6 of 1.7 ± 1.0 and 3.5 ± 3.4 $pg \cdot mL^{-1}$ (Fig. 3.8D) for young-FF and Older-FF respectively.

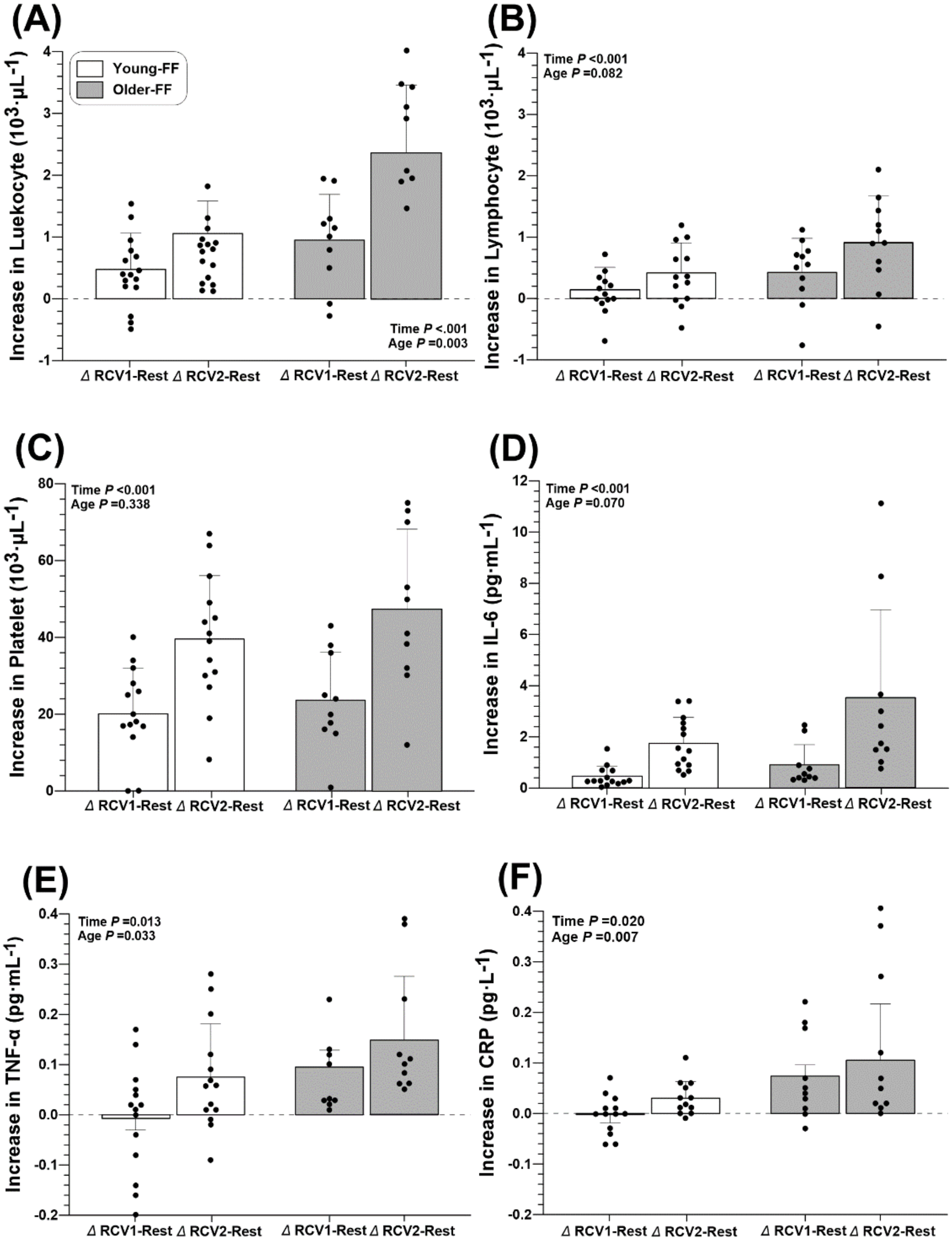


Fig. 3.7 Increase of Immune and inflammatory responses between recovery and rest between Young-FF and Older-FF

(A) Leukocyte (B) Lymphocyte (C) Platelet (D) IL-6 (E) TNF- α (F) CRP
Closed black circles were the values of firefighters.
Abbreviation: Young-FF young firefighters in their 20s and 30s (*N*=14), Older-FF middle-aged firefighters in their 40s and 50s (*N*=10). ⊿RCV1-Rest difference between first recovery and rest, ⊿RCV2-Resr difference between second recovery and rest.

3.3.4 Cardiovascular responses

Heart rate increased over time (*P*<0.001), where no differences were observed between the Young-FF and Older-FF (Fig. 3.8). The increased value (*Δ*RCV2-Rest) of HR tended to be higher for Older-FF (43 ± 10 bpm) than Young-FF (25 ± 8 bpm) (*P*=0.069). In addition, the change between RCV1 and rest was 16 ± 8 and 36 ± 15 bpm for Young-FF and Older-FF respectively.

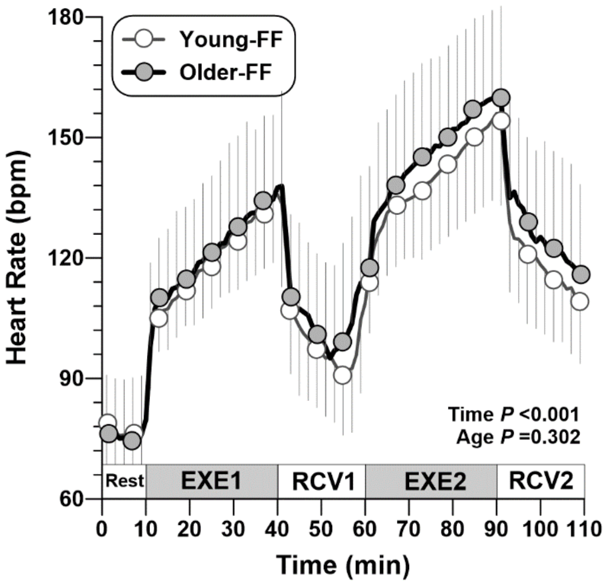


Fig. 3.8 Time course of heart rate between Young-FF and Older-FF

Abbreviation: Young-FF young firefighters in their 20s and 30s (*N*=14), Older-FF middle-aged firefighters in their 40s and 50s (*N*=10), EXE1 first exercise, RCV1 first recovery, EXE2 second exercise, RCV2 second recovery.

In the HRV, psycho-physiological response, SDNN, RMSSD (*P*<0.001), and LF/HF (*P*=0.002) showed the main effects of time, resulting in a gradual decrease in SDNN and RMSSD and an increase in LF/HF. However, there was no group effect according to age (Table 3.7).

Table 3.7 HRV responses between Young-FF and Older-FF

	Time	Young-FF (*N*=14)	Older-FF (*N*=10)	Time *P*-value	Age *P*-value
SDNN	Rest	53.2 ± 21.6	41.7 ± 24.1	<0.001	0.870
(ms)	RCV1	36.4 ± 22.4	24.9 ± 9.6		
	RCV2	20.2 ± 9.1	14.2 ± 6.8		
RMSSD	Rest	39.9 ± 21.4	27.2 ± 15.1	<0.001	0.443
(ms)	RCV1	22.0 ± 20.5	10.9 ± 7.9		
	RCV2	8.2 ± 8.6	5.0 ± 4.8		
LF/HF	Rest	2.0 ± 1.3	1.6 ± 1.0	0.781	0.460
	RCV1	3.9 ± 2.0	3.5 ± 2.0		
	RCV2	5.9 ± 6.0	5.9 ± 2.7		

All data reported as mean ± SD.
Abbreviation: Young-FF young firefighters in their 20s and 30s, Older-FF middle-aged firefighters in their 40s and 50s, RCV1 first recovery, RCV2 second recovery.

The change between RCV2 and Rest, decreased significantly in both SDNN and RMSSD than in RCV1 and rest, but there was no difference between age groups (Fig. 3.9A, B). Decreased SDNN values for Young-FF were -16.4 ± 15.5 and -31.7 ± 21.1 msec, and for Older-FF were -17.4 ± 21.9 and -28.9 ± 20.4 msec (Fig. 3.9A). The RMSSD difference between the Rest and RCV2 was lower (-30.7 ± 21.3 and -22.6 ± 13.6 msec for Young-FF and Older-FF) than the Rest and RCV1 (-17.5 ± 18.4 and -30.7 ± 21.3 msec for Young-FF and Older-FF) (Fig. 3.9B). In LF/HF, ΔRCV2-Rest (3.8 ± 5.0 for Young-FF and 2.2 ± 2.6 for Older-FF) tended to increase slightly more than ΔRCV1-Rest (2.2 ± 2.4 for Young-FF and 1.6 ± 1.6 for Older-FF) (*P*=0.075) without a statistical difference between the groups (Fig. 3.9C).

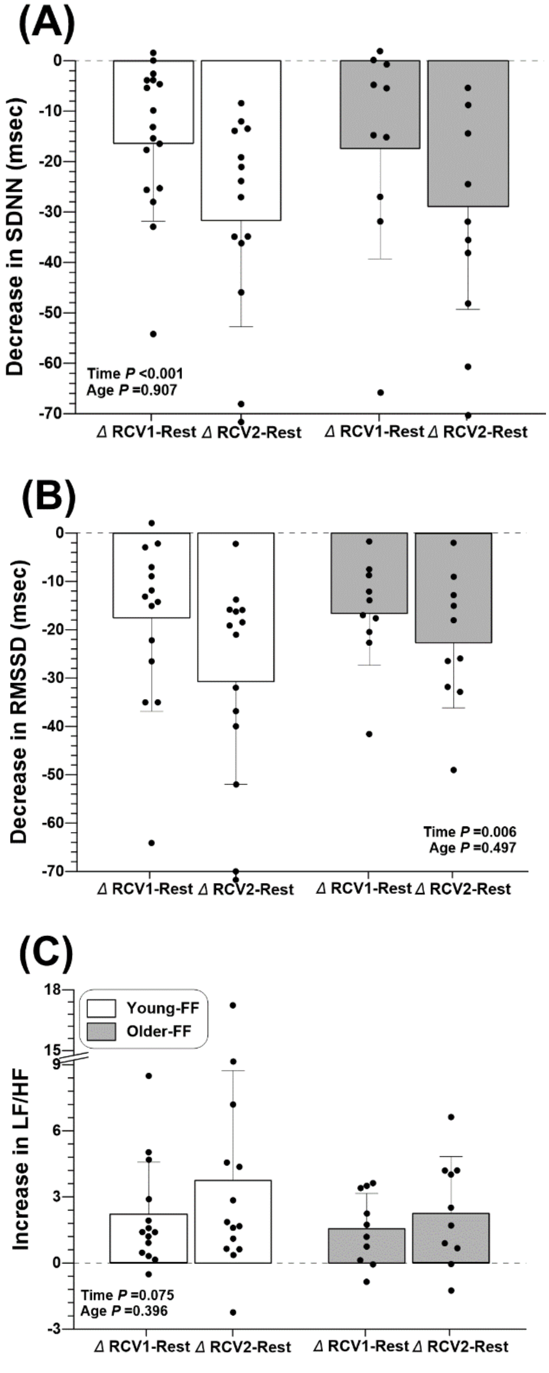


Fig. 3.9 Decrease or increase in SDNN (A), RMSSD (B), and LF/HF (C) between Young-FF and Older-FF

Closed black circles were the values of firefighters.

Abbreviation: Young-FF young firefighters in their 20s and 30s (*N*=14), Older-FF middle-aged firefighters in their 40s and 50s (*N*=10), ⊿RCV1-Rest difference between first recovery and rest, ⊿RCV2-Rest difference between second recovery and rest.

3.3.5 Thermal responses

T_{re} increased over time (P<0.001), where no differences were observed between the Young-FF and Older-FF (Fig. 3.10). The T_{re} difference between the Rest and the RCV2 values (1.6 ± 0.3 and 1.9 ± 0.5°C for Young-FF and Older-FF) was significantly greater than the RCV1 (0.8 ± 0.2 and 0.8 ± 0.3°C for Young-FF and Older-FF). As a result of checking the difference by group according to the delta value at the time point, there was a significant difference in RCV1-Rest, but RCV2-Rest did not show a significant difference due to the large standard deviation.

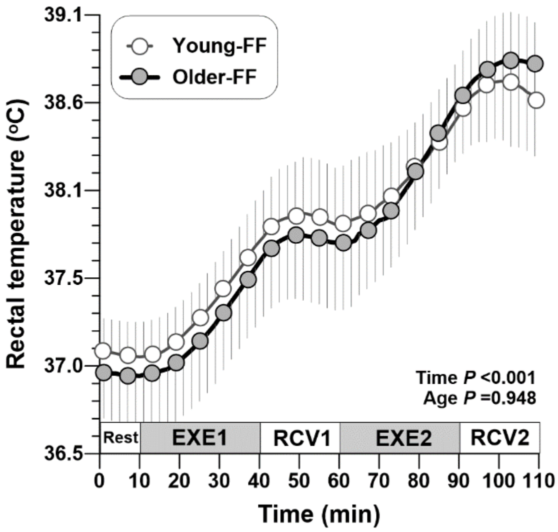


Fig. 3.10 Time course of rectal temperature between Young-FF and Older-FF

Abbreviation: Young-FF young firefighters in their 20s and 30s (N=14), Older-FF middle-aged firefighters in their 40s and 50s (N=10). EXE1 first exercise, RCV1 first recovery, EXE2 second exercise, RCV2 second recovery.

In the subjective responses, Older-FF (1.8 ± 0.9, 3.9 ± 0.2, 2.0 ± 1.1 for 60, 90 and 110 min) was higher than Young-FF (1.1 ± 1.3, 3.4 ± 0.7, 0.9 ± 1.2 for 60, 90 and 110 min) in TS during RCV1, EXE2, and RCV2, but it was not statistically significant. (Fig. 3.11A). The average RPE of Older-FF were 12.6 ± 2.5, 13.8 ± 2.3, 14.1 ±1.7, 15.3 ±2.5, 16.2 ± 2.7 for 20, 30, 40, 70, 80, 90 min. Young-FF felt less hard (10.4 ± 2.3, 11.4 ± 2.3, 12.1 ± 2.8, 11.4 ±2.7, 12.6 ± 2.9, 13.6 ± 3.2 for 20, 30, 40, 70, 80, 90 min)but there was no significant difference (Fig. 3.11B).

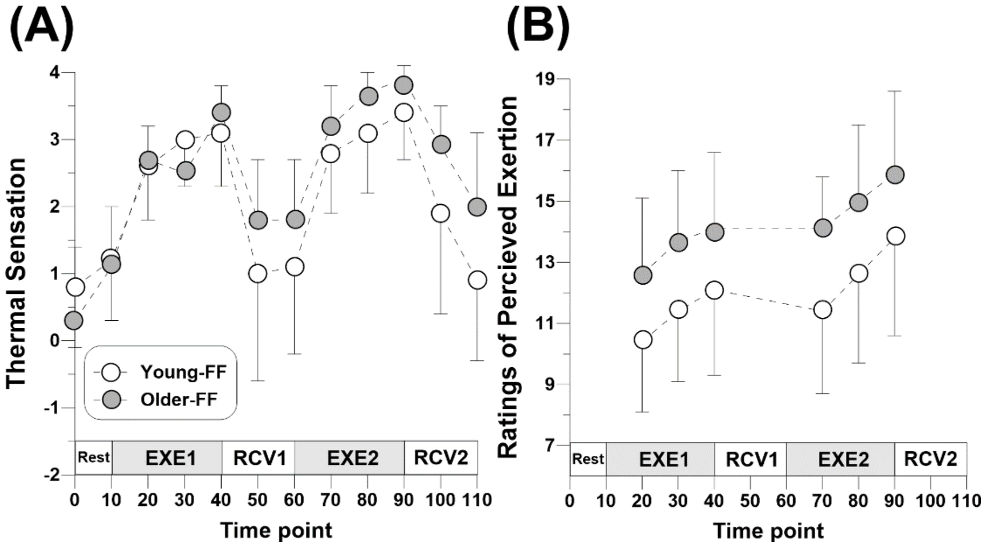


Fig. 3.11 Time courses of TS (A) and RPE (B) between Young-FF and Older-FF

Abbreviation: Young-FF firefighters in their 20s and 30s (N=14), Older-FF firefighters in their 40s and 50s (N=10). EXE1 first exercise, RCV1 first recovery, EXE2 second exercise, RCV2 second recovery.
Thermal Sensation: -2: Cool; -1: Slightly cool; 0: Neutral; 1: Slightly warm; 2: Warm; 3: Hot; 4: Very hot. Ratings of Perceived Exertion (scale: 6~20): 7: Very, very light; 9: Very light; 11: Fairly light; 13: Somewhat hard; 15: Hard; 17: Very hard; 19: Very, very hard. Because RPE was measured only during exercise, each value of 20, 30, 40, 70, 80 and 90 min was shown.

Chapter 4. Discussion

This study examined immune-inflammatory, cardiovascular, and thermal strain for firefighters when wearing Full PPE and repeatedly working in a hot and humid environment: (1) First, Full PPE caused a greater strain on immune-inflammatory, cardiovascular, and thermal responses than SU. (2) Secondly, the psycho-physiological strain of each firefighter was affected by age. (3) Third, Older-FF was more dangerous than Young-FF due to some measurements showing the greater physiological strain.

4.1. Immune-Inflammatory responses of Full PPE

One of the most intriguing observations is that the immune-inflammatory responses were elevated even though the experimental environment was not in the actual fire or extremely hot conditions. However, the increased level in this study is not in accordance with previous studies (similar to or less) than in some of the . For instance, Walker et al. (2015) reported a significant increase in leukocyte, platelet, TNF-α, IL-6, and CRP when twice exercise was repeated in an environment of 100 ± 5°C. In addition, Smith et al. (2005) also showed an increase in leukocytes and lymphocytes before and after fire training. It can be demonstrated that the previous studies were conducted in a significantly harder environment or in an actual fire with smoke and extreme temperatures, which made immune-inflammatory responses activated. On the other hand, when firefighters repeatedly exercised in a 35oC, 20% RH or 35oC 60%RH environment with the shorts and sandals, the platelet, IL-6, TNF-a, and CRP levels were similar or lower (Wright et al. 2014) than this study's results. Even though this experiment was conducted in a 30°C, 60% RH environment, the firefighters experienced greater immune-inflammatory responses due to wearing more impermeable clothing (Full PPE) and exercising for a longer (30 min) time. In conclusion, it should be highlighted that the findings of this study suggest the firefighters' immune-inflammatory responses may increase with Full PPE and performing tasks not in the "real-world" fire scene but in the warm - hot summer environment.

Each variable of the increased immune-inflammatory responses can affect a cardiovascular system as follows. Platelet activation is related to thrombosis, narrowing blood vessels, and preventing blood supply to heart muscles. It may cause a risk of myocardial infarction. Repeated exercise in a hot and humid environment also increases stress, which results in the activation of stress hormones such as catecholamine and cortisol. This can induce leukocytes. Furthermore, cortisol induces cell migration to lymphoid tissue. (Brenner et al., 1996). In light of this, it is possible to explain that the combination of a warm environment, PPE which causes more heat strain due to the inability to release sweat, and repetitive exercise caused stress and increased leukocytes. Meanwhile, Tre increased about 38.7oC on average (range: 37.7 - 39.6oC) at RCV2. Exercise in hot weather can increase rectal temperature, which changes the permeability of the gut lining. In addition, it may cause endotoxin or lipopolysaccharide (LPS) to flow from the gastrointestinal lumen to the blood. (Lambert et al. 2002). Heat-induced endotoxemia can cause the release of IL-6 and TNF-α (Main et al., 2020). They are inflammatory cytokines produced in the inflammatory response's early stages and released by cells to communicate with other cells. C-reactive protein, an acute protein produced in response to an increased IL-6 concentration in the liver (Ridker et al. 2000), is a key inflammatory marker and predictor of cardiac disease (Pearson et al. 2003). Elevated IL-6, TNF-α, and CRP can increase the risk of developing acute spontaneous calcific emboli and the pathogenesis of atherosclerosis (Koh and Park, 2018). Therefore, these increased immune inflammatory responses may affect the cardiovascular system if the activation is greater and repeatedly increased.

4.2. Psycho-physiological strain level through Entropy-TOPSIS model

This study analyzed the level of the psycho-physiological strain by applying the Entropy-TOPSIS model. TOPSIS model has been applied in various fields such as Health, Safety and Environment Management, and Energy Management (Behzadian et al. 2012). In addition, it has recently been applied to the physiological field. For instance, Guozhong et al. (2020) reported evaluating the physiological state of sanitation workers in high temperatures. Through that, this study can also explain the possibility of using entropy-TOPSIS for evaluating physiological and psychological strain.

In the calculation, finding the weight was the first step in evaluating the psycho-physiological strain. Since the simple average method proceeds without considering indicators with different units and detailed measurement goals, weighting is required for each measurement. The calculation of weights can be divided into subjective and objective methods. One of the most used methods is the

Analytic Hierarchy Process (AHP), which divides and compares pairs by layer through the answers of several experts. Thus, questions regarding objectivity may still exist because results through AHP are eventually based on subjective assessment. On the other hand, entropy weight is objective because it is generated through mathematical calculations along with information of measured values. The weights were high with low entropy in CRP and IL-6 of the inflammatory-immune response, meaning less information uncertainty and greater diversity. Moreover, it was possible to compare or rank the relative level of psycho-physiological strain for each firefighter by combining with TOPSIS within the measured range. Since the entropy calculated weights based on the amount of information, in order to explain the effect of age, the meaning of the changes in physiological and psychological measurements must be closely examined according to the age. That was why a third analysis was performed.

4.3. The effects of age on firefighters

The third important implication is that firefighters had a greater psycho-physiological strain as they age. In the correlation between age and immune-inflammatory response, IL-6 and CRP showed a significant positive correlation, while TNF-a showed an increasing tendency. This showed physiological aging with a chronic systemic inflammatory condition by elevated levels of serum-infectious cytokines (Franceschi et al. 2000). In addition, the increase in leukocyte, CRP, and TNF-a was significantly greater in Older-FF, while IL-6 and lymphocytes also tended to be higher. It suggested that Older-FF had a higher physiological strain than

Young-FF. Fuente et al. (2011) have pointed out that impairment of the physiological systems such as the immune system occurred along with aging. On the contrary, Wright-Beatty et al. (2014) showed no differences in inflammatory markers before and after exercise in the heat between young and older firefighters. It is noteworthy that this study showed statistically significant differences between age groups even though our older firefighter (47 ± 4 yr) was younger than the previous study (51 ± 1 yr).

In the heart rate, Older-FF started to be slightly greater in the second bout than in the first, although the increase in RCV2 from rest was not statistically significant with age. The HRV values of higher LF/HF and lower SDNN, RMSSD during recovery compared to rest mean that the subjects are under stress. In Abhishekh et al. (2013), subjects with 16 – 60 yr measured HRV in stable condition. They showed the predominance of sympathetic nervous tension and the reduction of amniotic nervous tension with aging led to a decrease in SDNN and RMSSD. Correspondingly, the older firefighters, the lower SDNN and RMSSD at any point, showing a negative correlation between age and value. At the same time, the degree of decrease over time did not differ by age group. This can be interpreted that although there was a difference in HRV value due to aging, there was no difference in the extent of decrease during the protocol, thus it would be under similar stress regardless of age group. Additionally, considering the elevated HRV brought on by the effects of sustained exercise (Levy et al. 1998), the VO2max of Older-FF was 42.2 ± 4.9 ml·kg-1·min-1, which means they were healthy subjects and also the cause of no significant HRV difference.

There was no difference in Tre by age group. This can be explained by Havenith et al. (1995). The thermoregulatory response like core temperature or sweat rate during heat stress can be more affected by other characteristics such as aerobic fitness. Additionally, in the perceptual response, TS had no difference according to age in the Rest, but some positive correlation with age began to be shown during the recovery. On the contrary, in RPE, a significant difference was shown 10 minutes after the exercise began, but no significant difference was found according to age as the exercise continued. In addition, there was no average difference by time point according to the age group, which may have been affected by the large deviation between subjects.

According to the confirmation for each measurement, Older-FF posed a greater burden than Young-FF in wearing complete PPE and engaging in repetitive tasks in the heat. The reason is interpreted as that some physiological indicators are increasing more significantly in the older firefighter group. These results imply it is necessary to coordinate the work-rest time and the intensity of repetitive work with age when work must be performed while wearing Full PPE in summer. Especially for older firefighters, it is possible to achieve safe and active occupational activities through truly efficient shifts, additional support for rapid recovery, and less repetitive tasks per person with a sufficient number of firefighters. It should be noted that older firefighters should not unconditionally prohibit professional activities just because their professional activities are difficult due to the increase in age. To maintain occupational productivity and to engage in physically and mentally healthy occupational activities, coordination and support based on the preceding contents are needed.

4.4. Limitation

The limitations of this study are as follows. This study conducted an experiment only with male firefighters. The number of female firefighters is increasing. At this time, the physiological and psychological strain in the heat wave will be more important for female firefighters working outside the office. There is a difference in the thermal response between females and males. Females have higher body fat than males. It is disadvantageous to heat because heat dissipation on the surface of the skin is not smooth. In addition, sweating is initiated at higher deep and skin temperatures than men (Bcerug et al., 1998), and has a smaller and narrower distribution of active sweat glands, which is disadvantageous for sweating responses (Havenith et al., 2008). In addition, until menopause, women undergo hormonal changes, which cause changes in heat tolerance (Charkoudian and Stachendeld, 2016). In fact, there are studies on the thermal regulation or heat tolerance of firefighters (Yamada & Golding, 2004; Perroni et al., 2021; Renberg et al., 2022). Based on this, it is necessary to examine the immune-inflammatory, cardiovascular, and thermal strains of female firefighters who repeat work in a hot environment while wearing full PPE. Since women are also restricted from matching of Full PPE and the actual activity behavior during firefighting (Park et al., 2015; Sokolowski et al., 2022), an experiment with them should be conducted.

Moreover, in this study, it is necessary to consider that Older-FF were in their 40s and 50s and had above-average age VO2max. Firefighters require higher physical strength than other occupational groups due to their job characteristics. In fact, in this study, it was higher than the average of the general age group, but there was a significant difference in VO2max according to the firefighter age group. Given that the retirement age in Korea is 60, future studies will be more meaningful by comprehensively examining the immune-inflammatory, cardiovascular, and thermal strains of firefighters in their 50s (especially in their late 50s) with diverse physical capacity.

Chapter 5. Conclusions

This study attempted to examine the immune-inflammatory, cardiovascular, and thermal strain of firefighters caused by repetitive activities, wearing Full PPE in a hot and humid environment. The heavy and non-permeable Full PPE caused greater physiological and psychological strains on firefighters. Moreover, each firefighter's psycho-physiological strain level was affected by age. Significant correlations with age were identified in some immune-inflammatory responses, HRV, and subjective responses. In addition, in order to confirm the difference in the degree of increase or decrease by age and time, firefighters were divided into two groups to confirm the difference. As a result, it was concluded that Older-FF was more dangerous in the same situation due to greater immune-inflammatory responses, even though Older-FF was similarly stressed to Young-FF. The results of this study can be used to discuss the coordination of work-rest time and intensity in summer with wearing Full PPE and repetitive work activities, also with consideration for the safe and active occupational activities of older firefighters.

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Appendix

A survey was conducted to understand the personal and job-related characteristics of 28 firefighters who participated in the experiment. There were a total of 31 questions related to personal characteristics. Among them, it consisted of 7 questions about demographic characteristics (A), 10 questions about self-identified heat resistance (B), and 6 questions about disease-related family history (C). Questions about job-related characteristics consisted of 8 questions (D).

In part (A), the health habit question (smoking, drinking, and exercise frequency) was also shown in Table 2.1 of the text . In part (B), 10 questions were used that were found to be highly internally consistent in heat-related indexes among the questionnaires used in Kim et al. (2016). The group was categorized as having low self-identified heat tolerance if the sum of questions 8 - 17 was less than 25 points (9, 15, and 17 were reverse calculation indexes). It was categorized into a group with a high self-identified heat tolerance if it was greater than 25 points. As a result, 21 respondents answered that the self-identified heat tolerance was high, and 7 answered low. With the part of (D): heat related experience, one respondent who mentioned experiencing heat cramps stated he often had them once a year. In addition, 11 subjects experienced heat fatigue. Five of them said it happened once a year, three answered it took place twice a year, two responded it occurred three times a year, and one said it happened six times a year. Lastly, in response to a question concerning other heat experiences, one respondent said he typically felt extremely hot five times a year.

Table A Individual and job-related characteristics of firefighters

Part	No	Questions	Total	
			N	%
		Total	28	100
(A)	1	What is your sex?		
		Male	28	100
		Female	0	0
	2	How old are you?		
		20-29	5	17.9
		30-39	11	39.3
		40-49	8	28.6
		50-59	4	14.3
	3	What is your educational background?		
		≤Middle school graduate	0	0
		High school graduate	6	21.4
		College graduate	19	67.9
		≥graduate school	3	10.7
	4	What is your marital status?		
		Single	14	50
		Married	14	50
		Bereavement or others	0	0
	5	What is your daily smoking frequency?		
		No	18	64.3
		<5	0	0
		5-9	4	14.3
		10-19	6	21.4
		≥20	0	0
	6	How many times a week do you drink?		
		No	10	64.3
		≤2	16	14.3
		3-5	2	21.4
		≥6	0	0
	7	How many times a week do you exercise?		
		No	0	0
		≤2	9	32.1
		3-5	13	46.4

		≥6	6	21.5
(B)	8	I am sensitive (intolerable) to heat in summer.		
		Absolutely yes	8	28.6
		Slightly yes	11	39.3
		Neutral	3	10.7
		Slightly no	6	21.4
		Absolutely no	0	0
	9	Is it enough to endure heat by using only electronic fans without the use of air-conditioners in summer?		
		Absolutely yes	2	7.1
		Slightly yes	3	10.7
		Neutral	11	39.3
		Slightly no	7	25.0
		Absolutely no	5	17.9
	10	I tend to enjoy cold foods such as iced-coffee, cold noodle, shaved ice, and ice-cream in summer.		
		Absolutely yes	2	7.1
		Slightly yes	9	32.1
		Neutral	10	35.7
		Slightly no	7	25.0
		Absolutely no	0	0
	11	I prefer to use an air-conditioner set at a low temperature in summer.		
		Absolutely yes	4	14.3
		Slightly yes	6	21.4
		Neutral	8	28.6
		Slightly no	9	32.1
		Absolutely no	1	3.6
	12	I used to feel heat even just after taking a cold shower in summer.		
		Absolutely yes	0	0
		Slightly yes	6	21.4
		Neutral	4	14.3
		Slightly no	13	16.4
		Absolutely no	5	17.9

13	It is hard to fall asleep without auxiliary cooling devices such as air conditioner and an electronic fans in summer.		
	Absolutely yes	3	10.7
	Slightly yes	13	46.4
	Neutral	3	10.7
	Slightly no	9	32.1
	Absolutely no	0	0
14	I tend to sweat a lot in summer.		
	Absolutely yes	14	50.0
	Slightly yes	6	21.4
	Neutral	3	10.7
	Slightly no	3	10.7
	Absolutely no	2	7.1
15	Which indoor temperature range do you think is ideal when you sleep in summer?		
	≤19	1	3.6
	19-22	4	14.3
	22-25	21	75.0
	25-28	2	7.1
	≥28	0	0
16	How long do you use air-conditioner a day in summer if you stay at home?		
	≥9	5	17.9
	6-9	6	21.4
	3-6	6	21.4
	1-3	8	28.6
	≤1	3	10.7
17	Which temperature range do you prefer when you use an air-conditioner in summer?		
	≤19	1	3.6
	19-22	3	10.7
	22-25	22	78.6
	25-28	4	7.1
	≥28	0	0

(C)	18	Has anyone in your immediate family (parent-brother) been diagnosed with the following diseases? angina pectoris		
		Yes	3	10.7
		No	25	89.3
	19	hypertension		
		Yes	16	57.1
		No	12	42.9
	20	diabetes mellitus		
		Yes	7	25.0
		No	21	75.0
	21	Heart attack		
		Yes	0	0
		No	28	100
	22	dyslipidemia		
		Yes	3	25.0
		No	25	75.0
	23	stroke		
		Yes	5	17.9
		No	23	82.1
(D)	24	How many years have you been working? (rounding off to the nearest whole number)		
		<5	11	39.3
		5-10	6	21.4
		11-15	3	10.7
		16-20	2	7.1
		21-25	4	14.3
		>25	2	7.1
	25	Have you ever lost a job in the past?		
		Yes	1	3.6
		No	27	96.4
	26	Have you worked extra shifts in the past month?		
		Yes	23	82.1
		No	5	17.9

27	Have you ever experienced HRI symptoms (heat cramps) during duties?		
	Yes	0	0
	No	28	100
28	Have you ever experienced HRI symptoms (heat cramps) during duties?		
	Yes	1	3.6
	No	27	96.4
29	Have you ever experienced HRI symptoms (heat fatigue) during duties?		
	Yes	11	39.3
	No	17	60.7
30	Have you ever experienced any other HRI symptoms during duties?		
	Yes	1	3.6
	No	27	96.4
31	Have you worked in the past 12 months even though you were sick? (includes both mental and physical due to injury, etc.)		
	Yes	13	46.4
	No	15	53.6

초 록

본 연구는 고온 다습한 환경에서 소방 방화복 착용에 의한 면역·염증, 심혈관, 서열 긴장 정도를 확인하고자 하였다. 또한, Entropy-TOPSIS model을 활용하여 소방관 개인별로 유발된 생리·심리적 긴장 수준을 확인하고, 개인의 특성 중 영향을 받는 인자를 확인하고자 하였다. 마지막으로, 심혈관계 부담 수준에 유의미하게 영향을 준 개인 특성을 기준으로 그룹을 나누어, 생리·심리적 측정치들을 세부적으로 확인하고자 하였다. 총 28명의 현직 소방관들은 두 가지 실험 조건(조건1: 기동복, 조건2: Full PPE)의 인체착용평가에 참여하였다. 기온 30ºC, 습도 61% RH의 인공기후실에서 10분 휴식 이후, 운동과 회복을 반복하였다. 본 연구의 결과는 첫째, 기동복 조건 보다 Full PPE 조건에서, 일부 면역-염증 반응, 심박수, 직장온, 피부온, 한서감, 인지적 힘들기의 값들이 유의하게 높았고, 심박변이도에서는 더 낮은 값을 보여(all $P<0.05$), 소방복 착용에 의해 생리· 심리적 면역·염증, 심혈관계, 체온조절 부담이 더 증가하는 것으로 나타났다. 둘째, Entropy-TOPSIS model을 활용하여 소방관 개개인의 상대적 생리·심리적 긴장 수준을 도출한 결과, 연령 증가에 따라 생리·심리적 긴장 수준도 증가함을 확인하였다. 시점별 연령과 측정치들 사이의 상관관계를 확인한 결과, 일부 염증 반응과 주관적 반응에서 양의 상관관계를, 시간 범위의 심박변이도에서 음의 상관관계가 확인되었다. 또한, 40-50대의 중장년 소방관 집단 (Older-FF)과 20-30대의 청년층 소방관 집단 (Young-FF)은

프로토콜이 진행되면서 감소되는 정도에 있어서 비슷한 수준으로 스트레스를 받고 있음에도, 면역 · 염증 반응이 중장년 소방관이 더 크게 증가하였다. 이러한 결과는 고온 다습 환경에서 소방 방화복과 같은 전신 개인보호구 착용은 발한량과 심부온을 증가시킬 뿐만 아니라 면역-염증 반응까지 촉진할 수 있음을 보여주며, 극한 화염 상황이 아닌 일반적인 여름철 환경에서의 보호복 착용임에도 면역-염증 반응이 증가된다는 결과는 주목할만하다. 또한, 중장년층 소방관과 청년층 소방관과의 비교 분석 결과는 여름철 화재 진압이나 구조 작업 중 작업-휴식 시간이나 반복 작업 구성 시 소방관들의 연령을 고려해야 함을 시사한다. 본 연구에서는 여름철 소방관들이 기동복만 착용한 경우에 비해 소방 방화복을 착용하고 작업하는 경우 체온조절 및 심혈관계 부담, 면역-염증 반응이 유의하게 증가함을 확인하였다. 이와 함께 소방관 개개인의 생리 · 심리적 긴장 수준을 도출하고, 중장년층 소방관들이 청년층 소방관들에 비해 여름철 화재 진압 및 구조, 구급 작업 시 더 위험할 수 있음을 확인하였다. 본 연구 결과는 여름철 소방관들의 심혈관계 부담 및 서열 부담 경감을 위한 소방방화복 개선 및 중장년층 소방관들의 건강과 안전을 위한 소방 작업 지침 개발에 활용될 수 있을 것이다.

주요어: 소방관, 개인보호구, 생리·심리적 긴장, 면역−염증 반응, 심혈관 부담, 서열 부담, 연령, 엔트로피 탑시스 모델

학번: 2021−21114