APPLIED SCIENCES

Older Firefighters Are Susceptible to Age-Related Impairments in Heat Dissipation

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[1]Human Environmental Physiological Research Unit, University of Ottawa, Ontario, CANADA; [2]Faculty of Physical Education and Sports, University of Sherbrooke, Sherbrooke, Quebec, CANADA; [3]Departments of Medicine, Cardiac Sciences and Community Health Sciences, Faculties of Medicine and Kinesiology, University of Calgary, Calgary, Alberta, CANADA; and [4]FAME Laboratory, Department of Exercise Science, University of Thessaly, Trikala, GREECE

ABSTRACT

KENNY, G. P., J. LAROSE, H. E. WRIGHT-BEATTY, P. BOULAY, R. J. SIGAL, and A. D. FLOURIS. Older Firefighters Are Susceptible to Age-Related Impairments in Heat Dissipation. *Med. Sci. Sports Exerc.*, Vol. 47, No. 6, pp. 1281–1290, 2015. **Purpose**: The aging-induced reduction in whole-body heat loss (H_L) capacity generates concerns regarding the continued participation of older workers in occupations such as firefighting. We compared H_L and change in body heat storage (S) during intermittent exercise in warm/dry and warm/humid conditions among older male firefighters (OLDER, n = 9, age = 54.7 ± 2.1 yr), older (age-matched) nonfirefighters (NON-FF, n = 9, age = 52.8 ± 1.2 yr), and young firefighters (YOUNG, n = 6, age = 26.7 ± 0.8 yr). **Methods**: We measured evaporative heat loss and dry heat exchange via the Snellen whole-body direct calorimeter while participants performed four 15-min bouts of cycling at 400 W of metabolic heat production separated by 15-min recovery periods in warm/dry (35 °C, 20% relative humidity) and warm/humid (35 °C, 60% relative humidity) conditions. **Results**: We found no differences ($P > 0.05$) in H_L or cumulative S (ΔS) between OLDER and NON-FF in the warm/dry (ΔS: OLDER = 233 ± 26 kJ, NON-FF = 270 ± 29 kJ) or warm/humid (ΔS: OLDER = 548 ± 24 kJ, NON-FF = 504 ± 47 kJ) conditions. The OLDER and NON-FF had lower H_L than the YOUNG during exercise in both environmental conditions ($P < 0.05$). The OLDER stored 40% ($P > 0.05$) and 46% ($P = 0.004$) more heat than YOUNG in the warm/dry and warm/humid conditions, respectively. The NON-FF stored 63% ($P = 0.016$) and 34% ($P = 0.025$) more heat than the YOUNG in the dry and humid conditions, respectively. **Conclusions**: Older firefighters and age-matched nonfirefighters demonstrate similar H_L and S during work in the heat. Moreover, H_L is significantly reduced in older compared to younger firefighters during exercise in both warm/dry and warm/humid conditions. Consequently, older firefighters may be more susceptible to thermal injury while on duty than their younger counterparts. **Key Words:** OCCUPATIONAL HEAT STRESS, WHOLE-BODY HEAT LOSS, FIREFIGHTING, CALORIMETRY, BODY HEAT STORAGE

Firefighting is a rewarding yet challenging profession. However, the physical demands associated with the job often become arduous and this can be exacerbated by the highly insulative properties of the protective clothing worn and the exposure to extreme heat (2,6,17,18). Despite the increased occupational demands of firefighting, the age distribution of this workforce is relatively even between young and older individuals. For example, of the ~1.1 million career and volunteer firefighters across the United States, 21.1% are between the ages of 20 and 29 yr, whereas 24% are 50 yr or older (8). However, the marked reduction in heat loss capacity as a function of age (7,9,12–14,26) generates health and safety concerns with respect to the continued participation of workers beyond the age of 50 yr in occupations such as firefighting. These concerns may be countered by the hypothesis that regular exposure to the hot and humid microenvironment created inside their protective clothing may confer some degree of heat acclimation and/or offset age-related decrements in thermoregulatory capacity otherwise seen in the general aging population (1,16,27). However, the literature addressing this topic is sparse, and studies using robust measurements of whole-body heat loss in this specific population group are lacking.

We recently showed that older firefighters reported lower perceived levels of thermal strain compared to age-matched nonfirefighters during exercise in the heat in both dry and humid conditions (27). While this supports the idea that frequent occupational exposures to hot environments may improve heat tolerance in older firefighters compared to age-matched nonfirefighters, we found no differences in physiological responses (i.e., rectal and skin temperatures, local sweat rate, and heart rate) between firefighters and nonfirefighters. These findings suggest that firefighting induces no

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favorable adaptations in heat tolerance. More importantly, the lack of superior heat tolerance coupled with the attenuated levels of perceived thermal strain may render older firefighters susceptible to heat injuries. However, before proposing changes in the organizational architecture of fire safety units (such as identifying tasks that should be avoided, if necessary, by older firefighters), it is necessary to compare whole-body heat dissipation of older firefighters against both age-matched nonfirefighters as well as younger firefighters. Therefore, our aim in this study was to compare whole-body heat loss and body heat storage during intermittent exercise in a warm/dry and a warm/humid environment among a group of older male firefighters, a group of older (age-matched) nonfirefighters, as well as a group of young firefighters. Since our participants did not wear firefighter protective clothing because it would restrict heat loss and, thus, undermine the measurements of our whole-body direct calorimeter, the warm/humid condition was used to simulate the hot and humid microenvironment inside the firefighter uniform created because of its high insulative capacity. We hypothesized that the older firefighters would demonstrate greater rates of whole-body heat loss and reduced body heat storage compared to nonfirefighters. We also hypothesized that age-related decrements in heat dissipation would be less pronounced in older firefighters than in age-matched nonfirefighters in both environmental conditions.

MATERIALS AND METHODS

Procedures and participants. The current experimental protocol was approved by the University of Ottawa Health Sciences and Science Research Ethics Board. Written informed consent was obtained from all volunteers before their participation in the study. A total of 24 male adults participated in the study and were separated into three groups: a group of older firefighters (OLDER, n = 9, age = 54.7 ± 2.1 yr, years of firefighting service = 27.3 ± 2.4 yr), a group of age-matched nonfirefighters (NON-FF, n = 9, age = 52.8 ± 1.2 yr), and a group of young firefighters (YOUNG, n = 6, age = 26.7 ± 0.8 yr, years of firefighting service = 2.8 ± 0.2 yr). All participants were healthy and did not report any history of cardiovascular, respiratory and metabolic disease, or uncontrolled hypertension. Also, they all underwent a graded exercise test and body composition assessment before participating in study.

Experimental design. Participants were instructed to refrain from consuming alcohol and caffeine for 12 h before the experimental sessions. They were also asked to avoid strenuous physical activity and major thermal stimuli for 24 h before the sessions. No fluids were provided during the experimental sessions. The study protocol involved two separate experimental sessions, one in a warm/dry condition (35°C and 20% relative humidity [RH]) and the other in a warm/humid condition (35°C and 60% RH). The same exercise protocol was used during both sessions: participants performed four 15-min bouts of recumbent cycling (termed exercise bouts 1, 2, 3, and 4 [Ex1, Ex2, Ex3, and Ex4]) at a constant rate of heat production of 400 W. Each exercise bout was separated by a 15-min recovery period (termed recovery bouts 1, 2, 3, and 4 [R1, R2, R3, and R4]) for a total duration of 2 h. The sessions were performed in a random order at approximately the same time of day and were separated by a minimum of 72 h.

Instrumentation took place in a thermoneutral room. Thereafter, participants were seated inside a whole-body direct calorimeter where they rested for a period of 30 min while a steady-state baseline condition was achieved. The exercise protocol was initiated after the baseline period. Clothing during the experimental sessions was standardized to running shorts and sandals.

Perceptual measurements. At the end of each phase (Baseline, Ex1, R1, Ex2, R2, Ex3, R3, Ex4, and R4) in both conditions, we assessed rate of perceived exertion (RPE) using the Borg Scale (4), which ranges from 6 (no exertion at all) to 20 (maximal exertion). At the same time points, we also measured thermal sensation (TS) using the ASHRAE 7-point scale, which ranges from 0 (neutral) to 7 (very, very hot). The RPE and TS were used to calculate the Perceptual Strain Index (PeSI) as follows:

$$\mathrm{PeSI} = (5[\mathrm{TS}/7]) + (5[\mathrm{RPE} - 6]/14)$$

where 7 and 14 represent the number of values on the scale above rest for TS and RPE, respectively, and 6 represents the RPE at rest (25).

Physiological measurements. Peak oxygen uptake ($\dot{V}O_{2peak}$) was measured during a progressive cycle ergometer protocol which consisted of a 2-min warm-up at 40 W followed by 20-W increments every minute until the participant could no longer maintain a pedaling cadence of at least 60 rpm. Continuous ECG monitoring was used on OLDER and NON-FF during the maximal exercise test as they were all 50 yr of age or older. Body density was measured using the hydrostatic weighing technique, and body fat percentage was calculated using the Siri equation (21). Body surface area was calculated from the measurements of weight and height according to DuBois and DuBois (5).

Direct calorimetry was used to measure whole-body evaporative heat loss and dry heat exchange (through radiation, conduction and convection) with an accuracy of ±2.3 W. A full peer-reviewed technical description of the performance and calibration characteristics of the Snellen whole-body calorimeter is available elsewhere (19). Evaporative heat loss (H_E) was measured using the following equation:

$$H_E = \frac{(\text{massflow} \times [\text{humidity}_{\text{out}} - \text{humidity}_{\text{in}}]) \times 2.426}{60}$$

where mass flow is the rate of air mass (kilogram of air per second); ($\text{humidity}_{\text{out}}$ – $\text{humidity}_{\text{in}}$) is the difference in absolute humidity (grams of water per kilogram of air) between the in and out flows of the calorimeter; and 2.426 is the latent heat of vaporization of sweat (joules per gram of sweat). Dry heat exchange (H_D) was measured as follows:

$$H_D = \frac{(\text{massflow} \times [\text{temperature}_{\text{out}} - \text{temperature}_{\text{in}}]) \times 1.005}{60}$$

where mass flow is the rate of air mass (kilogram of air per second); (temperature$_{\text{out}}$ – temperature$_{\text{in}}$) is the difference in air temperature (°C) between the inflow and outflow of the calorimeter; and 1.005 is the specific heat of air (joules per kilogram of air [°C]). Total body heat loss (H_L) was calculated as the sum of evaporative heat loss and dry heat exchange. Data from the direct calorimeter were collected continuously at 8-s intervals during the experimental sessions. Real-time data were displayed and recorded on a personal computer with LabVIEW software (version 7.0; National Instruments, Austin, TX). Indirect calorimetry was used to measure the rate of metabolic heat production (M-W) from measurements of oxygen and carbon dioxide concentrations in a known volume of expired gas (Moxus modular metabolic system; AEI Technologies, Bastrop, TX). Oxygen and carbon dioxide concentrations were analyzed using electrochemical gas analyzers (AMETEK models S-3A/1 and CD 3A, respectively; Applied Electrochemistry, Pittsburgh, PA) located outside the calorimeter chamber. Expired air was recycled back into the calorimeter chamber to account for respiratory dry and evaporative heat loss. Before each session, gas mixtures of 4% carbon dioxide, 17% oxygen, and balance nitrogen were used to calibrate the gas analyzers, and a 3-L syringe was used to calibrate the turbine ventilometer. The changes in body heat storage (S) were calculated during each exercise and recovery period as the temporal summation of heat production and total heat loss. The cumulative change in body heat storage (ΔS) was calculated as the temporal summation of heat production and total heat loss over the entire experimental session:

$$\Delta S = (\text{M} - \text{W}) - H_E \pm H_D$$

The rate of evaporative heat loss required to achieve heat balance (E_{req}) was calculated as follows:

$$E_{\text{req}} = (\text{M} - \text{W}) \pm H_D$$

Rectal temperature (T_{re}) was measured continuously by inserting a thermocouple probe (Mon-a-therm General Purpose Temperature Probe; Mallinckrodt Medical, St. Louis, MO) to a minimum of 12 cm past the anal sphincter. Skin temperature was measured at four sites using 0.3-mm-diameter T-type thermocouples (Concept Engineering, Old Saybrook, CT) attached to the skin with surgical tape. Mean skin temperature (T_{sk}) was subsequently calculated from the four skin temperatures weighted to the following regional proportions: upper back = 30%, chest = 30%, quadriceps = 20%, and back calf = 20%. Temperature data were collected using a HP Agilent data acquisition module (model 3497A) at a sampling rate of 15 s and simultaneously displayed and recorded in spreadsheet format on a personal computer with LabVIEW software (version 7.0; National Instruments).

Statistical analysis. All measurements were converted to 1-min averages, and only the values measured at the end of baseline, at the end of each exercise bout (Ex1, Ex2, Ex3, and Ex4), and at the end of each recovery bout (R1, R2, R3, and R4) were used for statistical purposes. A MANOVA with group (three levels: OLDER, NON-FF, YOUNG) and condition (two levels: dry, humid) set as factors was used to investigate the differences across time (Ex1, Ex2, Ex3, and Ex4) in RPE and PeSI because these variables were recorded only during exercise. Changes across time (Baseline, Ex1, R1, Ex2, R2, Ex3, R3, Ex4, and R4) in all the remaining variables were analyzed in a subsequent MANOVA using group and condition set as factors. *Post hoc* one-way ANOVA followed by *t*-tests incorporating a Bonferroni adjustment was used for further analysis of a significant main and/or interaction effect. An additional one-way ANOVA was used to analyze group differences in physical characteristics. An α level of ≤0.05 was considered statistically significant. The statistical software package SPSS 21 (SPSS, Inc., Chicago, IL) was used for all analyses.

RESULTS

There were no significant differences between groups for height (OLDER: 1.75 ± 0.02 m; NON-FF: 1.78 ± 0.02 m; YOUNG: 1.80 ± 0.03 m), weight (OLDER: 88.2 ± 3.0 kg; NON-FF: 86.4 ± 2.4 kg; YOUNG: 85.2 ± 1.8 kg), or body surface area (OLDER: 2.04 ± 0.04 m^2; NON-FF: 2.04 ± 0.03 m^2; YOUNG: 2.05 ± 0.03 m^2). As expected, the OLDER (54.7 ± 2.09 yr) and NON-FF (52.8 ± 1.16 yr) were significantly older than the YOUNG (26.7 ± 0.76 yr, P < 0.001), whereas the YOUNG demonstrated a greater $\dot{V}O_{2\text{peak}}$ (44.5 ± 2.2 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$) and a lower percentage of body fat (16.5% ± 1.7%) than the OLDER ($\dot{V}O_{2\text{peak}}$ = 34.0 ± 2.0 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$, P = 0.021; % body fat = 26.0% ± 2.0%, P = 0.043, respectively) and the NON-FF ($\dot{V}O_{2\text{peak}}$ = 37.5 ± 2.3 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$, P = 0.001; % body fat = 23.3% ± 1.5%, P = 0.004, respectively). Moreover, the OLDER (27.3 ± 2.4 yr) reported increased years of firefighting service than the YOUNG (2.8 ± 0.2 yr, P < 0.05).

The first MANOVA incorporating RPE and PeSI detected statistically significant main effects of group (Pillai trace = 0.626, $F_{16,72}$ = 2.049, P = 0.021) and condition (Pillai trace = 0.355, $F_{8,35}$ = 2.404, P = 0.035), but there were no significant interaction effects of group–condition (P > 0.05) across both variables as a whole. Looking at each variable separately, we found significant main effects of group on both RPE (Ex1, Ex2, Ex3, and Ex4 [all P < 0.001]; Table 1) and PeSI (Ex1, Ex2, Ex3, and Ex4 [all P < 0.001]; Table 1). In addition, we found significant main effects of condition on PeSI during Ex1 (P = 0.033) and Ex2 (P = 0.016) (Table 1). No significant interaction effects of group–condition (P > 0.05) were detected on either RPE or PeSI (P > 0.05).

The second MANOVA incorporating all variables except RPE and PeSI detected no statistically significant main

TABLE 1. Perceptual measurements of thermal sensation, RPE, and perceptual strain index during intermittent exercise in dry and humid heat stress conditions (mean ± SE).

	TS			RPE			PeSI		
	OLDER	NON-FF	YOUNG	OLDER	NON-FF	YOUNG	OLDER	NON-FF	YOUNG
Dry Condition (35°C, 20% RH)									
Base	1.9 ± 0.3	1.8 ± 0.3	1.2 ± 0.6	—	—	—	—	—	—
Ex1	2.6 ± 0.3	2.8 ± 0.4	2.3 ± 0.2	11.0 ± 0.3	11.7 ± 0.6*	9.2 ± 0.7	3.6 ± 0.3	4.1 ± 0.3	2.8 ± 0.3
R1	2.2 ± 0.4	1.8 ± 0.1	1.3 ± 0.2	—	—	—	—	—	—
Ex2	3.2 ± 0.2**	2.9 ± 0.2	2.5 ± 0.4	11.4 ± 0.4	12.1 ± 0.3*	10.2 ± 0.5	4.2 ± 0.3*,**	4.2 ± 0.2*	3.3 ± 0.3
R2	1.8 ± 0.4	1.9 ± 0.3	1.5 ± 0.2	—	—	—	—	—	—
Ex3	3.1 ± 0.3**	2.8 ± 0.2	2.7 ± 0.4	11.9 ± 0.2**	12.3 ± 0.3*	10.7 ± 0.6	4.3 ± 0.2**	4.3 ± 0.2	3.6 ± 0.4
R3	1.9 ± 0.4	1.8 ± 0.3	1.5 ± 0.2	—	—	—	—	—	—
Ex4	3.4 ± 0.3**	3.0 ± 0.3	2.7 ± 0.4	11.7 ± 0.2*,**	12.3 ± 0.4*	10.3 ± 0.6	4.5 ± 0.3**	4.4 ± 0.3	3.5 ± 0.3
R4	1.7 ± 0.3	1.6 ± 0.3	1.7 ± 0.3	—	—	—	—	—	—
Humid Condition (35°C, 60% RH)									
	TS			**RPE**			**PeSI**		
	OLDER	**NON-FF**	**YOUNG**	**OLDER**	**NON-FF**	**YOUNG**	**OLDER**	**NON-FF**	**YOUNG**
Base	2.0 ± 0.2	2.2 ± 0.3	1.7 ± 0.4	—	—	—	—	—	—
Ex1	3.1 ± 0.2	3.3 ± 0.3	2.7 ± 0.3	11.3 ± 0.3	12.0 ± 0.3*	9.9 ± 0.6	4.1 ± 0.2	4.5 ± 0.2*	3.3 ± 0.3
R1	2.1 ± 0.4	2.3 ± 0.4	1.8 ± 0.3	—	—	—	—	—	—
Ex2	3.6 ± 0.2	3.6 ± 0.3	2.8 ± 0.3	11.9 ± 0.2**	12.5 ± 0.4*,**	10.6 ± 0.6	4.7 ± 0.1**	4.9 ± 0.3*	3.7 ± 0.3
R2	2.3 ± 0.3	2.6 ± 0.4	1.5 ± 0.3	—	—	—	—	—	—
Ex3	3.7 ± 0.3	3.7 ± 0.4	3.2 ± 0.3	12.0 ± 0.4*	12.5 ± 0.3*,**	10.3 ± 0.6	4.8 ± 0.2**	5.0 ± 0.3*	3.8 ± 0.3
R3	2.3 ± 0.3	2.4 ± 0.4	1.7 ± 0.3	—	—	—	—	—	—
Ex4	3.3 ± 0.4	3.8 ± 0.3	3.2 ± 0.3	12.7 ± 0.4*,**	12.8 ± 0.4*,**	10.5 ± 0.6	4.8 ± 0.4	5.1 ± 0.4**	3.9 ± 0.3
R4	2.4 ± 0.4	2.6 ± 0.4	1.7 ± 0.2	—	—	—	—	—	—

Base, baseline steady state; Ex, exercise period; R, recovery period; TS, thermal sensation; PeSI, perceptual strain index; OLDER, group of older firefighters; NON-FF, group of older nonfirefighters; YOUNG, group of young firefighters.
*Significantly different from YOUNG ($P < 0.05$).
**Significantly different Ex period compared to Ex1 ($P < 0.05$).

effects of group or condition as well as no interaction effects of group–condition ($P > 0.05$) across all variables as a whole. Looking at each variable separately, we found significant main effects of group on: (i) TS during Ex2 ($P = 0.05$) (Table 1); (ii) H_L during Ex1 ($P = 0.003$), Ex2 ($P < 0.001$), R2 ($P = 0.02$), Ex3 ($P = 0.001$), and Ex4 ($P < 0.001$) (Table 2); (iii) H_E during Ex1 ($P = 0.05$) and Ex2 ($P = 0.047$) (Fig. 1); and (iv) S during Ex1 ($P = 0.002$), Ex2 ($P = 0.002$), R2 ($P = 0.039$), Ex3 ($P = 0.015$), Ex4 ($P = 0.016$), as well as the overall ΔS ($P = 0.001$) (Fig. 2).

TABLE 2. Physiological measurements of metabolic heat production and total heat loss during intermittent exercise in dry and humid heat stress conditions (mean ± SE).

	M-W (W)			H_L (W)		
	OLDER	NON-FF	YOUNG	OLDER	NON-FF	YOUNG
Dry Condition (35°C, 20% RH)						
Base	117 ± 9	104 ± 4	113 ± 5	105 ± 11*	72 ± 7	81 ± 10
Ex1	393 ± 13	406 ± 2	406 ± 5	276 ± 11	283 ± 8	289 ± 10
R1	127 ± 16	117 ± 4	129 ± 16	146 ± 8	128 ± 8	131 ± 16
Ex2	390 ± 20	404 ± 4	402 ± 3	321 ± 6**,***	315 ± 9**,***	351 ± 9**
R2	133 ± 14	112 ± 2	114 ± 4	158 ± 7*	131 ± 7	149 ± 9
Ex3	399 ± 13	402 ± 4	396 ± 3	330 ± 6**,***	323 ± 7**,***	363 ± 5**
R3	130 ± 9	120 ± 3	121 ± 4	159 ± 7	137 ± 8	159 ± 12
Ex4	387 ± 17	406 ± 4	410 ± 4	327 ± 18**,***	329 ± 8**,***	359 ± 6**
R4	109 ± 4	114 ± 4	120 ± 5	153 ± 6	149 ± 6	157 ± 10
Humid Condition (35°C, 60% RH)						
	M-W (W)			**H_L (W)**		
	OLDER	**NON-FF**	**YOUNG**	**OLDER**	**NON-FF**	**YOUNG**
Base	121 ± 6	116 ± 6	121 ± 8	58 ± 12	66 ± 10	63 ± 9
Ex1	396 ± 4	405 ± 3	410 ± 3	200 ± 11***	205 ± 9***	266 ± 12
R1	122 ± 8	119 ± 3	117 ± 4	117 ± 5***	110 ± 6***	143 ± 8
Ex2	405 ± 4	401 ± 5	406 ± 8	245 ± 10**,***	247 ± 8**,***	291 ± 8**
R2	121 ± 3	121 ± 6	127 ± 4	143 ± 5***,****	128 ± 11***	156 ± 9
Ex3	401 ± 6	412 ± 5**	409 ± 5	261 ± 9**,***	271 ± 12**	301 ± 7**
R3	124 ± 3	119 ± 6	133 ± 5	160 ± 7****	144 ± 12****	155 ± 11
Ex4	415 ± 4**,*	399 ± 3	405 ± 5	281 ± 4**	274 ± 9**,***	300 ± 5**
R4	121 ± 4	110 ± 8	121 ± 5	151 ± 10****	144 ± 7****	136 ± 7

Base, baseline steady state; Ex, exercise period; R, recovery period; M-W, metabolic heat production; HL, total heat loss; OLDER, group of older firefighters; NON-FF, group of older nonfirefighters; YOUNG, group of young firefighters.
*Significantly different from NON-FF ($P < 0.05$).
**Significantly different Ex period compared to Ex1 ($P < 0.05$).
***Significantly different from YOUNG ($P < 0.05$).
****Significantly different R period compared to R1 ($P < 0.05$).

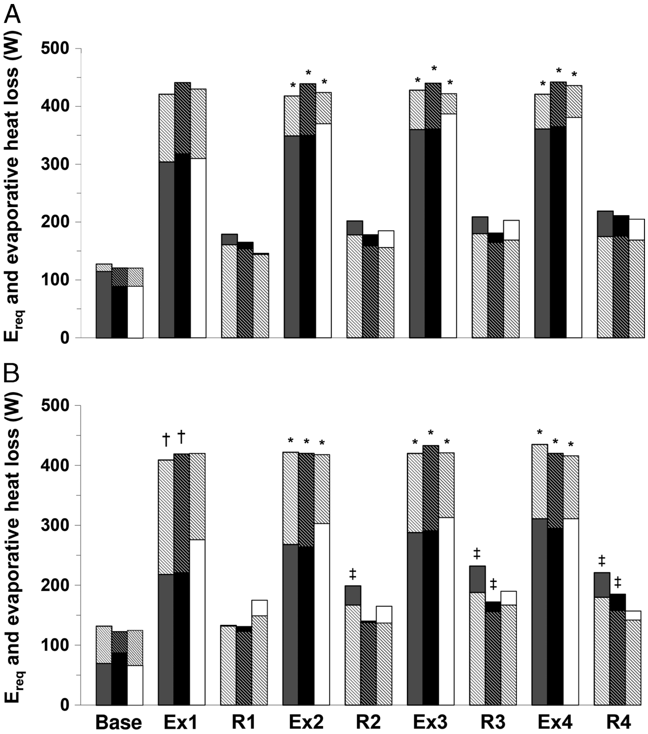

FIGURE 1—Mean values for evaporative heat loss (*solid bars*) and the required amount of evaporation for heat balance (E_{req}) (*lined bars*) measured over baseline (Base), four 15-min exercise bouts (Ex1, Ex2, Ex3, and Ex4) and four recovery bouts (R1, R2, R3, and R4) in a dry (35°C and 20% RH) (A) and humid (35°C and 60% RH) (B) environment. The *gray shade* represents the group of older firefighters (OLDER, *n* = 9), the *black shade* represents the group of older nonfirefighters (NON-FF, *n* = 9), and the *white shade* represents the group of young firefighters (YOUNG, *n* = 6). *Significantly different from Ex1. ‡Significantly different from R1. †Significantly different from YOUNG.

The second MANOVA also detected significant main effects of condition on: (i) TS during Ex3 (P = 0.033) and R4 (P = 0.048) (Table 1); (ii) H_L during Baseline (P = 0.006), Ex1 (P < 0.001), Ex2 (P < 0.001), and Ex3 (P < 0.001) (Table 2); (iii) H_E during Baseline (P = 0.007), Ex1 (P < 0.001), R1 (P = 0.044), as well as Ex2, Ex3, and Ex4 (all P < 0.001) (Fig. 1); (iv) H_D during Baseline (P = 0.044), Ex1 (P = 0.003), Ex2 (P = 0.035), Ex3 (P = 0.032), and Ex4 (P = 0.044) (Table 3); (v) S during Baseline (P = 0.005) as well as Ex1, R1, Ex2, R2, Ex3, R3, Ex4, R4, and overall ΔS (all P < 0.001) (Fig. 2); and (vi) T_{sk} during Ex1 (P = 0.003), R1 (P = 0.016), Ex2 (P = 0.001), R1 (P = 0.001), as well as Ex3, R3, Ex4, and R4 (all P < 0.001) (Table 3).

The second MANOVA detected significant group–condition interaction effects on H_L during Ex1 (P = 0.035; Table 2) as well as on S during Ex1 (P = 0.014; Fig. 1). It is worth mentioning that the group–condition interaction effect on H_E during Ex1 was strong, yet not statistically significant (P = 0.07). According to these interaction effects, H_L and—to a lesser extent—H_E were significantly reduced during the humid condition, whereas S was significantly increased during the humid condition. More importantly, these changes were observed mainly in the OLDER and NON-FF groups compared to the YOUNG group. These results are analyzed further in the following sections that present the results of the *post hoc* analyses. We assumed that whole-body heat loss would be significantly reduced in the humid than in the dry condition for all groups based on recent data showing that heat loss is significantly impeded for young through to older adults during exercise in a humid environment compared to exercise in a dry environment (13). Therefore, the results of the *post hoc* analyses are presented separately for each condition.

Between-group differences in the dry condition. The ANOVA between groups detected statistically significant differences in RPE during Ex1 ($F_{2,21}$ = 5.48, P = 0.012), Ex2 ($F_{2,21}$ = 5.02, P = 0.016), Ex3 ($F_{2,21}$ = 5.43, P = 0.013), and Ex4 ($F_{2,21}$ = 7.27, P = 0.004). *Post hoc t*-tests (Table 1) demonstrated that the NON-FF reported higher RPE than the YOUNG during Ex1 (P = 0.011), Ex2 (P = 0.014), Ex3 (P = 0.012), and Ex4 (P = 0.003). Also, the OLDER reported higher RPE than the YOUNG, yet the P value of the

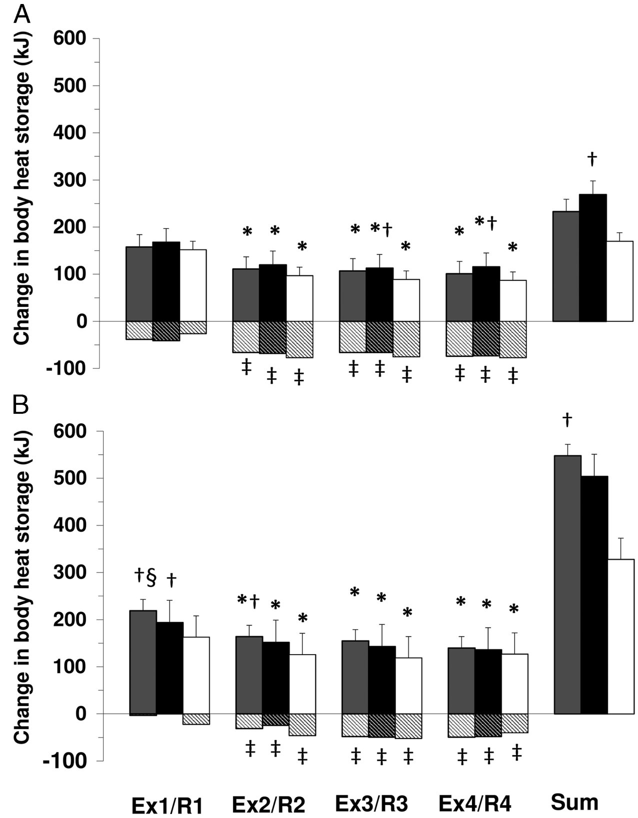

FIGURE 2—Mean values for changes in body heat storage during each exercise/recovery cycle as well as the cumulative change in body heat storage over the 2-h exercise protocol (Sum) in a dry (35°C and 20% RH) (A) and humid (35°C and 60% RH) (B) environment. The *solid bars* represent changes in body heat storage during exercise, the *lined bars* represents the changes in body heat storage during recovery. The *gray shade* represents the group of older firefighters (OLDER, *n* = 9), the *black shade* represents the group of older nonfirefighters (NON-FF, *n* = 9), and the *white shade* represents the group of young firefighters (YOUNG, *n* = 6). *Significantly different from Ex1. ‡Significantly different from R1. †Significantly different from YOUNG. §Significantly different from NON-FF.

APPLIED SCIENCES

TABLE 3. Physiological measurements of dry heat exchange and mean skin temperature during intermittent exercise in dry and humid heat stress conditions (mean ± SE).

Dry Condition (35°C, 20% RH)						
	H_D (W)			T_{sk} (°C)		
	OLDER	NON-FF	YOUNG	OLDER	NON-FF	YOUNG
Base	−14 ± 2	−20 ± 8	−11 ± 3	33.98 ± 0.17	33.92 ± 0.15	34.10 ± 0.15
Ex1	−28 ± 4	−35 ± 11	−24 ± 3	34.39 ± 0.15	34.34 ± 0.12	34.58 ± 0.09
R1	−16 ± 3	−27 ± 10	−13 ± 4	34.26 ± 0.15	34.10 ± 0.14	34.40 ± 0.13
Ex2	−28 ± 4	−35 ± 12	−22 ± 5	34.53 ± 0.18	34.46 ± 0.12*	34.63 ± 0.18
R2	−20 ± 3**	−28 ± 11	−13 ± 5	34.13 ± 0.18	34.09 ± 0.13	34.39 ± 0.19
Ex3	−30 ± 5	−38 ± 12	−26 ± 5	34.50 ± 0.19	34.47 ± 0.12*	34.64 ± 0.22
R3	−21 ± 4	−29 ± 9	−14 ± 3	34.24 ± 0.17	34.07 ± 0.14	34.38 ± 0.21
Ex4	−35 ± 5	−36 ± 12	−26 ± 6	34.49 ± 0.18	34.44 ± 0.18	34.60 ± 0.22
R4	−22 ± 4**	−27 ± 11	−13 ± 4	34.23 ± 0.16	34.08 ± 0.15	34.37 ± 0.20
Humid Condition (35°C, 60% RH)						
	H_D (W)			T_{sk} (°C)		
	OLDER	NON-FF	YOUNG	OLDER	NON-FF	YOUNG
Base	−10 ± 4	−6 ± 3	−3 ± 3	33.99 ± 0.12	34.21 ± 0.12	34.19 ± 0.09
Ex1	−18 ± 4	−10 ± 4	−10 ± 4	34.62 ± 0.12	34.91 ± 0.12	34.83 ± 0.11
R1	−15 ± 4	−8 ± 4	−6 ± 5	34.45 ± 0.11	34.63 ± 0.14	34.54 ± 0.13
Ex2	−23 ± 6	−10 ± 5	−12 ± 6	34.82 ± 0.13*	35.13 ± 0.12*	34.97 ± 0.16
R2	−24 ± 8	−11 ± 6	−11 ± 8	34.55 ± 0.12**	34.84 ± 0.13**	34.56 ± 0.14
Ex3	−27 ± 9	−11 ± 7	−12 ± 8	34.98 ± 0.14*	35.22 ± 0.11*	34.99 ± 0.16
R3	−28 ± 10	−10 ± 7	−12 ± 9	34.67 ± 0.14**	34.91 ± 0.14**	34.64 ± 0.17
Ex4	−30 ± 12	−10 ± 8	−11 ± 9	35.03 ± 0.15*	35.28 ± 0.12*	35.00 ± 0.22
R4	−29 ± 12	−12 ± 8	−6 ± 9	34.75 ± 0.12**	35.06 ± 0.14**	34.70 ± 0.22

Base, baseline steady-state; Ex, exercise period; R, recovery period; HD, dry heat exchange; Tsk, mean skin temperature; OLDER, group of older firefighters; NON-FF, group of older nonfirefighters; YOUNG, group of young firefighters.
*Significantly different Ex period compared to Ex1 ($P < 0.05$).
**Significantly different R period compared to R1 ($P < 0.05$).

difference was 0.07 during Ex1, Ex2, and Ex3, reaching the 0.05 threshold during Ex4. The ANOVA demonstrated between-group differences in PeSI during Ex1 ($F_{2,21}$ = 3.87, P = 0.037) and Ex2 ($F_{2,21}$ = 4.95, P = 0.017). *Post hoc t*-tests (Table 1) demonstrated that the NON-FF reported higher PeSI than the YOUNG during Ex1 (P = 0.034) and Ex2 (P = 0.031), whereas the OLDER reported higher PeSI than the YOUNG during Ex2 (P = 0.031). Differences between groups were also detected in H_L during baseline ($F_{2,21}$ = 3.78, P = 0.04), Ex2 ($F_{2,21}$ = 5.06, P = 0.02), R2 ($F_{2,21}$ = 3.61, P = 0.04), Ex3 ($F_{2,21}$ = 8.40, P = 0.002), and Ex4 ($F_{2,21}$ = 5.29, P = 0.01). *Post hoc t*-tests demonstrated that the YOUNG showed higher H_L values than OLDER and NON-FF during Ex2, Ex3, and Ex4 (P < 0.05; Table 2). Additional between-group effects were detected in S during Ex3 ($F_{2,21}$ = 3.38, P = 0.05) and Ex4 ($F_{2,21}$ = 6.21, P = 0.008). *Post hoc t*-tests demonstrated that the NON-FF showed higher S values than YOUNG during Ex2, Ex3, and Ex4 (P < 0.05; Fig. 2). Overall, the YOUNG (166 ± 18 kJ) stored less heat than the OLDER (233 ± 26 kJ) and the NON-FF (270 ± 29 kJ), yet none of these differences reached statistical significance (P > 0.05). Given the similar M-W, H_D, and E_{req} (Tables 2 and 3; Fig. 1), the aforementioned differences in H_L and S probably emerged because of the greater H_E observed in YOUNG compared to OLDER and NON-FF (Fig. 1) which, however, did not reach statistical significance (P > 0.05).

Between-group differences in the humid condition. The ANOVA between groups detected statistically significant differences in RPE during Ex1 ($F_{2,21}$ = 6.85, P = 0.005), Ex2 ($F_{2,21}$ = 5.56, P = 0.012), Ex3 ($F_{2,21}$ = 6.50, P = 0.006), and Ex4 ($F_{2,21}$ = 7.08, P = 0.004). *Post hoc t*-tests (Table 1) demonstrated that the NON-FF reported higher RPE than the YOUNG during Ex1 (P = 0.004), Ex2 (P = 0.01), Ex3 (P = 0.006), and Ex4 (P = 0.007). Also, the OLDER reported higher RPE than the YOUNG, yet the P value of the difference was 0.08 during Ex1 and Ex2, reaching the significance threshold during Ex3 (P = 0.037) and Ex4 (P = 0.011). The ANOVA demonstrated between-group differences in PeSI during Ex1 ($F_{2,21}$ = 5.93, P = 0.009), Ex2 ($F_{2,21}$ = 6.27, P = 0.007), and Ex3 ($F_{2,21}$ = 4.12, P = 0.031). *Post hoc t*-tests (Table 1) demonstrated that the NON-FF reported higher PeSI than the YOUNG during Ex1 (P = 0.008), Ex2 (P = 0.008), and Ex3 (P = 0.035), whereas the OLDER reported higher PeSI than the YOUNG during Ex2 (P = 0.03). Differences between groups were also detected in M-W during Ex4 ($F_{2,21}$ = 4.07, P = 0.03). *Post hoc t*-tests demonstrated that the OLDER had greater M-W values than NON-FF during Ex4 (P < 0.05; Table 2). Additional between-groups effects were detected in H_L during Ex1 ($F_{2,21}$ = 10.32, P = 0.001), R1 ($F_{2,21}$ = 6.77, P = 0.005), Ex2 ($F_{2,21}$ = 6.64, P = 0.006), Ex3 ($F_{2,21}$ = 3.43, P = 0.05), and Ex4 ($F_{2,21}$ = 3.49, P = 0.05). *Post hoc t*-tests demonstrated that the YOUNG showed higher H_L values than OLDER and NON-FF during Ex1, R1, Ex2, R2, and Ex3 (P < 0.05; Table 2). Furthermore, significant effects were detected between groups in H_E during Ex1 ($F_{2,21}$ = 7.93, P = 0.003), whereby YOUNG demonstrated greater values than OLDER and NON-FF (P < 0.05; Fig. 1). The H_E in YOUNG remained higher than OLDER and NON-FF during Ex2 and Ex3, yet these differences did not reach statistical significance (P > 0.05). The ANOVA also demonstrated significant between-group differences in S during Ex1 ($F_{2,21}$ = 14.94, P < 0.001) and Ex2 ($F_{2,21}$ = 6.48, P = 0.006), whereby the OLDER showed higher S values than the YOUNG ($P < 0.05$; Fig. 2). The ANOVA also revealed significant group differences in ΔS ($F_{2,21} = 5.54$, $P = 0.012$). Overall, the OLDER (548 ± 24 kJ, $P = 0.011$) but not the NON-FF (504 ± 47 kJ, $P = 0.064$) stored significantly more heat than the YOUNG (375 ± 23 kJ) (Fig. 2).

Changes across time in the dry condition. The OLDER reported increasingly greater levels of TS, RPE, and PeSI during successive exercise bouts ($P < 0.05$), whereas the NON-FF and the YOUNG reported marginally greater values that were not statistically different from the initial levels ($P > 0.05$). In all groups, the four successive exercise bouts did not elicit any differences in M-W, E_{req}, and T_{sk} during the dry condition (Tables 2–3 and Fig. 1; $P > 0.05$). In the OLDER, the H_D (Table 3; $P < 0.05$) was reduced during R2 and R4 compared to R1. The H_L (Table 2; $P < 0.001$) and H_E (Fig. 1; $P < 0.001$) increased in all groups during Ex2, Ex3, and Ex4 compared to Ex1 resulting in reduced S during Ex2, Ex3, and Ex4 compared to the amount of heat stored during Ex1 in all groups (Fig. 2; all $P \leq 0.015$). Nevertheless, S was positive during all exercise bouts and, consequently, T_{re} significantly increased with successive exercise bouts in each group (Fig. 3; all $P \leq 0.009$).

Changes across time in the humid condition. The OLDER and the NON-FF reported increasingly greater levels of RPE during successive exercise bouts ($P < 0.05$), which resulted in increased PeSI ($P < 0.05$). In all groups, there were no significant differences between the successive exercise bouts for H_D and E_{req} in the humid condition (Table 3 and Fig. 1; $P > 0.05$). The OLDER demonstrated a small increase in M-W during Ex4 and the NON-FF showed a similar response during Ex3 ($P < 0.05$). In all groups, the H_L ($P < 0.001$) and H_E ($P < 0.001$) were greater during Ex2, Ex3, and Ex4 compared to Ex1 (Table 2 and Fig. 1; all $P \leq 0.041$), resulting in reduced S during Ex2, Ex3, and Ex4 compared to the amount of heat stored during Ex1 (Fig. 2, all $P \leq 0.018$). Nevertheless, S was positive during all exercise bouts, and consequently, the T_{re} significantly increased with successive exercise bouts in all groups (all $P \leq 0.005$) (Fig. 3). Moreover, T_{sk} significantly increased with repeated exercise bouts for OLDER and NON-FF only (all $P \leq 0.024$).

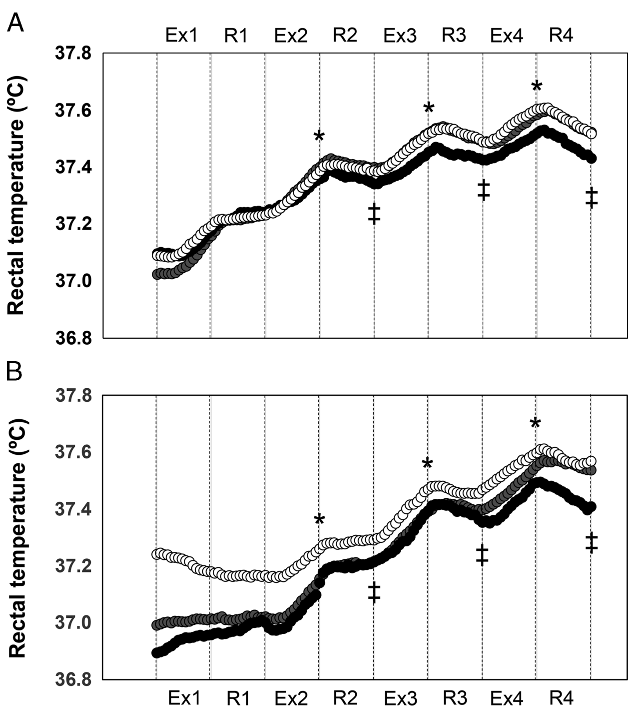

FIGURE 3—Mean values for rectal temperature throughout the 2-h experimental protocol in a dry (35°C and 20% RH) (A) and humid (35°C and 60% RH) (B) environment. The *gray circles* represent the group of older firefighters (OLDER, *n* = 9), the *black circles* represent the group of older nonfirefighters (NON-FF, *n* = 9), and the *white circles* represent the group of young firefighters (YOUNG, *n* = 6). *Significantly different from Ex1. ‡Significantly different from R1.

DISCUSSION

We recently used a thermometry approach to show that older firefighters demonstrate similar heat tolerance and attenuated levels of perceived thermal strain compared to age-matched nonfirefighters (27)—a combination that may render older firefighters susceptible to heat injuries. In this study, we adopted a direct calorimetry approach to compare whole-body heat loss and body heat storage during intermittent exercise in a warm/dry and a warm/humid environment among a group of older male firefighters, a group of older (age-matched) nonfirefighters, as well as a group of young firefighters. Our main findings are that (i) older firefighters report relatively lower perceived levels of thermal and exertional strain (i.e., TS, RPE, and PeSI) compared to age-matched nonfirefighters, (ii) older firefighters and age-matched nonfirefighters demonstrate similar whole-body heat loss and body heat storage, and (iii) whole-body heat loss is significantly reduced in older compared to younger firefighters during exercise in both dry and humid environmental conditions. Taken together, these results demonstrate that long-term occupational heat exposure does not offset the age-related decrements in heat loss capacity in older firefighters.

A growing body of research indicates that the physiological capacity of older individuals to dissipate heat is reduced with advancing age (7,9,12–14,24,26). However, recent data suggested that older experienced firefighters may develop some amount of heat resiliency over their years of occupational heat exposure or a reduced perception of risk to heat stress (27). The premise of this conclusion was entirely based on the fact that older nonfirefighters had a greater level of perceived heat strain during exercise in both dry and humid conditions compared to older firefighters. However, the local physiological responses measured in that study (i.e., T_{re}, T_{sk}, local sweat rate, and hydration status) were not different between these two groups. In the present study, we used the gold standard approach (i.e., direct calorimetry) to study heat loss capacity from a whole-body perspective to determine whether there was in fact a benefit to long-term occupational heat exposure in terms of improving heat loss capacity in older firefighters. Our results indicate that total heat loss capacity (which combines both evaporative heat loss and dry heat exchange with the environment) is similar in older firefighters and in nonfirefighters during exercise and recovery in both dry and humid heat stress conditions. In addition, the cumulative changes in body heat storage over the 2-h experimental sessions in dry and humid heat were comparable between these two groups. Hence, both the present and our previous (27) findings do not support that the physiological capacity of older firefighters to dissipate heat is enhanced above that of the general aging population.

In view of the fact that older firefighters seem just as susceptible to age-related decrements in heat loss capacity as the average older adult, it is important to consider the repercussions this may have on the health and safety of those who remain on active firefighting duty until mandatory retirement. Older firefighters are expected to be able to perform the same job-related tasks as their younger peers (3,15). However, it is well known that aging is associated with a myriad of unfavorable physiological changes in—among others—cardiorespiratory fitness, muscular strength, and heat tolerance (3,10,20). For example, an age-associated attenuation of $\dot{V}O_{2peak}$ at a rate of ~5 $mL \cdot kg^{-1} \cdot min^{-1}$ per decade has been reported in firefighters after the age of 30 yr (11,20), whereas performance in firefighting simulations is reduced with age even when firefighters are matched for $\dot{V}O_{2peak}$ (23). Moreover, aging is associated with an increased prevalence of obesity in firefighters (22). In the present study, the rate of total heat loss was lower in both older firefighters and age-matched nonfirefighters during exercise. As a result, older firefighters stored 40% and 46% more heat during exercise in the dry and humid conditions, respectively, compared to young firefighters. This was similar to the 63% (dry) and 34% (humid) more heat stored by older nonfirefighters relative to young firefighters. Taken together, these results suggest that older firefighters store more heat and are thus more vulnerable to heat-related injuries while on duty than their younger counterparts. It is important to note that our participants did not wear firefighter protective clothing because it would restrict heat loss and, thus, undermine the measurements of our whole-body direct calorimeter. We addressed this limitation via the warm/humid condition that simulated the hot and humid microenvironment inside the firefighter uniform created because of its high insulative capacity. Nevertheless, it would be valuable to confirm our results in clothed firefighters.

The results derived from the present study have important implications for the design of future heat exposure safety standards that are currently administered uniformly to industry workers irrespective of age. As the global population ages, the proportion of older workers will increase substantially in the coming years. Consequently, there is an urgency to develop heat exposure safety guidelines that take into consideration the fact that older workers report lower perceived levels of thermal strain and yet they cannot physiologically regulate body temperature to the same extent as younger workers owing to their lower capacity for heat dissipation. In the case of firefighters, our findings have implications for workers of advancing age because the required demands for successful completion of firefighting activities remain the same regardless of age. Hence, the results of the present study can be used to inform those responsible for the health and safety of older workers regarding the potential risks associated with conditions conducive to increased levels of heat strain.

In conclusion, this study shows that older firefighters and age-matched nonfirefighters demonstrate similar whole-body heat loss and body heat storage and that whole-body heat loss is significantly reduced in older compared to younger firefighters during exercise in both dry and humid environmental conditions. As a result, older firefighters may be more susceptible to work-related thermal injury while on duty than their younger counterparts, unless appropriate heat safety exposure guidelines are developed to better protect aging workers.

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