CARDIOVASCULAR EFFECTS OF COMPRESSION GARMENTS DURING UNCOMPENSABLE HEAT STRESS

JOSHUA BAUTZ,[1] DAVID HOSTLER,[2] PRIYA KHORANA,[1] AND JOE SUYAMA[1]

[1]*Department of Emergency Medicine, University of Pittsburgh School of Medicine, Pittsburgh, Pennsylvania; and* [2]*Center for Research and Education in Special Environments, Exercise and Nutrition Sciences, SUNY University at Buffalo, Buffalo, New York*

ABSTRACT

Bautz, J, Hostler, D, Khorana, P, and Suyama, J. Cardiovascular effects of compression garments during uncompensable heat stress. *J Strength Cond Res* 35(4): 1058–1065, 2021—This study examined the potential hemodynamic benefits of wearing lower extremity compression garments (CGs) beneath thermal protective clothing (TPC) worn by wildland firefighters, while exercising in a heated environment. Using in a counterbalanced design, 10 male subjects ([mean ± *SD*] age 27 ± 6 years, height 1.78 ± 0.09 m, body mass 74.8 ± 7.0 kg, body fat 10.6 ± 4.2%, and $\dot{V}O_2max$ 57.8 ± 9.3 $ml \cdot kg^{-1} \cdot min^{-1}$) completed control (no CG) and experimental (CG) conditions in randomly assigned order. Protocols were separated by a minimum of 3 days. Subjects exercised for 90 minutes (three, 30-minute segments) on a treadmill while wearing wilderness firefighter TPC and helmet in a heated room. Venous blood was drawn before and after exercise to measure hemoglobin (Hgb), hematocrit (Hct), serum osmolarity (OSM), and serum creatine phosphokinase (CPK). Vital signs and perceptual measures of exertion and thermal comfort were recorded during the protocol. Data were analyzed by the paired *t*-test. There were no differences in the change in heart rate (84 ± 27 vs. 85 ± 14 $b \cdot min^{-1}$, $p = 0.9$), core temperature rise (1.8 ± 0.6 vs. 1.9 ± 0.5° C, $p = 0.39$), or body mass lost (−1.72 ± 0.78 vs. −1.77 ± 0.58 kg, $p = 0.7$) between the conditions. There were no differences in the change in Hgb (0.49 ± 0.66 vs. 0.33 ± 1.11 $g \cdot dl^{-1}$, $p = 0.7$), Hct (1.22 ± 1.92 vs. 1.11 ± 3.62%, $p = 0.9$), OSM (1.67 ± 6.34 vs. 6.22 ± 11.39 $mOsm \cdot kg^{-1}$, $p = 0.3$), or CPK (22.2 ± 30.2 vs. 29.8 ± 19.4 $IU \cdot L^{-1}$, $p = 0.5$). Total distance walked (3.9 ± 0.5 vs. 4.0 ± 0.5 miles, $p = 0.2$), exercise interval (88.6 ± 3.5 vs. 88.4 ± 3.6 minutes, $p = 0.8$), and perceptual measures were similar between conditions. Compression garments worn beneath TPC did not acutely alter the physiologic response to exertion in TPC. With greater use in the general public related to endurance activities, the data neither encourage nor discourage CG use during uncompensable heat stress.

KEY WORDS thermal protective clothing, performance enhancement, wildland firefighter

Address correspondence to Joe Suyama, suyamaj@upmc.edu.

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INTRODUCTION

Wildland fire suppression is a dangerous occupation. Although the physical demands of structural firefighting require high-intensity exertion for short intervals, wildland firefighting is more aerobically demanding and requires individuals to perform physical activity for extended periods of time (25). Wildland firefighters may work 12–16 hours of shifts in which they cover large distances on foot leading to daily energy expenditures that can exceed 6,000 $kCal \cdot d^{-1}$ (22). Wildland firefighters are often exposed the heat stress for long periods of time and may not have easy access to structured rest periods (7). Although the hyperthermia experienced by wildland firefighters is typically mild, core temperature can occasionally reach levels seen in structural firefighters (6,7). Cardiovascular stress from exertion is exacerbated in these individuals by persistently elevated body temperature and high water turnover. The thermal protective clothing (TPC) worn by firefighters shields their bodies from thermal injury and protects against burns; however, these garments interfere with evaporative cooling and the resultant sweating under the TPC leads to the loss of large volumes of body water without the benefit of cooling (10).

The combination of exertion, heat stress, and hypohydration strains the cardiovascular system (4,5). While multiple studies have been conducted to investigate the optimal ways to recover firefighters after exertion, most have focused on decreasing core temperature and rehydration techniques (4,11–13). Previous studies have not attempted to decrease cardiovascular strain by maintaining intravascular volume during the time of physical exertion. Sweating reduces intravascular volume ultimately leading to an increase in heart rate (HR) to maintain perfusion to major organs. Thus, maintaining intravascular volume during exertion could result in decreased HR and ultimately decrease the cardiovascular strain of firefighting.

Table 1. Subject demographics and morphometrics ($N = 10$).*†

Height (cm)	Body mass (kg)	BMI ($kg \cdot m^{-2}$)	Body fat (%)	Age (y)	$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)
178 ± 9.2	74.8 ± 7.0	23.6 ± 2.2	10.6 ± 4.2	27 ± 6	57.8 ± 9.3

*BMI = body mass index; $\dot{V}O_2max$ = maximal oxygen consumption.
†Data are presented as mean ± *SD*.

Lower extremity compression garments (CGs), originally used for deep venous thrombosis prophylaxis, are used by athletes to improve performance and recovery (19). Studies have shown that calf compression stockings augment venous return leading to decreased lower extremity blood pooling and improved tissue oxygenation (3,17). A meta-analysis has since investigated the physiological effects of CG use and reported mixed results (19). Although some studies have failed to demonstrate changes in blood lactate level, ratings of perceived exertion (RPE), or time to exhaustion (TTE) in subjects exercising in CGs (3,14,19), other studies have shown potential benefits to wearing CGs during and after exercise for performance and recovery (1,8,15).

If CGs decrease extravascular fluid accumulation in the lower extremity during exertion, more fluid returns through the venous system and consequently cardiac preload increases. This would thus allow a firefighter wearing CGs to stay on the favorable side of the Starling curve for a longer period of time, despite large volumes of fluid loss secondary to sweat while wearing TPC. In the setting of uncompensable heat stress, we hypothesized that by augmenting venous return from the lower extremities, the use of CGs would preserve intravascular volume leading to a lower HR while working in a hot environment simulating fire suppression.

Methods

Experimental Approach to the Problem

This study used a laboratory protocol to determine the physiological effects of wearing lower extremity compression socks while performing simulated fire suppression. The study required 3 visits. The first visit was to screen the subject for exclusion and inclusion criteria and establish $\dot{V}O_2max$. The second and third visits were protocol visits to compare the effects of the CGs. The 2 protocol visits required subjects to complete a treadmill protocol while wearing TPC in a heated room. The CGs and control conditions were assigned in counterbalanced order. The protocols were identical except for the addition of commercially available below-the-knee (calf length) compression socks during one protocol. All subjects completed both the CG and control conditions separated by at least 76 hours to ensure recovery but not more than 2 weeks apart. Variation between visits was due to laboratory and subject availability.

Subjects

All procedures were approved by the Institutional Review Board at the University of Pittsburgh. Subjects were informed of the risks and benefits of the study before any data collection and then signed an institutionally approved written informed consent document. Male subjects aged 18 years and older were recruited from the university population (Table 1). We estimated that 10 subjects would be needed to detect a 6 $b \cdot min^{-1}$ difference between groups with a *SD* of 5 and a power of 80%.

Before enrolling in the study, the subjects underwent a physical examination and exercise stress test by a study physician. A metabolic cart (Parvomedics, Sandy, UT) was used to assess aerobic capacity ($\dot{V}O_2max$) and cardiovascular function. Information on demographics, medical history, physical activity frequency, and calf size

Table 2. Vital sign changes during exercise.*†

	HR pre-exercise ($b \cdot min^{-1}$)	HR post-exercise ($b \cdot min^{-1}$)	ΔHR ($b \cdot min^{-1}$)	Tc pre-exercise (°C)	Tc post-exercise (°C)	ΔTc (°C)
CG	74 ± 12	156 ± 19	84 ± 27	36.91 ± 0.28	38.70 ± 0.56	1.8 ± 0.6
Control	80 ± 10	165 ± 13	85 ± 14	36.90 ± 0.14	38.80 ± 0.47	1.9 ± 0.5
p	0.02	0.36	0.90	0.88	0.36	0.39

*HR = heart rate; Tc = core temperature; CG = compression garment condition.
†Data are presented as mean values ± *SD*.

Table 3. Mean skin temperature.*†

	Tskin pre-exercise (°C)	Tskin post-exercise (°C)	ΔTskin (°C)
CG	33.8 ± 0.9	37.2 ± 1.0	3.5 ± 1.1
Control	33.7 ± 0.6	37.7 ± 0.8	3.9 ± 0.7
p	0.86	0.18	0.04

*Tskin = skin temperature averaged from 4 sites; CG = compression garment condition.
†Data are presented as mean values ± *SD*.

were obtained. Current smokers, subjects using compression socks in the past 30 days, and those with a history of heart, respiratory, or renal disease, gastrointestinal surgery, diverticulosis, and deep vein thrombosis were excluded.

Subjects completed the first protocol 1–2 weeks after the screening visit. Subjects were provided with an indigestible radiofrequency core temperature-monitoring pill (HQ, Inc., Palmetto, FL) to swallow 8 hours before arrival in the laboratory for their protocols. They were instructed to refrain from exercise for 12 hours before the protocol and to drink 500 ml of water 1 hour before the session to ensure physical readiness for the study and appropriate hydration. Subjects were told to maintain their normal routines aside from these instructions. On arrival, subjects were provided a meal replacement bar (Clif Bar, Berkeley, CA) to ensure adequate pre-exercise nutrition. A urine sample was then collected, and a urine specific gravity measured to ensure appropriate hydration using a handheld refractometer (SUR-NE Clinical, Atago Labs, Tokyo, Japan).

Procedures

Compression Garments. Compression garments were purchased from a single manufacturer (Skinz, Encinitas, CA) whose products have been used in previous studies on the effects of CG on exercise performance. Trained study researchers sized the subjects' calves using the manufacturer's recommendations. It was decided not to use a placebo sock, as this could also have an effect on core body temperature and thus would not be the appropriate control for the scenario of interest. Before enrollment, the order of the protocols for each subject was randomized.

Performance Tests. Subjects donned TPC used by wildland firefighters (Lion Apparel, Dayton, OH) over standard station wear (cotton-polyester long pants, 100% cotton T-shirt). Thermal protective clothing consisted of nomex coat, pants, and helmet as well as a backpack weighted to 11.3 kg. Subjects then entered a room heated to 40.2 ± 2.5° C and began the exercise protocol. The exercise protocol consisted of three, 30-minute intervals of treadmill walking in the heated room while wearing the TPC and backpack. Each interval was separated by a 10-minute break. The treadmill was started at a speed of 2.5 mph and 10% incline. Every 5 minutes, a check of $\dot{V}O_2$ was conducted using the same metabolic cart used for the $\dot{V}O_2max$ testing but recalibrated for the heated room. To ensure stable measurements, the subject placed the mouthpiece and nose clip 90–120 seconds before recording the data. More frequent measurement of $\dot{V}O_2$ was considered but rejected due to the length of the protocol and the potential for subjects withdrawing due to discomfort. The speed of the treadmill was adjusted after every measure to ensure that the subject was performing the protocol at 40–45% of predetermined $\dot{V}O_2max$. After each 30-minute interval, subjects were permitted to leave the hot room and enter the main laboratory (~22° C) for exactly 10 minutes. At this time, subjects were provided 100 ml of water to drink. Subjects who needed to urinate were permitted to do so, but this urine was collected and factored into mass loss measurements. At the conclusion of this 10-minute break, subjects re-entered the hot room and began another 30-minute treadmill session. The speed of the treadmill before the break was used to restart exercise. The protocol continued until the subject completed three, 30-minute sessions or requested to stop. The protocol was stopped and

Table 4. Change in blood chemistry.*†

	ΔHgb ($g \cdot dl^{-1}$)	ΔHct (%)	ΔSerum OSM ($mOsm \cdot kg^{-1}$)	ΔCPK ($IU \cdot L^{-1}$)
CG	0.49 ± 0.66	1.22 ± 1.92	1.67 ± 6.34	22.2 ± 30.2
Control	0.33 ± 1.11	1.11 ± 3.62	6.22 ± 11.39	29.8 ± 19.4
p	0.7	0.9	0.3	0.5

*OSM = osmolarity; CPK = creatine phosphokinase; CG = compression garment condition.
†Data are presented as mean values ± *SD*.

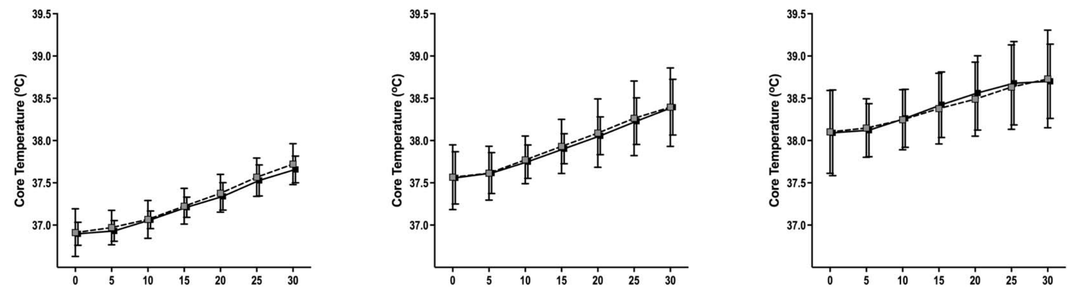

Figure 1. Core temperature during exercise in the first (left panel), second (middle panel), and third (right panel) exercise intervals. Each 30-minute interval was separated by a 10-minute break. Data are presented as mean ± *SD*. Control condition represented by solid line/closed symbols. Compression garment condition represented by dashed line and open symbols.

the subject began the recovery phase if predetermined physiologic endpoints (core body temperature [Tc] > 39.5 or HR > [220-age] + 10 $b \cdot min^{-1}$) or significantly altered gait was noted. Immediately on completion of the protocol, the subject exited the hot room to recover before being discharged from the laboratory.

Physiological Measurements. On arrival in the laboratory, subjects were weighed nude in a private room. Baseline blood work was drawn from a forearm vein to measure hemoglobin (Hg), hematocrit (Hct), serum osmolarity (OSM), and creatine phosphokinase (CPK). Skin temperature probes were then attached over their left chest, back, triceps brachii, and anterior thigh using an adhesive tape. Subjects were fitted with a HR monitor (Polar Electro-USA, Lake Success, NY) around their chests. Baseline vital signs (pulse [HR], blood pressure [BP], respiratory rate, and core temperature [Tc]) and skin temperatures (Tskin) on the chest, back, triceps, and thigh were recorded standing on the treadmill before exercise. Subjects were then read standardized instructions for the protocol and use of the perceptual measures of exertion (0–10), thermal comfort (1–5), thermal stress (1–4), and perceived sweat rate (1–10). Heart rate was monitored continuously for safety. Vital signs and perceptual measures were recorded every 5 minutes during exercise and during recovery until they returned to baseline. After finishing the protocol, blood was drawn for post-exertion values of Hg, Hct, OSM, and CPK. After thoroughly drying themselves with towels, subjects were again weighed nude.

Statistical Analyses

Mean skin temperature (Tskin) was measured by obtaining skin temperatures over the subjects' pectoralis major, infraspinatus, triceps brachii, and quadriceps femoris muscles using surface thermistors (Physitemp Instruments, Inc., SST-1 Skin sensors, Clifton, NJ). These values were then input into a validated formula to calculate Tskin: Tskin = chest (0.25) + back (0.25) + thigh (0.3) + arm (0.2) (2). Physiologic variables, total distance traveled, and exercise duration were compared between the 2 conditions using

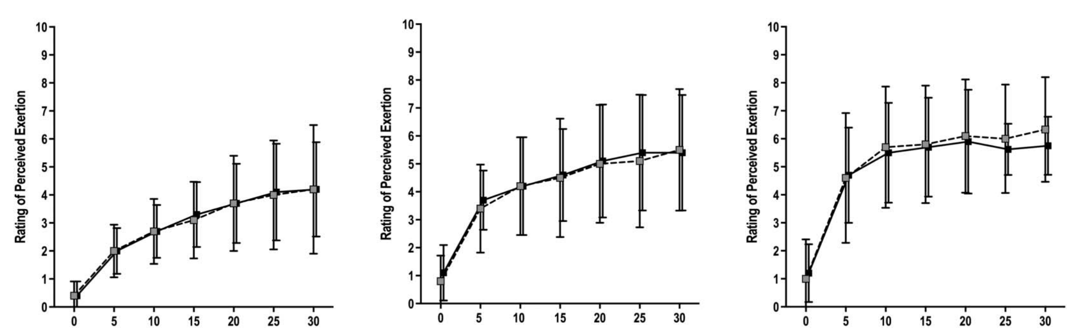

Figure 2. Rate of perceived exertion during exercise in the first (left panel), second (middle panel), and third (right panel) exercise intervals. Each 30-minute interval was separated by a 10-minute break. Data are presented as mean ± *SD*. Control condition represented by solid line/closed symbols. Compression garment condition represented by dashed line and open symbols.

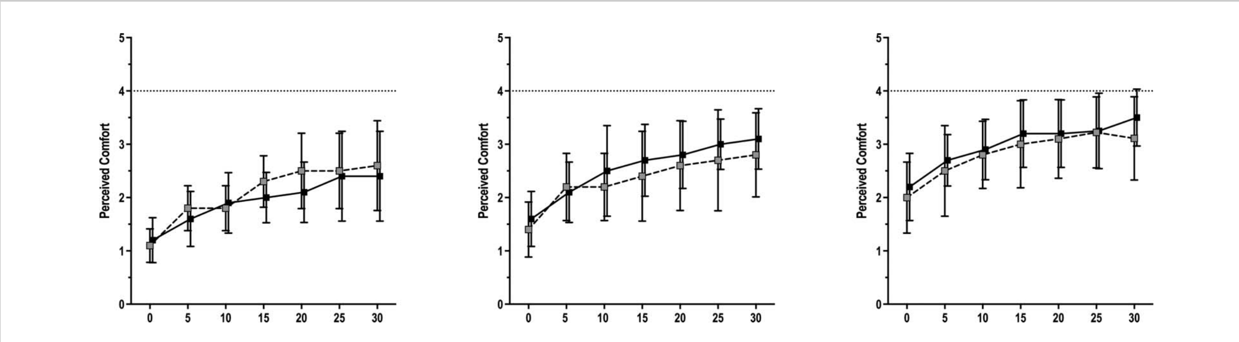

Figure 3. Perceived thermal comfort during exercise in the first (left panel), second (middle panel), and third (right panel) exercise intervals. Each 30-minute interval was separated by a 10-minute break. Data are presented as mean ± *SD*. Control condition represented by solid line/closed symbols. Compression garment condition represented by dashed line and open symbols. Scale maximum indicated by horizontal dotted line.

paired samples *t*-tests. These analyses were performed with SPSS statistical package (SPSS, Inc., Chicago, IL) with significance set at $p \leq 0.05$. Perceptual measures of exertion, comfort, thermal stress, and sweat were also compared using *t*-tests after using the Shapiro-Wilks test to assess normality. A mean value was calculated at each time point for each variable. Each mean was then compared between the 2 experimental conditions. These analyses were performed using STATA statistical package (StataCorp LP, College Station, TX).

Results

All 10 subjects completed the experiment; however, during 2 protocols (one CG and one control), 2 different subjects reached core body temperatures greater than 39.5° C ending the protocols early. This occurred at total exercise times of 87 minutes (CG) and 85 minutes (Control), respectively. In addition, one subject requested to end his protocols prematurely due to fatigue. This occurred at 79 minutes in both conditions. The mean room temperature was slightly warmer during the CG condition (40.8 vs. 40.6° C, $p = 0.03$).

Subjects exercised for the same amount of time (88.6 ± 3.5 vs. 88.4 ± 3.6 minutes, $p = 0.8$) and covered the same distance (6.3 ± 0.8 vs. 6.4 ± 0.8 km, $p = 0.2$) in both conditions. There were no differences in HR rise between the 2 conditions (Table 2). There was a small difference in the change in mean skin temperature during exercise (Table 3) such that those in the control condition had a greater rate of rise in mean skin temperature.

There were no significant differences in the amount of mass lost by subjects during the protocols (1.7 ± 0.8 vs. 1.8 ± 0.6 kg, $p = 0.7$). Analysis of laboratory data indicative of hydration level and muscle damage also revealed no differences between the conditions (Table 4).

There were no differences in the change in core temperature during the exercise protocol (Figure 1). In addition, there were no differences in any of the perceptual measures of perceived exertion (RPE), comfort, thermal stress, or sweating sensation (Figures 2–5).

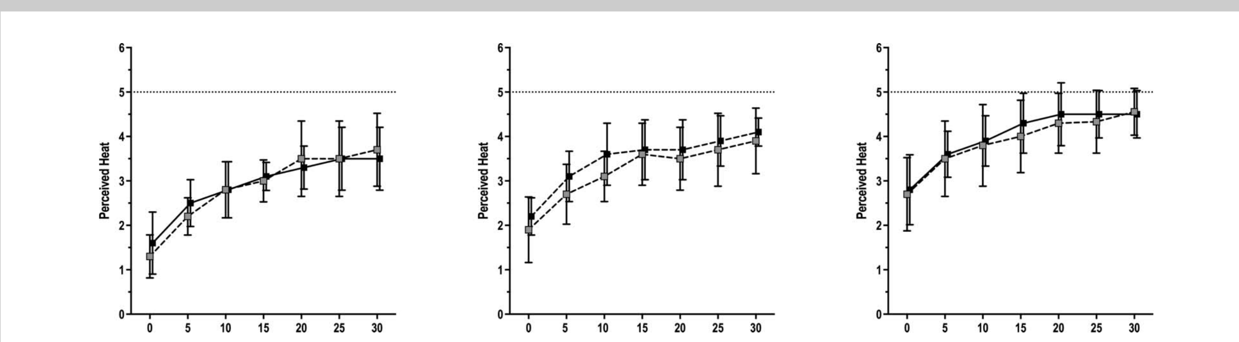

Figure 4. Perceived thermal sensation during exercise in the first (left panel), second (middle panel), and third (right panel) exercise intervals. Each 30-minute interval was separated by a 10-minute break. Data are presented as mean ± *SD*. Control condition represented by solid line/closed symbols. Compression garment condition represented by dashed line and open symbols. Scale maximum indicated by horizontal dotted line.

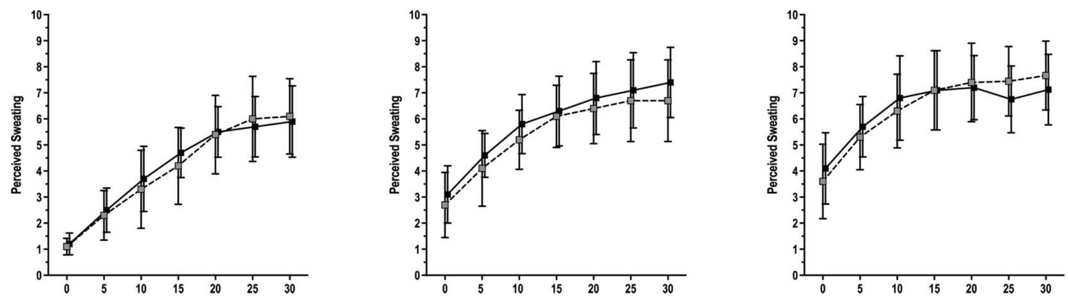

Figure 5. Perceived sweating during exercise in the first (left panel), second (middle panel), and third (right panel) exercise intervals. Each 30-minute interval was separated by a 10-minute break. Data are presented as mean ± *SD*. Control condition represented by solid line/closed symbols. Compression garment condition represented by dashed line and open symbols.

Discussion

This study examined the potential physiological benefits of using lower extremity CGs as a means of improving venous return to maximize cardiac preload while performing prolonged bouts of work in a hot environment with minimal access to fluids.

Compression socks have recently increased in use significantly among athletes for perceived benefits in performance and recovery. Multiple studies have been performed to attempt to demonstrate quantifiable advantages in performance and recovery. Ali et al. (1) reported decreased delayed onset muscle soreness with use of calf length CG during and for 24 hours after a 10-km run. In a later study, Kemmler (15) reported that calf length CG increased the duration of time, runners could exercise at both aerobic and anaerobic thresholds before failure. De Glanville (8) also found improved performance and power output on repeated cycling time trials when athletes wore CG for 24 hours after initial time trial performance. These improved measures of performance after repeated bouts of exercise are believed to be related to improved active recovery caused by improved tissue oxygenation and anaerobic waste removal secondary to the improved venous circulation as an effect of the CG (18,23).

Given this proposed mechanism, it is logical to theorize that by decreasing lower extremity blood pooling and augmenting venous return, one could optimize cardiac preload. This theory is substantiated by findings from NASA that the use of commercially available CGs resulted in increased systolic BP, stroke volume, and cardiac output, and decreased incidence of presyncopal symptoms after spaceflight (24). Thus, it follows that by preserving intravascular volume, one could improve cardiovascular function in a subject exercising under conditions of volume depletion such as in fire suppression. We hypothesized that the use of lower extremity CGs would result in a smaller increase in HR in users performing work in protective clothing in a hot environment. Although several previous studies failed to identify differences in HR, these studies were mostly performed for shorter periods of time and under more moderate temperature conditions than uncompensable heat stress, and thus, the effect may not have been realized because subjects were not adequately volume depleted (19).

If the CG forced more fluid from the extravascular space back into the vasculature, it follows that this increased intravascular fluid volume should cause blood solutes to be more dilute in contrast to the expected effect of dehydration. However, we found no differences in serum OSM, Hgb, or Hct between the 2 conditions. This would argue that CG did not lead to intravascular volume preservation.

The change in HR during exercise between the conditions was not different. However, the initial HR was lower in the CG group, and further analysis of the HR vs. time graph suggests that the rate of increase is less in the CG condition. It is possible that the effect of CG may only be demonstrated when someone is significantly volume depleted and thus, that a longer protocol may be needed to demonstrate this benefit. Our subjects did not exercise until complete sweat depletion. To the best of our knowledge, however, this is the longest time length protocol examining physiologic results of CG use, and even longer study duration may be needed to examine this hypothesis further.

The physiologic demands of fire suppression, however, are not merely related to cardiovascular strain. The high environmental temperatures also represent a significant physiologic challenge to firefighters. Accordingly, any study investigating new gear for firefighters must also take into account how such gear will affect their ability to thermoregulate. As CG represents an additional layer of clothing, the potential exists that they could increase core body temperature. MacRae (20) investigated the interaction of CG use on both cardiovascular mechanics and thermoregulation by having subjects' cycle for 60 minutes on an indoor trainer and then perform a 6-km time trial. This study found that while skin temperature under the CG did increase more than in the control condition, there was no additional increase in the core temperature in the CG condition. That study also noted that there was no improvement in performance with the CG and a trend toward slightly higher HR in those wearing CGs. This study, however, was conducted at 24° C, a more temperate condition compared with those in which firefighters work.

Another study that attempted to investigate the question of environmental temperature's interaction with the use of CGs found no change in core temperature or HR when subjects performed a run to exhaustion while wearing CGs under 2 different temperature conditions (9). Interestingly, that study found a moderate effect size indicating decreased RPE and increased TTE when subjects used the CGs during the protocol. This study, however, had subjects exercise at high intensity such that the entire protocol lasted less than 25 minutes. As many of the endurance events at which CGs are used last significantly longer than 25 minutes, this study does not fully answer the question of the additional risk for heat illness when using CGs for longer periods.

Our data confirm the results of these studies. Despite the prolonged time duration of our exercise bout and the significantly warmer environment than that of previous studies, we saw no differences in core temperature rise during exercise between the 2 conditions. Although there was a small difference in mean skin temperature change between the 2 conditions (3.9° C increase in the control group vs. 3.5° C in the CG group), we feel this is unlikely to be related to the CG, as the effect was small and the inverse from what would be expected by adding a layer of clothing. This finding is important, however, as it suggests that there is not an additional risk of heat illness in those using CGs in hot environments even during prolonged bouts of exercise such as distance runners competing in warm weather races.

There are limitations studying the present report. First, there is only a loose definition as to what constitutes a CG. There are studies using calf compression sleeves, lower-body tights, and even whole-body compression suits. We chose to use calf compression socks, as we felt this would be the most practical for a firefighter to put on while already wearing turnout gear and quickly preparing for deployment. As there was existing literature showing benefit with even this limited amount of body surface area compressed, we felt that if a benefit could be shown with these socks, further study could look at the potential additive effect of increased body surface coverage. Because we did not identify a difference using the calf sleeves, one could argue that additional coverage of the upper legs could result in a larger hemodynamic effect leading to a decreased HR.

The use of compression socks continues to be prevalent in endurance sports. Given the results of several studies, which have failed to demonstrate hemodynamic benefit, it has been argued that the increased popularity is due in part to placebo effect. Although we found no quantifiable differences between our 2 conditions in the perceptual scales of exertion or comfort, several subjects remarked that their legs felt better while wearing the CG. We chose to use global scales rather than create scales specific to lower extremity perceptions because there was not a placebo sock used in the control condition.

It also remains possible that the CG intervention did have beneficial results on muscle function and recovery that could be beneficial to firefighters but in ways in which this study was not designed to identify. Firefighters can be required to perform repeated bouts of physical exertion over multiple days with limited rest and time for recovery. Thus, an intervention that would allow them to recover faster could lead to improved job performance, which is intricately tied to job safety in this profession. A recent study of soccer players competing in different environmental temperatures failed to find any markers of additional muscle damage associated with work in the heat but clearly demonstrated high elevations in myoglobin and CPK after games (21). Although we did not find any differences in CPK between the 2 conditions, previous studies have found decreased elevation in this marker of muscle breakdown when wearing CGs (16). As CPK increases over time, it is possible that repeated blood analysis after a period of hours could show a difference in CPK elevation between the conditions. It is also possible that the benefits of CGs on muscle recovery are more pronounced when they are worn during the recovery period of muscle inactivity rather than during the activity itself.

Practical Applications

Lower extremity compression socks worn beneath TPC did not acutely alter the physiologic response to treadmill exercise in a hot environment. The use of CGs showed no effect on a wearer's overall performance, HR, BP, or serum markers of hydration and muscle injury. As such, our research does not indicate any advantage to using them in situations of uncompensable heat stress. It is important to note, however, as the use of these compression socks becomes more prominent in endurance exercise, we found no effect on a wearer's core temperature.

Acknowledgments

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