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Effectiveness of a state-of-the-art coat with fans and coolants over standard coats

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ABSTRACT

Objective: Firefighters use personal protective equipment when containing fires. The coat, called standard hereafter, that is part of the personal protective equipment has not changed for many years. A new coat was designed with novel features. Its inner layer is made of a carbon nanotube-based fabric, two pouches with coolants, and fans. The new coat and standard coat were to be compared on several metrics including core body temperature, heart rate, heart rate variability, heat storage, aerobic capacity, Borg scale, Thermal Comfort scale, and Respiratory Distress in a live burn facility.

Principle results: The new coat was significantly better than the standard coat on all metrics with one exception, namely, Thermal Comfort scale. The coats significantly impact the average core body temperature across all epochs with $p < 0.0001$. They also impact heart rate with $p < 0.0001$, heart rate variability with $p = 0.0019$, and heat storage with $p < 0.0001$.

Major conclusion: One important mission for any coat was to ensure that the core body temperature does not reach the hyperthermia level temperature (38°C) when a firefighter is working inside a live burn facility. The new coat worked on this count better than the standard coat with $p = 0.0144$.

1. Introduction

Firefighters use personal protective equipment (PPE) when controlling fires to minimize hazards stemming from the job. The PPE consists of a coat, pants, face mask, helmet, boots, gloves, and self-contained breathing apparatus. The focus of the article is three coats, one of which is the standard firefighter (SF) coat. The SF coat has been in vogue for many years. It has two layers. The material used in making the layers is discussed in [1]. LION is a worldwide company which makes safety wear [2]. According to their website, garment fiber consist of 45 % Meta-Aramid, 32 % Lenzing FR, 17 % Polyamide, 6 % Para-Aramid [3]. Despite using the PPE, firefighters were beset with many medical problems. A comprehensive account of fatalities, while on duty, was presented by LeBlanc and Fahy [4]. Other medical issues were discussed in Morris and Chander [5], Van Gelder et al [6], and Soteriades et al [7]. According to the website of U.S. Fire Administration, in 2022, 94 firefighters died while on duty, 62 firefighters died from activities related to an emergency incident, 17 firefighters died from activities at a non-fire scene, 35 firefighters died from activities at a fire scene, 33 firefighter died from heart attacks, 14 firefighters died while responding to or

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returning from emergency incidents, and 9 firefighters died while participating in training activities [8].

A need arises to improve the SF coat. The proposed state-of-the-art coat consisted of two layers like the SF coat. The inner layer is made of carbon nanotube (CNT) based fabric, different from the SF coat. The fabric was already experimented on by engineers in 2015. CNT fabric is impermeable to air and water, lightweight and flexible, flame resistant, and thermally and electrically conductive [9–11]. Two pouches are sewn on the inner layer of the coat. The pouches can accommodate coolants (ice packs or dry ice). At the bottom, fans are installed with a switch. Fans circulate air inside the coat through the coolants. The design, cut, and fabric were the responsibility of the engineering and designing team. In short, this is the story of three coats.

1. SF coat. Every recruited firefighter in the study has his own SF coat tailor-made.
2. Cooling system (CS) coat. This is an evolving state-of-the-art coat.
3. Final LION cooling system (LC) coat. The CS coat metamorphosed into the LC coat. Only dry ice, about a quarter kilo in weight in each pouch is used.

The overarching goal was to compare performance of the coats on several metrics including core body temperature (CBT), heart rate (HR), heart rate variability (HRV), heat storage, aerobic capacity, Borg scale, Thermal Comfort scale, and Respiratory Distress. A special protocol was designed for comparison. The setting for comparison is a live burn facility which is a three-storey structure. A fire is started deliberately in the structure. A firefighter, wearing any of the three coats, enters the live burn facility and data then is obtained on the metrics of interest. Comparisons are done in two stages.

Stage 1 (First year): SF coat versus CS coat. It was demonstrated that the evolving CS coat was not inferior to the SF coat on all metrics of interest [12].

Stage 2 (Second year): SF coat versus LC coat. This is the substance of the current paper. The LC coat was experimented in the second year. The data on SF coat, from the first year, is used for a comparison.

The evolution of LC coat in its final form is worth discussing. When the team designed the new coat, it was not clear whether it would be functional at the same level as the SF coat. The new coat was made of a different cloth on the interior portion, which included a CNT based fabric. In addition, two pouches were sewn inside the coat where coolants could be placed. Further, a fan with a switch was installed to pump air past the coolants and throughout inside the coat. With this initial design, it was not clear whether ice packs or dry ice should be utilized and at what speed the fans should run. Some of the factors that needed to be considered were the impact of completing firefighting activities inside the live burn facility that require strenuous exertions, lifting, moving, dragging, bending, stretching, etc. All these activities could impact on the functionality of the fans and cooling system. If a fan fails, the new coat is no different from the SF coat functionally. To document this functionality in the first phase of development, a researcher checked the status of the coolants and functionality of the fans when a firefighter emerged from the live burn facility. There were cases of ice melting prematurely and fan(s) stopping. These circumstances have resulted in improved designs including usage of dry ice in specialized pouches, fans running through all exertions, and longer lasting batteries in the next generation new LC coat.

The inclusion of pouches, coolants, and fans is a novel feature of the new coat. They are very effective as a moisture and thermal barriers. A picture of the LC coat is displayed in Fig. 1 [12].

In summary, the state-of-the-art coat has three distinct features.

1. New fabric
2. Two pouches inside the inner layer to accommodate coolants
3. A fan with a battery-operated switch in each pouch to circulate air running through the coolants inside the coat

A key idea of current research is to test the novel coat to see whether it helps control the core body temperature (CBT) significantly better than the SF coat when a firefighter is involved in controlling fire. The proposal was approved and funded for two years.

The objective was to compare the performance of the SF and LC coats with respect to several metrics when working in a live burn facility. Most importantly, whether the CBT remains below the hyperthermia temperature was assessed.

In the language of clinical trials, LC coat is an intervention and SF

Fig. 1. The LION Cooling System coat, which used carbon nanotube-based fabric with two pouches and a fan to cool the firefighter. The arrows identify the location of the pouches which can take dry ice.

coat control. In the past, several interventions were tried and tested vis-à-vis a control. Some of previous interventions included ice vests, dry ice air-cooled vests, and liquid-circulated garments [13]. Other potential interventions are passive recovery, extractor, and misting fans, hand and forearm water immersion, or vests made of phase-changing material [14]. To ensure wide use and effective protection, it is important that the cooling intervention be practical and comfortable for the firefighters. Some of these interventions worked effectively but testing was done in an artificial environment inside a lab. In an in-depth literature review, Douzi and associates [15] concluded that cooling garments, ice vests, and air ventilation are the most effective cooling techniques. Cooling vests work by dissipating heat away from the body [14]. The LC coat had built-in cooling fans and coolant modules designed to optimize dissipation of heat.

In summary, there are two important features inherent in this paper. One is showcasing a state-of-the-art safety coat with fans and coolants. The other is comparing the SF and LC coats in a realistic environment such as a live burn facility.

2. Methods

2.1. Experimental protocol

A protocol was set up for the firefighters to follow at the live burn facility in both years. A document on work to be performed inside the live burn facility is read to each firefighter. The document is included in the appendix at the top. After donning a coat (SF or LC), baseline measurements were taken on each participant. The contentious part is the execution of the protocol. Even though each firefighter is asked to stay inside the facility for fifteen minutes each time, adherence to time is problematic. Variation is bound to occur when we are dealing with human subjects. The question is whether to include the data coming from a firefighter whose times in the facility are not strictly conformable to the protocol. In Table A.1 in the appendix, times spent by the firefighters inside and outside the live burn facility were recorded. We should exclude data coming from firefighters 7-10 on SF coat. Their times inside the facility are too low. The picture is not clear when it comes to LC coat, especially, firefighter #9. One way to settle the issue is through multiple regression. In the case of CBT, for example, the response variable (Y) is the average CBT by epoch, coat, and time spent. The data for multiple regression, now, consists of 144 (6*6+18*6) observations. One can do multiple regression with all firefighters included and another multiple regression with firefighter #9 on LC coat excluded. On simplistic level, on average, firefighters with SF coat, stayed 17.1 minutes per scenario, and firefighters with LC coat, stayed 14.5 minutes. No significant difference is perceived ($p = 0.08$).

The protocol and data collection procedure (what variables are measured) are outlined in Fig. 2. The physiological measurements, such as CBT, HR, and HRV, are taken in one second intervals. Data on perceptions (exertion scales BORG, Thermal Comfort (TC), and Respiratory Distress Scales (RD)) [16–18] were collected during the baseline time and at the end of scenarios.

2.2. Data collection

Data came from several sources. The bio harness provided data on physiological measurements. Data on perceptions came from surveys. Data on heat storage and aerobic capacity were obtained following formulas for such measurements.

2.2.1. Participants

Data was sought from ten firefighters on SF coat (mean ± SD: age 36.5 ± 7.9 years; weight 114.7 ± 10.2 kg; height 182.5 ± 10.7 cm) and nineteen on LC coat (mean ± SD: age 37.7 ± 8.8 years; weight 120.7 ± 20.8 kg; height 180.7 ± 10.0 cm). The inclusion criteria were that only full-time firefighters from Ohio were recruited. Only a few state-of-the-art coats were made by LION. They fit only males. Thus, females were excluded from the study due to the restricted cut and fit of the gear. In addition, only four percent of workforce of firefighters are females [19]. Recruitment of females would pose a problem. Age, weight, and height were statistically compared between the firefighters who used SF and LC coats. There was no significant difference between the average ages, average heights, and average weights. The weights were measured after donning PPEs.

The Institutional Review Board (#2022-0682) approved the study. Each participant gave written informed consent before the experiment started.

Each firefighter was acquainted with the protocol, which was reported in the appendix. They were asked to work inside the facility (Scenarios 1, 2, and 3) for 15 minutes. With human subjects, the protocol may not be adhered strictly. For four firefighters on SF coat, time spent inside the facility was far less than the stipulated 15 minutes. Their data on physiological measurements was not used. However, we used their data on perception. It was not the case with firefighters on LC coat. However, one firefighter with LC coat was not readable because of equipment malfunction.

2.2.2. Core body temperature, heart rate, heart rate variability, heat storage, and aerobic capacity

The live-burn exercise served to mimic the conditions of routine firefighting, during which physiological measurements of HR, HRV, and CBT on the firefighters were monitored during the protocol using a bio harness system (ZEPHYR™ Performance Systems). The bio harness was placed across the subject's bare chest upon their arrival at the live burn facility. At the end of testing, the bio harness was removed. In addition, the following metrics were derived:

a) Heat Storage (HS) (watts per hour) = (average CBT (°C) at scenarios – average CBT (°C) at the baseline) * body weight (kg) * specific heat capacity of body tissue (0.97 watts per hour/kg °C) [6,20];
b) aerobic capacity $= \frac{(\text{WORK HR} - \text{RESTING HR})}{(\text{MAX HR} -- \text{RESTING HR})}$, where MAX HR = 220 – Age [21,22];

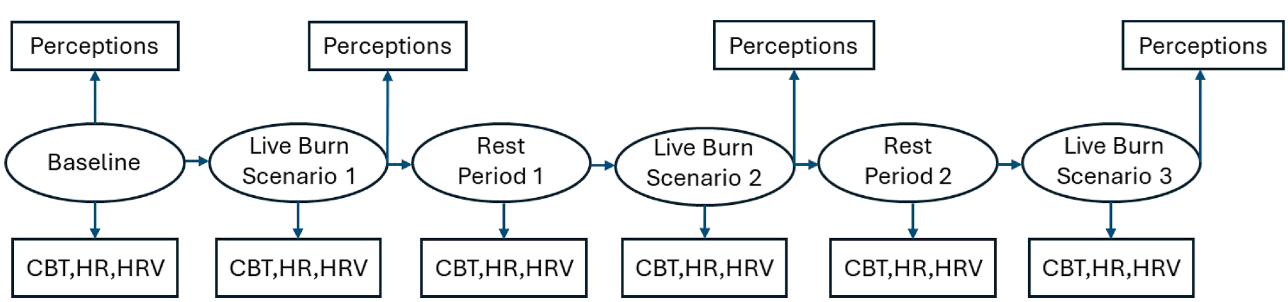

Fig. 2. Protocol of the order of sessions in the Live Burn Facility. Sessions at which measurements on core body temperature (CBT), heart rate (HR), and heart rate variability (HRV) were collected. Sessions at the end of which data on Thermal Comfort, Respiratory Distress, and Borg Scale was collected.

c) percent of total time spent over the threshold for hyperthermia temperature (38°C) at baseline, Scenarios 1, 2, and 3, and Rest periods 1 and 2. (Table A.7 and Fig. 3f.)

Progression of HR from the baseline to the Rest periods 1 and 2 was identified. (Fig. 3b.)

2.2.3. Perceptions

The BORG scale ranged from 6 (being very, very light) to 20 (being very, very hard). The Thermal Comfort Scale ranged from 0 (unbearably cold) to 4 (comfortable) to 8 (unbearably hot). The Respiratory Distress scale ranged from 1 (my breathing is ok right now) to 7 (I cannot breathe) (Fig. 4a) [16–18].

2.3. Data analysis

2.3.1. General description

The protocol has six epochs (Baseline, Scenario 1, Rest period 1, Scenario 2, Rest period 2, Scenario 3). For each epoch, the average CBT for each firefighter is under focus. The average Y would depend on the epoch, time spent, and coat used. A multiple regression model is deployed to explore connection between Y and factors identified.

$$Y = \beta_0 + \beta_1 \times \mathit{Time\ spent} + \beta_2 \times \mathit{Epoch} + \beta_3 \times \mathit{Coat\ used} + \mathit{Noise}$$

The variable 'Time spent' is numeric, 'Epoch' is categorical with six levels for CBT, HR, and HRV, and three levels for HS, and 'Coat used' is categorical with two levels. An analogous model was entertained for all other physiological measurements. It was discovered that 'Time spent' was not significant in all cases of CBT, HR, HRV, and HS. (Details are provided in the 'Results' section.) Following the discovery, connection between average CBT and 'Coat used' was explored by episodes using multivariate methods. Let μ_i be the population mean of CBT and σ_i^2 the population variance at epoch i for a random firefighter wearing an SF coat. Let λ_i and σ_i^2 be the corresponding entities for the LC coat. The null hypothesis H_0: $\mu_1 = \lambda_1$, $\mu_2 = \lambda_2$, $\mu_3 = \lambda_3$, $\mu_4 = \lambda_4$, $\mu_5 = \lambda_5$, and $\mu_6 = \lambda_6$ is tested. The multivariate t-test (Hotelling T^2-test) is used. The p-value is calculated then. The Hotelling T^2 test is a generalization of the two-sample t-test. It combines several two-sample tests in one omnibus test with a major advantage of avoiding multiple testing adjustment. For the validity of Hotelling T^2 test, normality of the measurements is needed. Normality assumption at every epoch is checked, and the assumption is valid. Analogous null hypothesis was formulated and tested for every other physiological metric and perception.

2.3.2. Physiological responses

The key measurements for comparison are the averages of each physiological measurement for each scenario, rest period, and baseline were calculated. The numerical results are reported in the appendix (Tables A.2-6) and the graphs (Fig. 3) in the main paper.

2.3.3. Perceptions

For each firefighter, under each coat and each perception scale, data was collected at the baseline and after each scenario. The summary statistics along with p-values are reported in the appendix (Tables A.9-11) and the graphs (Fig. 4) in the main paper.

2.3.4. Time spent above the hyperthermia temperature

For each firefighter, how much time his CBT was above the hyperthermia temperature of 38°C in the live burn facility from Scenario 1 through Scenario 3, was calculated. The Wilcoxon two sample test was used to compare the coats on the observed times. In addition, the coats were also compared with respect to the percentage of times spent in the facility above the hyperthermia temperature (Table A.7-8).

3. Results

3.1. Fulfillment of the protocol

Each firefighter with each coat was asked to spend fifteen minutes in each scenario. However, there is variability in time spent. Only six firefighters with SF coats deemed to have completed the stipulated protocol with average time spent inside about fifteen minutes. All nineteen firefighters deemed to have completed the protocol with the LC coat with average time spent inside close to fifteen minutes. The difference between the coats on completion rates (six out of ten on the SF coat versus nineteen out of nineteen on the LC coat) was not significant with $p = 0.324$. One of the reviewers disputed the inclusion of nine firefighters on LC coat, each one spent only 8 minutes under scenarios, in

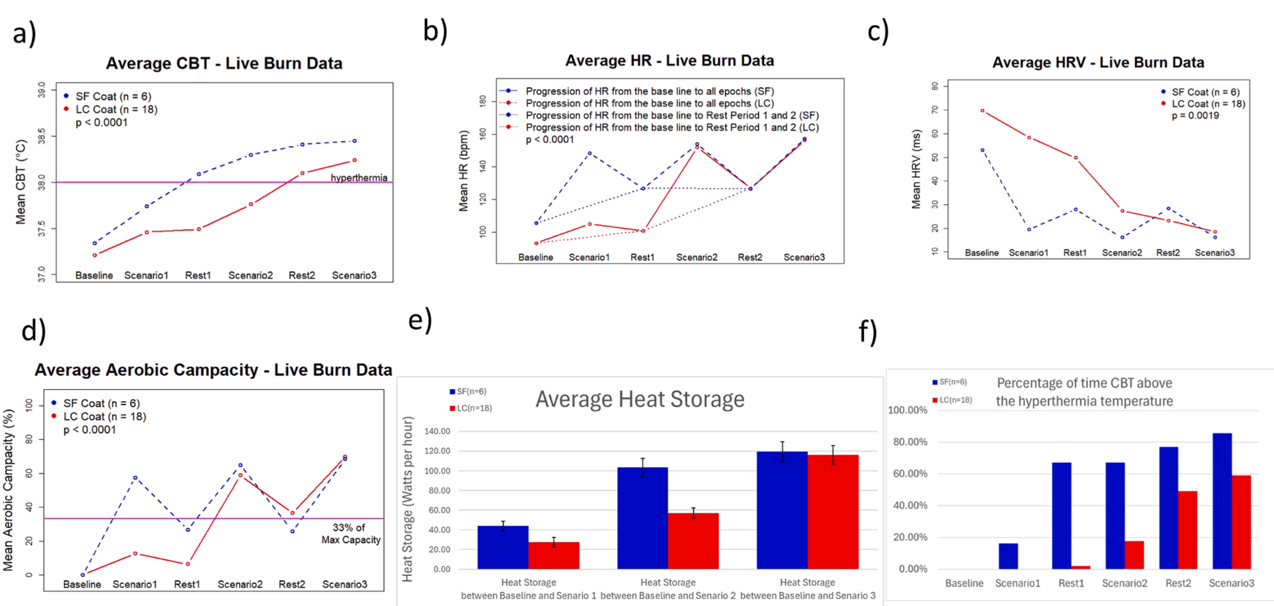

Fig. 3. Physiological measurements for Standard coat (SF) and LION Cooling System coat (LC) as a function of the session (scenario and rest): a) Average Core Body Temperature (CBT); b) Average Heart Rate (HR); c) Average Heart Rate Variability (HRV); d) Aerobic Capacity; e) Heat Storage; and f) Percentage of time CBT exceed hyperthermia temperature by Scenario Versus Baseline.

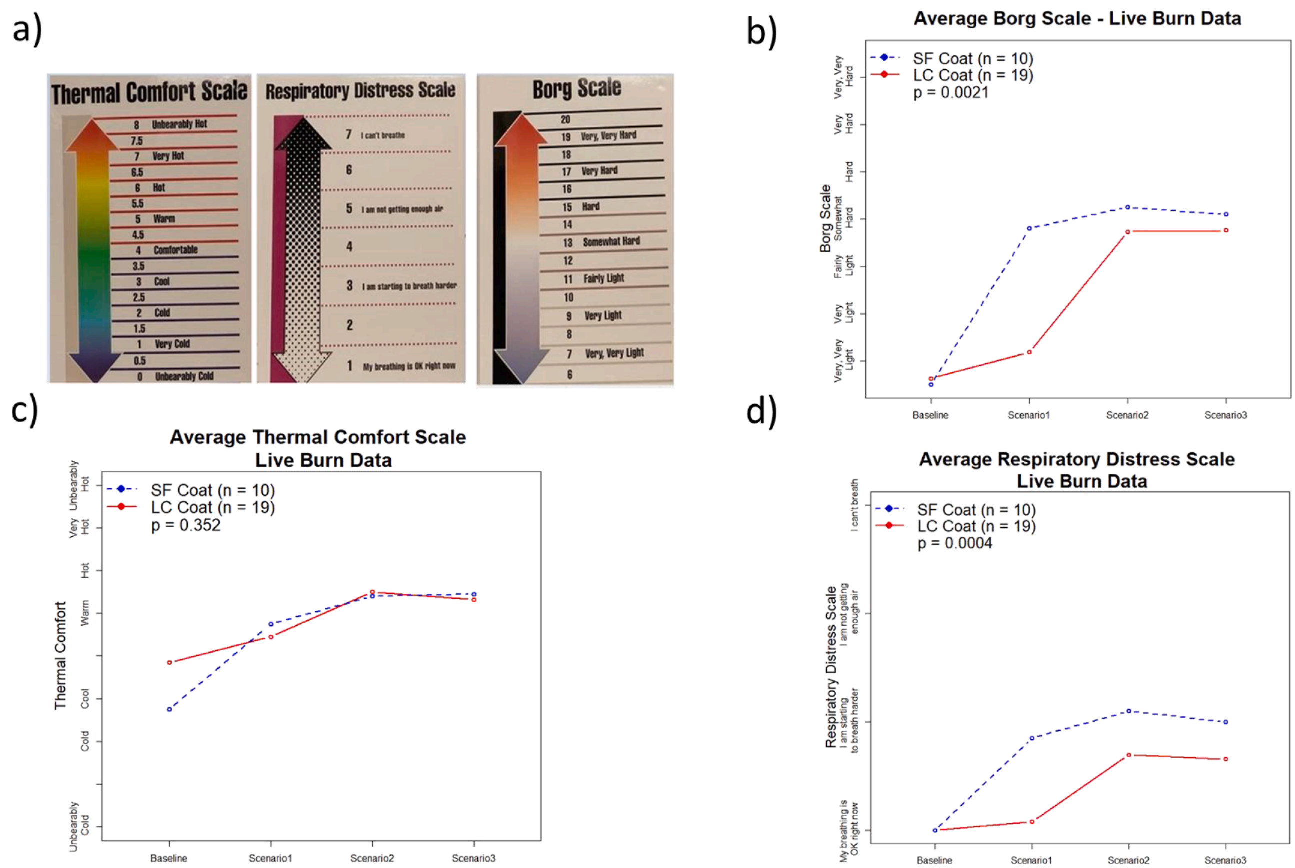

Fig. 4. Subjective Perceptions for Standard coat (SF) and LION Cooling System coat (LC) as a function of session (scenario and rest): a) Description of all scales; b) Borg Scale (6 to 20); c) Thermal Comfort (0 to 8); and d) Respiratory Distress (1 to 7).

all regression models. We will settle the dispute via a multiple regression model.

3.2. Physiological measurements

The firefighters on SF coat reached the hyperthermia temperature sooner (during Rest Period 1) than the firefighters under the LC coats (during Rest Period 2). The average CBT under the SF coat at different epochs of the protocol was always higher than that under the LC coat. The difference was significant with p-value less than 0.0001.

All four regression models were fitted to the data consisting of six firefighter on SF coat and eighteen firefighters on LC coat. The output is presented in Table 1.

In all these regressions analyses 'Time spent' was never significant. As anticipated, 'Epoch' was significant overall following the ANOVA procedure applied to the regression model output. 'Coat used' was significant in all the analyses.

As expected, HR increased in response to firefighting inside the live burn facility. Again, as expected, HR decreased during the Rest Periods (Fig. 3b.). However, HR never achieved the baseline level HR suggesting increased fatigue coupled with dehydration [23]. There is a significant difference between the coats with reference to the metric HR ($p < 0.0001$). There was a significant difference between the SF and LC coats on HRV ($p = 0.0019$), HS ($p < 0.0001$), and aerobic capacity ($p < 0.0001$). On aerobic capacity, one aims for a threshold of 33 % or below [23]. The LC coat is closer to the ideal capacity than the SF coat.

A difference in the baseline HR within the two groups is observed and also in other physiological measurements. (Fig. 3) Specifically, look at the average CBT graph at the baseline. There is a difference, contrary to what is expected. However, no significant difference in the averages is observed ($p = 0.17$). Similar calculations were done on HR and HRV, with p-values 0.11 and 0.62, respectively.

We now settle the issue of whether, in particular, firefighter #9 on LC coat should be included. We fitted regression models covering all physiological metrics. Virtually, there is no difference in the outputs. This means that firefighter #9 on LC coat is not influential.

3.3. Perceptions

3.3.1. Perceived exertion (Borg scale)

The firefighters felt equally comfortable with both coats at the baseline. When performing tasks inside the live burn facility, the coats became more oppressive but never reached an unbearable stage, and the difference between the coats is significant ($p = 0.0021$). The rise from the baseline to Scenario 1 is very sharp under the SF coat than under the LC coat (Fig. 4b).

3.3.2. Thermal comfort

The coats were not significantly different ($p = 0.352$) under the Thermal Comfort metric. When inside the live burn facility, perception hovered between 'comfortable' and 'unbearably hot' (Fig. 4c).

3.3.3. Respiratory distress

At the baseline, there was no difference between the coats. Throughout the protocol, LC coats were perceived to be better, and the difference was significant ($p = 0.0004$) (Fig. 4d).

4. Discussion

When the second-year project was launched, the state-of-the-art LC coat was in the final form and ready to be tested. The fabric was new, fans were working though all strenuous activities, and coolants lasting

Table 1
Estimates, standard errors, and p-values under multiple regression models.

a. Y = average CBT

Predictor	Estimate	Standard Error	p-value
Time spent	0.0071	0.0056	0.2069
Epoch			
Baseline	Baseline		
Scenario 1	0.2942	0.0947	0.0023 **
Rest 1	0.3338	0.1045	0.0017 **
Scenario 2	0.6564	0.0992	< 0.0001 ***
Rest 2	0.8618	0.0998	< 0.0001 ***
Scenario 3	1.0796	0.1025	< 0.0001 ***
Coat used			
SF coat	Baseline		
LC coat	−0.3649	0.0629	< 0.0001 ***

b. Y = average HR

Predictor	Estimate	Standard Error	p-value
Time spent	−0.4442	0.2801	0.1151
Epoch			
Baseline	Baseline		
Scenario 1	18.63	4.77	0.0001 ***
Rest 1	13.68	5.26	0.0103 *
Scenario 2	49.26	4.99	< 0.0001 ***
Rest 2	32.10	5.02	< 0.0001 ***
Scenario 3	55.58	5.16	< 0.0001 ***
Coat used			
SF coat	Baseline		
LC coat	−16.25	3.16	<0.0001 ***

c. Y = average HRV

Predictor	Estimate	Standard Error	p-value
Time spent	−0.69	0.81	0.3960
Epoch			
Baseline	Baseline		
Scenario 1	−11.89	13.83	0.3914
Rest 1	−3.77	15.26	0.8052
Scenario 2	−39.37	14.48	0.0074 **
Rest 2	−35.25	14.56	0.0168 *
Scenario 3	−52.56	14.96	0.0006 ***
Coat used			
SF coat	Baseline		
LC coat	19.43	9.18	0.0361 *

d. Y = average HS

Predictor	Estimate	Standard Error	p-value
Time spent	0.21	0.66	0.7459
Epoch			
Scenario 1	Baseline		
Scenario 2	37.75	8.43	< 0.0001 ***
Scenario 3	86.47	8.81	< 0.0001 ***
Coat used			
SF coat	Baseline		
LC coat	−21.26	7.81	0.0083 **

longer time throughout the workload of firefighters in the live burn facility. Nineteen firefighters were recruited to test the LC coat. The goal of this paper was to compare the SF coat with data coming from the first-year project, and the LC coat, with data coming from the second-year project. The main metric of interest is CBT. The main safety concern is staying within the hyperthermia temperature of 38°C, while working through the scenarios interspersed with rest periods in the live burn facility. LC coat is found to be significantly superior to the SF coat in controlling CBT and good in staying below the hyperthermia temperature most of the time (Fig. 3.f and Table A.7, A.8).

The coats were compared on metrics such as HR, HRV, HS, and aerobic capacity from the physiological perspective. The LC coat outperformed the SF coat on all these metrics (Fig. 3 and Table A.2-8). For each firefighter, data was collected on Borg scale, Thermal Comfort scale, and Respiratory Distress. The LC coat was significantly more comfortable than the SF coat on Borg scale and Respiratory Distress (Fig. 4b, 4.d and Table A.9, A.11). On the Thermal Comfort scale, the coats were even (Fig. 4c and Table A.10). Results on all these metrics were summarized in Table A.12.

Firefighter protective gear increases the metabolic rate of firefighters due to movement resistance and increased body mass. Moreover, the PPE, whether it is fitted with the SF coat or LC coat, weighs about 26 kilograms [14,24]. The LC coat has coolants, fans, and switches but a lighter inner layer. On the other hand, the SF coat has no special features on the inner layer. The PPE is heavy. As a result, firefighters experience increased oxygen consumption, skin temperature, CBT, HR, and perception scales [14]. Firefighters were unable to rely on natural thermoregulation to cool the body due to their encompassing protective gear and extreme environmental conditions (e.g., extreme heat). Thus, cooling interventions to protect from the negative effects of heat stress are necessary to reduce physiological strain and adverse health effects [13].

Bennet and associates [25] compared four-pack cool vests versus six pack cool vests in reducing heat strain, but the experiment was conducted in a lab. Smolander and associates [26] examined the effects of wearing an ice vest on some physiological measurements, but the experiment was conducted in a lab. Selkirk and associates [27] compared active and passive cooling during work in a warm environment while wearing firefighting protective clothing, but the experiment was conducted in a controlled environment. Carter [28], Giesbrecht [29] and their associates examined the effectiveness of immersing hands and forearms in water under heat stress while working with heavy gear in a hot and humid environment. Two major differences between these studies and the current study are: a) the fire coat used was CNT based fabric, b) a live burn facility was used where firefighters were carrying out fire suppression tasks providing real-time data about CBT, HR, and HRV. Roossien et al [30] compared two protective suits, one traditional and the other with three layers, on core body and inner-ear temperatures. The setting was a room with a controlled temperature and humidity. Approved tasks were used to monitor temperatures with two different instruments. The current experiment was similar in spirit, but one coat was a state-of-the-art LC coat, and the setting was inside a live burn facility.

Firefighting is a dangerous job. A PPE is essential to help firefighters mitigate adverse conditions emanating from the job. A sizable literature focused on PPEs and their role in the safety of firefighters. The issues they addressed were different from the current study. A common overarching goal between the current research and theirs was to find a way to improve the safety of firefighters. A review article by Ramezanifar et al [31], examined the impact of weight of PPE on several physiological measurements. Moraes et al [32] focused on the impart of fit and sizing of PPE on movements of firefighters. Yu et al [33] examined how a specific fabricated composite aerogel achieved an efficient thermal buffer performance in response to high temperatures. Tian et al [34] examined the effect air gap under clothing on heat transfer. Sokolowski et al [35] focused on female firefighters' PPE's fitting and sizing to improve safety. Kollock et al [36] were concerned about the effect of PPE on the static and postural stability. Stability of firefighters while working in a live burn facility was examined but this was discussed elsewhere [37]. Kesler et al [38] focused on hood design, laundering, and doffing with reference to smoke protection and heat stress. Again, the LC coat design had nothing to do with hood design. Shakeriaski et al [39] discussed sensing systems in monitoring metrics when firefighting. Bio harness was used as the sensing mechanism for data on metrics of interest.

5. Limitations

The study population was limited to Caucasian males, with an average age in their thirties. Furthermore, the live burn scenarios were only simulations of fire activities rather than active fires. While the live burn facility allowed fire and environmental conditions to be controlled, actual physiological responses may be different in real life conditions where firefighters have additional life-threatening stresses. Some researchers [32,35] demonstrated significant impact of sizing and fit on some metrics. This issue was not addressed at all here. Further, female firefighters were not recruit in the study. Humidity inside the facility was not measured when firefighters were working. It was not feasible to install a humidity meter inside the live burn facility. However, the temperature inside ranged between 400 to 800°F. Monitoring temperature inside the live burn facility continually was hard. This was a limitation. The bio harness a firefighter wears gives only core body temperature.

6. Conclusion

Overall, most metrics including core body temperature, heart rate, heart rate variability, heat storage, aerobic capacity, Borg scale, and Respiratory Distress were found to be significantly different between the SF and LC coats. The averages at each epoch for all the metrics are presented in the appendix. The novel features of having fans and coolants inside the coat were providing benefits. A case concerning the usability and marketability of the new LC coat was made. One must wait to see the health benefits of the new coat in the long stretch when the firefighters start using it.

Funding

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Ethical approval

Institutional Review Board (#2022-0682) of the University of Cincinnati.

CRediT authorship contribution statement

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Declaration of competing interest

There are no competing interests from each of the authors of the article.

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Appendix

Instructions on what to do inside the live burn facility

"Scenario 1, you will carry the hose into the burn room on the 1st floor for fire control. You will then climb the stairs 10 times to the second floor with the hose. If you finish this scenario before 15 minutes, you will continue to climb the stairs WITHOUT the hose until 15 minutes are up."

"Scenario 2, First floor search, then come out. Then hose advancement to the burn room for fire control. If you finish this scenario before 15 minutes, you will climb the stairs WITHOUT the hose until 15 minutes are up."

"Scenario 3, Bring hose to the 2nd floor landing, then leave hose. Do 2nd floor search and once that is complete, bring hose back down the stairs to the fire room for fire control. If you finish this scenario before 15 minutes, you will climb the stairs until the 15 minutes are up."

We recorded time spent under each activity in Table 1. Only six firefighters (1-6) with SF coats followed the stipulated protocol on time under the scenarios. All nineteen firefighters with LC coats followed the protocol.

Table 1
Time spent (in minutes) in the Live Burn Facility.

SF COAT FF ID	Scenario1	Rest1	Scenario2	Rest2	Scenario3
1	15	29	26	33	25
2	15	18	15	21	15
3	15	29	26	33	25
4	11	30	12	39	12
5	15	18	15	21	15
6	17	20	16	19	17
7	3	20	9	15	9
8	6	19	1	19	3
9	6	19	1	19	3
10	3	20	9	15	9
LC COAT FF ID	Scenario1	Rest1	Scenario2	Rest2	Scenario3
1	27	35	16	37	14
2	24	28	9	26	8
3	22	33	17	26	12
4	22	32	8	23	10

(continued on next page)

Table 1 (*continued*)

LC COAT FF ID	Scenario1	Rest1	Scenario2	Rest2	Scenario3
5	21	20	9	20	11
6	24	28	9	26	8
7	14	33	17	26	12
8	8	34	19	24	11
9	16	32	8	23	10
10	21	20	9	20	11
11	21	20	9	20	11
12	14	33	17	26	12
13	8	34	19	24	11
14	27	35	16	37	14
15	8	23	19	24	11
16	22	33	17	26	12
17	22	33	17	26	12
18	24	28	9	26	8
19	8	23	19	24	11

The average CBT for each session under each coat is given in Table 2 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 2.a of the main paper.

Table 2
Mean CBT by coats – live burn data.

CBT	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value
SF(n=6)	37.3	37.7	38.1	38.3	38.4	38.5	< 0.0001
LC(n=18)	37.2	37.5	37.5	37.8	38.1	38.2	

The average HR for each session under each coat is given in Table 3 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 2.b of the main paper.

Table 3
Mean HR by coats – live burn data.

HR	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value
SF(n=6)	105.5	148.5	126.7	154.1	126.7	157.2	< 0.0001
LC(n=18)	93.2	105.0	100.9	152.1	126.7	156.3	

The average HRV for each session under each coat is given in Table 4 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 2.c of the main paper.

Table 4
Mean HRV by coats – live burn data.

HRV	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value
SF(n=6)	53.1	19.6	28.0	16.1	28.4	16.3	0.0019
LC(n=18)	69.8	58.5	49.8	27.5	23.3	18.6	

The average aerobic capacity for each scenario under each coat is given in Table 5 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 2.d of the main paper.

Table 5
Mean Aerobic capacity by coats – live burn data.

HRV	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value
SF(n=6)	0.15	57.55	26.82	64.87	25.93	68.43	< 0.0001
LC(n=18)	0.13	12.74	6.43	58.85	36.58	69.71	

The average HS for each scenario under each coat is given in Table 6 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 2.e of the main paper.

Table 6
Heat Storage by coats – live burn data.

Coat	Scenario1	Scenario2	Scenario3	p-value
SF(n=6)	43.90	103.28	119.56	< 0.0001
LC(n=18)	27.73	57.21	116.28	

The average percentage of time above hyperthermia temperature for each scenario under each coat is given in Table 7 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 2.f of the main paper.

Table 7
Percentage of time above hyperthermia temperature by coats – live burn data.

Coat	Baseline	Scenario1	Rest1	Scenario2	Rest2	Scenario3	p-value
SF(n=6)	0	16.26	67.24	67.17	77.03	85.60	0.0012
LC(n=18)	0	0	2.03	17.69	49.17	59.03	

The total time in minutes above hyperthermia temperature within the protocol under each coat is given in Table 8 along with the p-value for the comparison of the coats.

Table 8
Total time in minutes above hyperthermia temperature.

							Average	Sd	P-value
SF(n=6)	120	71	35	96	10	76	68	40	0.0144
LC(n=18)	6	21	40	59	45	38	23	22	
	1	35	0	0	20	36			
	65	0	5	0	0	35			

The average Borg Scales for each scenario under each coat is given in Table 9 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 3.b of the main paper.

Table 9
Averages of Borg Scales by coat.

Coat	Baseline	Scenario1	Scenario2	Scenario3	p-value
SF(n=6)	6	12.6	13.5	13.2	0.0021
LC(n=18)	6.26	7.37	12.5	12.5	

The average Thermal Comfort for each scenario under each coat is given in Table 10 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 3.c of the main paper.

Table 10
Averages of thermal comfort scales by coat.

Coat	Baseline	Scenario1	Scenario2	Scenario3	p-value
SF(n=6)	2.75	4.75	5.4	5.45	0.352
LC(n=18)	3.84	4.45	5.5	5.32	

The average Respiratory Distress for each scenario under each coat is given in Table 11 along with the p-value for the comparison of the coats. The graph of the data is presented in Figure 3.d of the main paper.

Table 11
Averages of respiratory distress by coat.

Coat	Baseline	Scenario1	Scenario2	Scenario3	p-value
SF(n=6)	1	2.7	3.2	3	0.0004
LC(n=18)	1	1.16	2.39	2.32	

Table 12
Summary of statistical analyses comparing the performance of coats.

Research Interest		Test	p-value	Comment on Coats
Physiology	CBT	Hotelling's T-squared test	< 0.0001	Significant difference.
	HR	Hotelling's T-squared test	< 0.0001	Significant difference.
	HRV	Hotelling's T-squared test	0.0019	Significant difference.
	HS	Hotelling's T-squared test	< 0.0001	Significant difference.
	Aerobic capacity	Hotelling's T-squared test	< 0.0001	Significant difference.
	Total time CBT above hyperthermia	Wilcoxon rank sum test	0.0144	Significant difference.
	Percentage of Time CBT exceed hyperthermia	Hotelling's T-squared test	0.0012	Significant difference.
Perceptions	Borg Scale	Hotelling's T-squared test	0.0021	Significant difference.
	Thermal Comfort Scale	Hotelling's T-squared test	0.352	No difference.
	Respiratory Distress Scale	Hotelling's T-squared test	0.0004	Significant difference.

Data availability

Data will be made available on request.

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