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Physiological response to firefighting activities of various work cycles using extended duration and prototype SCBA

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ABSTRACT

Firefighters' self-contained breathing apparatus (SCBA) protects the respiratory system during firefighting but increases the physiological burden. Extended duration SCBA (>30 min) have increased air supply, potentially increasing the duration of firefighting work cycles. To examine the effects of SCBA configuration and work cycle (length and rest), 30 firefighters completed seven trials using different SCBA and one or two bouts of simulated firefighting following work cycles common in the United States. Heart rate, core temperature, oxygen consumption, work output and self-reported perceptions were recorded during all activities. Varying SCBA resulted in few differences in these parameters. However, during a second bout, work output significantly declined while heart rates and core temperatures were elevated relative to a single bout. Thirty seven per cent of the subjects were unable to complete the second bout in at least one of the two-bout conditions. These firefighters had lower fitness and higher body mass than those who completed all assigned tasks.

Practitioner Summary: The effects of extended duration SCBA and work/rest cycles on physiological parameters and work output have not been examined. Cylinder size had minimal effects, but extended work cycles with no rest resulted in increased physiological strain and decreased work output. This effect was more pronounced in firefighters with lower fitness.

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KEYWORDS
Firefighting; heart rate; core temperature; work cycle, self-contained breathing apparatus

1. Introduction

Firefighters wear unique personal protective equipment (PPE) to minimise the risk of injury or death. In particular, the use of a self-contained breathing apparatus (SCBA) reduces the risk of asphyxiation and the inhalation of dangerous by-products of combustion. While the SCBA reduces the risk of exposure, it increases the load that a firefighter must carry and shifts the centre of mass away from the firefighter's core, limiting the range of motion and decreasing overall gait performance (Park et al. 2011).

Firefighting involves strenuous work that leads to maximal or near-maximal heart rates (HR) and rapid changes in core temperature (Tco) (Barr, Gregson, and Reilly 2010; Hostler et al. 2010; Colburn et al. 2011; Walker et al. 2015). The SCBA worn during structural firefighting activities has been shown to negatively affect firefighters' work performance and increase cardiac strain even during short duration firefighting activities (Louhevaara et al. 1984, 1985; Helneman, Shy, and Checkoway 1989; Huck 1991; Louhevaara et al. 1995; Hooper, Crawford, and Thomas 2001; Punakallio, Lusa, and Luukkonen 2003).

The amount of time that a firefighter is able to operate on the fireground (work cycle) is often limited by the air available within the SCBA cylinder; in the United States (US) and many other countries, this is commonly a 30-min SCBA cylinder (rated for 30 min when breathing at 40 liters/minute). Following recommendation from NFPA 1584 (National Fire Protection National Fire Protection Association 2008), a work cycle may consist of a first bout of firefighting (duration depending on work intensity), a short (~5 min) break to replace the air cylinder, followed by a second bout of firefighting before firefighters report to an area designated for rehabilitation (e.g. a formal location set up on the fireground for rest, recovery, hydration, and

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medical monitoring). Sothmann et al. (1992) reported an average working time of 15 min (range 8–28 min) when conducting real fire suppression emergencies with a 30-min SCBA. Recently, studies with physiological status monitoring tools have shown a typical work cycle may range from 10 to 40 min (dependent upon job assignment and SCBA size), including physical activities conducted outside of the fire building prior to going 'on-air' (Smith et al. 2010; Horn et al. 2013).

There has recently been a significant increase in the use of larger (and consequently heavier) extended duration SCBA cylinders in the US Fire Service (45-min or 60-min). The use of these extended duration SCBA cylinders is partially driven by attempts to minimise the concerns of smoke exposure and risk of asphyxiation associated with running out of air. Increased usage of extended duration SCBA cylinders has also been attributed to the recent change in the end of service time indicator from 25 to 33% capacity in NFPA 1981 (National Fire Protection Association 2013b). The use of extended duration SCBA cylinders is already prominent in rapid intervention teams and hazardous materials operations, as well as in departments performing high-rise operations. However, the fire service is lacking holistic quantifiable data to evaluate the tradeoffs between the increased physiological strain caused by increased size and weight and the ability to complete longer work cycles.

It is known that firefighters will experience an increase in physiological strain with increased duration of firefighting activity (Horn et al. 2013). In 2014, Smith et al. studied the impact of PPE configuration on firefighters conducting multiple bouts of treadmill walking in the laboratory, showing elevated core temperatures and increased thermal sensations in the second bout of exercise after a 10 min rest. Research has also recently been conducted during simulated live fire training and response scenarios. For example, Horn et al. (2013) reported core temperature increases of 1.9 °C over baseline values following multiple live-fire training evolutions consisting of 15–20 min-long work cycles with more than 30 min-long breaks between activity. When activity resumed following breaks, not only did core temperature continue to increase, but the rate of change increased. Walker et al. (2015) found increased physiological strain (heart rate and core temperature), reduced grip strength and increased rate of air consumption following a second bout of search and rescue activities, relative to the first bout. Hostler et al. (2016) found that increasing fireground work bouts from two to three increased thermal strain and reduced performance on activities conducted after fireground rehabilitation. While the scenarios conducted in each of these three studies are relevant for common firefighting activities, they did not allow quantification of changes in abilities to complete the activities *during* the second bout of fireground work. Furthermore, the impact of a short duration rest (~5 min that is necessary to change an air cylinder) on subsequent capabilities has not been investigated.

In this study, we examined the impact of four SCBA configurations (30-, 45- and 60-min standard cylindrical SCBA and a 45-min low-profile prototype) and three specific work cycles of varying duration with and without defined rest periods (single bout, back-to-back bouts and two bouts with a 5 min rest between them). Firefighters' physiological responses were analysed during controlled bouts of firefighting activity in a highly replicable thermal environment with quantifiable work outputs for fixed durations of 14 min (single bout), 30 min (back-to-back bouts), and 33 min (two bouts with a 5 min rest between them). To examine the effect of extended duration SCBA and the potential subsequent changes in work cycle, we studied: (1) completion of a single bout of simulated firefighting activity with varying SCBA cylinder size/duration and design, (2) completion of one versus two bouts (5 min rest versus no rest) of firefighting performed with a large extended duration SCBA cylinder and (3) the interaction between SCBA size and the work duration (1 vs. 2 bouts) of simulated firefighting activity on physiological and perceptual measures.

2. Methods

2.1. Subjects

Thirty firefighters (29 male, 1 female), all free of known cardiovascular, neurological or gastrointestinal disease, participated in this study. The group included 14 volunteer firefighters, 14 career firefighters and two individuals who served as career firefighters and were members of a volunteer department. Subjects ranged in age from 19 to 48 years with an average ± standard error of 30.4 ± 1.5 years. Subjects were 1.82 ± 0.01 metres tall and weighed 91.2 ± 2.8 kilograms, with a BMI of 27.4 ± 0.7 kg/m^2. Further, subjects had maximal values of 43.7 ± 1.3 ml/kg/min for $\dot{V}O_{2max}$, 124.9 ± 3.4 l/min for $\dot{V}_{E,max}$, and 190 ± 2 beats/min for HR_{max}. Prior to testing, all subjects completed a health history inventory, a Physical Activity Readiness Questionnaire (Thomas, Reading, and Shephard 1992), and provided written informed consent. This study was approved by the University of Illinois at Urbana-Champaign Institutional Review Board.

2.2. Study design

This study used a quasi-counterbalanced design to investigate the effects of different SCBA size and design and work cycle on heart rate, core temperature, oxygen consumption, perceptual measures and work output. In order

Table 1. SCBA characteristics.

Weights and dimensions of SCBA configurations			
SCBA configuration	Total pack weight (kg)	Cylinder length (cm)	Cylinder diameter (cm)
S30	9.9	55	14
S45	11.8	59	16
S60	13.3	60	18
	Total pack weight (kg)	Pack length (cm)	Pack width (cm)
P45	13.1*	76	34.7

*P45 was weighed and used empty. Research staff followed subjects with a full SCBA cylinder in P45 conditions to allow the subject to breathe through an SCBA, as in all other conditions.

to address the specific aims of the study, firefighters completed 7 trials that involved different combinations of SCBA cylinder size (30, 45, and 60 min capacity) and design (currently available carbon fiber wrapped cylinders carried in a traditional harness and a new prototype, Table 1) and work cycle (single bout [14 min]; two bouts separated by 5 min rest [33 min]; two bouts back to back with no rest [30 min]). The following combinations of four different SCBA configurations and three different work cycles were conducted:

1. Standard *30-min* cylinder with *1 bout* of activity (S30_1B)
2. Standard *45-min* cylinder with *1 bout* of activity (S45_1B)
3. Standard *60-min* cylinder with *1 bout* of activity (S60_1B)
4. Prototype *low-profile 45-min* pack with *1 bout* of activity (P45_1B)
5. Standard *30-min* cylinder with *2 bouts* of activity and *rest* in between bouts (S30_2B)
6. Standard *60-min* cylinder with *2 bouts* of activity and *rest* in between bouts (S60_2B)
7. Standard *60-min* cylinder with *2 bouts* of activity *back-to-back* (S60_BB).

Trials are coded as *SCBA design/size_work cycle* (i.e. P45_1B or S60_BB). Work cycle/duration of the various protocols (1B, 2B, BB) are shown in Figure 1.

2.3. Timeline

Subjects initially completed a baseline visit, where the subjects' height and weight were measured and body mass index (BMI) was computed. Subjects also completed a maximal treadmill test in which maximal oxygen consumption ($\dot{V}O_{2max}$) and maximal heart rate (HR_{max}) were recorded. These procedures are described in detail in a previous report focusing on the accuracy of these assessments (Klaren et al. 2014). Firefighters then returned to complete the seven different simulated firefighting trials, where each trial was separated by a minimum of 24 h and performed at roughly the same time of day. The single bout activities were conducted first, with conditions 1–3 presented in a counter-balanced order. Half of the subjects completed condition 4 prior to conditions 1–3, while the other half completed condition 4 following conditions 1–3. Conditions 5–7 were then completed in a counter-balanced order. Conditions were presented in this fashion in an attempt to minimise order effects.

Six to 12 h prior to arrival (dependent upon the individual digestive pace of each subject), the subjects ingested a core temperature monitoring pill. Upon arrival subjects were fitted with a physiological status monitor (Equivital, Phillips Respironics, Andover, MD) to measure heart rate and collect data transmitted by the ingested core temperature pill. Subjects then donned NFPA 1971 compliant PPE including coat, pants, boots (Globe Manufacturing, Pittsfield, NH); Nomex hood (PAC II, Majestic Fire Apparel, Lehighton, PA); helmet (Cairns, MSA, Cranberry Township, PA) and the appropriate NFPA 1981 compliant SCBA (Firehawk M7 or prototype design, MSA, Cranberry Township, PA). Once fully dressed for firefighting activities (not breathing from SCBA), the subjects completed an obstacle course developed to measure gait characteristics and functional balance (Bradley et al. 2014; Deetjen et al. 2015).

2.4. Measures

Prior to entering the environmental chamber, subjects rated ease of breathing, thermal comfort and overall feeling. Perception of respiratory distress was assessed using a seven-point scale (Morgan and Raven 1985). The scale is anchored with descriptions (e.g. 'My breathing is okay right now,' 'I can't breathe'). Perceptions of thermal sensations, ranging from 'unbearably cold' to 'unbearably hot' were assessed using an eight-point rating scale (Young 1987). The subjects rated how they were feeling using the Feeling Scale (Hardy and Rejeski 1989). For this 11-point scale, anchors are provided at 0 (neutral) and at odd integers, ranging from −5 (very bad) to +5 (very good). The subjects verbally responded to the questions for each scale and pointed to the level of exertion on a posted scale, which was verified and recorded by an investigator.

Inside the chamber, subjects were fit with a modified SCBA facepiece (Kesler et al. 2014) and metabolic monitoring equipment ($K4b^2$, Cosmed s.r.l., Rome, Italy) to measure oxygen consumption while breathing from their SCBA. Following the three-minute setup period, and two minutes of pre-activity resting data collection, subjects completed the firefighting tasks protocol with assigned SCBA. While the subjects were completing the simulated firefighting activities, heart rate, core temperature, oxygen consumption ($\dot{V}O_2$) and minute ventilation ($\dot{V}_E$) were

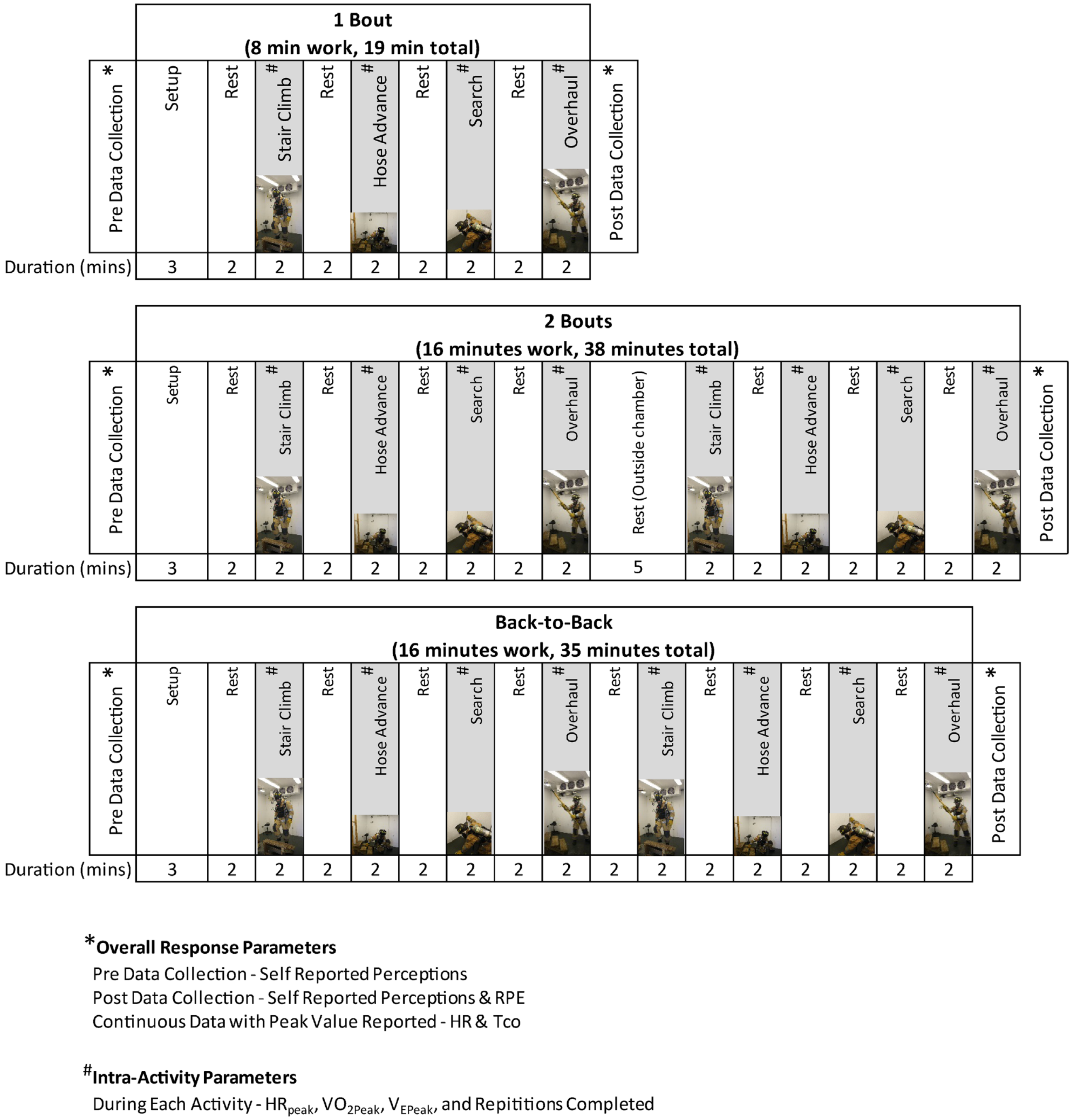

Figure 1. Structure/duration of work cycles. Prior to each work cycle beginning, firefighters sat in the chamber for 3 minutes of data acquisition set up and 2 minutes of resting data collection.

measured continuously. The following discrete measures were selected to describe the firefighters' physiology during the activities: the highest heart rate achieved throughout the test session (HR_{Peak}), the average heart rate during the simulated firefighting activity (HR_{ave}), the peak core temperature measured during the simulated firefighting activity ($Tco_{Peak,FF}$), the change in core temperature during the simulated firefighting activity ($\Delta Tco_{Peak,FF}$), peak oxygen consumption ($\dot{V}O_{2,Peak}$) and peak minute ventilation ($\dot{V}_{EPeak}$).

After exiting the environmental chamber, the subjects removed the facepiece and the hood, and again provided rating of breathing effort, thermal comfort and overall feeling. A rating of perceived exertion was recorded immediately after the activity using the 15-point, 6–20 Borg scale (Borg 1970). The subjects were then asked to complete the obstacle course two more times. Following the obstacle course, subjects removed the SCBA and were allowed to recover for a minimum of ten minutes. Core temperature was monitored through the entire scenario. From these data, the peak core temperature ($Tco_{Peak,Tot}$) and the change in core temperature during the entire session ($\Delta Tco_{Peak,Tot}$) were recorded as core temperature continued to rise after the conclusion of the simulated firefighting activities.

2.5. Simulated firefighting activities

All simulated firefighting activities were conducted in an environmental chamber with temperature and humidity set at 47 °C and 30%, respectively. Throughout each scenario, two trained staff members remained with the subject completing the activities; one to record the amount of work and monitor heart rate, the other to act as a safety escort, demonstrating each activity during the rest periods and ensuring that the subject completed each activity in a safe manner. During the activities, all interior lights were turned off and the chamber was illuminated by a flashlight carried by the safety escort to simulate working in a dark structure with common fireground illumination. Simulated firefighting was comprised of four activities completed on a two-minute work–rest cycle and performed on a compact Firefighting Activities Station (Horn et al. (2015)). Briefly, the activities consisted of: (1) a stair climb, (2) a simulated hose advance, (3) a simulated search and (4) a simulated overhaul task, and were always completed in the same order. All activities were performed at a self-selected pace with instructions to simulate the effort each subject would expend on the fireground. Subjects were allowed to modify their technique or to rest at any time throughout the activity. If the subjects chose to take a break at any point during the simulated firefighting activities, they were allowed to either rest and then resume activity, or exit the chamber and terminate firefighting activities altogether. Subjects were instructed to inform the safety escort if they felt too hot, dizzy, nauseous or otherwise unsafe to continue the activities and exit the chamber as necessary.

2.6. Statistical analysis

In general, the seven trials were grouped into three comparison groups (Figure 2) such that analysis included the effect of:

- *SCBA* (cylinder size and design comparing results from all four single-bout conditions – S30_1B, S45_1B, S60_1B, P45_1B)
- *Work Cycle* structure/duration of firefighting activity (1 bout, 2 bouts, or back-to-back bouts using the identical '60-min' SCBA – S60_1B, S60_2B, S60_BB)
- Interaction between *SCBA* and *Work Cycle* (S30_1B, S30_2B, S60_1B, and S60_2B)

For analyses of work output in multiple bout conditions, the maximum number of subjects available was analysed (i.e. any firefighters who exited the chamber prior to completing the entire protocol were excluded from the analysis). An examination of potential interaction between *SCBA* and *Work Cycle* revealed no significant results and thus will not be discussed in detail.

Each of these analyses were performed by repeated measures analysis of variance (ANOVA) in SPSS (v. 23 IBM, Armonk, NY) with significance set at $p = 0.05$. In all analyses of multi-bout conditions (S30_2B, S60_2B, and S60_BB), data from the second bout were used with the largest

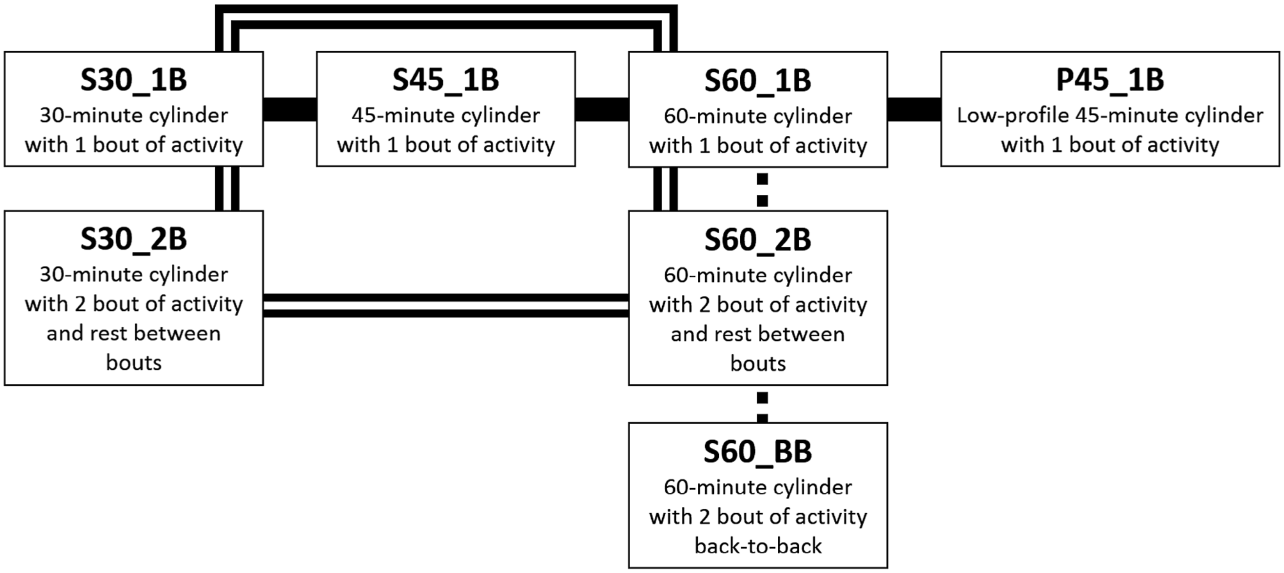

Figure 2. Multiple trials allowed examination of (a) SCBA size and design (solid line), (b) duration of simulated firefighting activity (dashed line) and (c) the interaction of SCBA and work cycle structure/duration (double line).

number of subjects available, given that some subjects were unable to complete the entire firefighting activity protocol. The statistical model utilised for each variable depended on the nature of the data being analysed.

2.6.1. Overall response to firefighting work

Data describing the physiological and perceptual responses to the overall work cycle consist of measurements conducted pre- and post-firefighting activity or as single discrete variables within each trial describing maximum values or average values over the complete scenario (see measures identified by * in Figure 1).

- For heart rate, core temperature and rating of perceived exertion:
    - *SCBA* effects were examined using a one-way ANOVA with four levels (four different SCBA)
    - *Work Cycle* was analysed with a one-way ANOVA with three levels (one bout, two bouts, back-to-back bouts)
- For self-reported perceptions collected before and after firefighting, the impact of *Time* periods (pre- vs. post-activity) were examined, as well as any interaction effects. Thus,
    - *SCBA* effects were tested with a 2 × 4 (*Time* x *SCBA*) ANOVA
    - *Work Cycle* analysis consisted of a 2 × 3 (*Time* x *Work Cycle*) ANOVA

2.6.2. Intra-activity parameters – work performed and heart rate per activity

Physiology, cardiorespiratory and work output data collected to describe each of the four *Activities* (e.g. stairs, hose advance, search and overhaul) within the work cycle were analysed to allow comparisons between the different types of work where possible (see measures identified by # in Figure 1).

- Effects of *SCBA* design on HR_{peak}, $\dot{V}\text{O}_{2\text{Peak}}$ and $\dot{V}_{\text{EPeak}}$ were analysed using a 4 × 4 ANOVA (*SCBA* x *Activities*)
- Unlike the physiological measurements (heart rate, $\dot{V}\text{O}_2$ and $\dot{V}_{\text{EPeak}}$), the amount of work completed (stairs climbed, distance searched, and number of movements of hose and overhaul tool) cannot be directly compared across the four activities, so it was compared across different *SCBA* for each activity individually using a one-way ANOVA with four levels.

Using the multiple bout 60-min SCBA trials (S60_2B, S60_BB), *Work Cycle* could be studied as a function of *Work Cycle Bout* (1st bout vs. second bout of activity) and *Work Cycle Rest* (5 min rest [2B] vs. no rest [BB]). There were no differences between any of the measures in S60_1B and the first bout of both S60_2B and S60_BB trials.

- HR_{peak}, $\dot{V}\text{O}_{2\text{Peak}}$ and $\dot{V}_{\text{EPeak}}$ data from S60_2B and S60_BB were analysed using a 2 × 2 × 4 ANOVA (*Work Cycle Bout* x *Work Cycle Rest* x *Activity*)
- Again, the amount of work completed cannot be directly compared across the four activities, so it was quantified for each activity individually using a 2 × 2 ANOVA (*Work Cycle Bout* x *Work Cycle Rest*).

2.6.3. Work cycle completion

Descriptive statistics were calculated for the sub-groups of firefighters who were able to complete the entire trial for each two-bout protocol (S30_2B, S60_2B and S60_BB) for those who were unable to complete at least one of the two bout protocols. Comparisons of body measurements and fitness levels between these groups were analysed with independent samples t-tests.

3. Results

3.1. Overall response to firefighting work

The physiological impact of *SCBA* and *Work Cycle* on overall response to firefighting work in each of the seven scenarios is shown in Table 2. We did not detect a significant *SCBA* main effect on heart rate. However, heart rate measurements had a significant *Work Cycle* main effect ($p < 0.001$). HR_{peak} increased significantly from S60_1B to S60_2B ($p = 0.001$) and from S60_2B to S60_BB ($p = 0.018$) (Table 2). HR_{avg} was not significantly different between S60_1B and S60_2B conditions, but was higher in S60_BB ($p = 0.003$).

The highest core temperature attained during simulated firefighting activities ($\text{Tco}_{\text{Peak,FF}}$) and the highest core temperature attained during the entire visit ($\text{Tco}_{\text{Peak,Tot}}$) were significantly affected by *SCBA* ($p = 0.032$ and 0.039 respectively), with S60_1B significantly greater than S45_1B and P45_1B ($p = 0.005$ and $p = 0.046$, respectively, for $\text{Tco}_{\text{Peak,FF}}$; $p = 0.013$ and $p = 0.031$, respectively, for $\text{Tco}_{\text{Peak,Tot}}$). Simulated firefighting *Work Cycle* affected $\text{Tco}_{\text{Peak,FF}}$ ($p < 0.001$), $\Delta\text{Tco}_{\text{FF}}$ ($p < .001$), $\text{Tco}_{\text{Peak,Tot}}$ ($p = 0.001$) and $\Delta\text{Tco}_{\text{Tot}}$ ($p < 0.001$) such that higher core temperature and larger core temperature changes were found in S60_2B and S60_BB relative to S60_1B ($p = 0.001$ and $p < 0.001$, respectively, for $\text{Tco}_{\text{Peak,FF}}$; $p < 0.001$ for both for $\Delta\text{Tco}_{\text{FF}}$; $p = 0.019$ and $p = 0.001$, respectively, for $\text{Tco}_{\text{Peak,Tot}}$; $p < 0.001$ for both for $\Delta\text{Tco}_{\text{Tot}}$), but no differences were found between S60_2B and S60_BB (Table 2).

There were no differences in how subjects rated their ability to breathe, overall feeling, thermal sensations, and perceived exertion among the different *SCBA* (Table 3). Following the completion of all conditions, subjects

Table 2. Heart rate and core temperature parameters for each condition (Mean (SE)).

		1 Bout				2 Bouts		Back-to-Back
		S30	S45	S60	P45[†]	S30	S60	S60
N = 30	Peak Heart Rate (HR$_{peak}$, bpm)	182.5 (2.3)	181.8 (2.2)	*182.0 (2.2)*[WC]	180.2 (2.6)	189.2 (2.4)	*186.8 (2.3)*[WC]	*189.0 (2.3)*[WC]
N = 30	Average Heart Rate (HR$_{ave}$, bpm)	151.2 (2.5)	150.7 (2.4)	*151.5 (2.6)*[WC]	148.7 (3.2)	154.5 (2.3)	*151.5 (2.6)*[WC]	*156.2 (2.6)*[WC]
N = 22	Peak Core Temp during firefighting (Tco$_{Peak,FF}$, °C)	37.79 (0.08)	**37.79 (0.05)**[S]	**38.01 (0.08)**[S,WC]	37.79 (0.08)[S]	38.53 (0.09)	*38.45 (0.11)*[WC]	*38.60 (0.11)*[WC]
N = 22	Change in Core Temp during firefighting (ΔTco$_{FF}$, °C)	0.61 (0.09)	0.58 (0.05)	*0.59 (0.05)*[WC]	0.54 (0.05)	1.24 (0.10)	*1.26 (0.11)*[WC]	*1.39 (0.10)*[WC]
N = 18	Peak Core Temp during trial (Tco$_{Peak,Tot}$, °C)	38.33 (0.09)	**38.26 (0.07)**[S]	**38.50 (0.08)**[S,WC]	38.28 (0.10)[S]	38.90 (0.10)	*38.88 (0.14)*[WC]	*39.03 (0.12)*[WC]
N = 18	Change in Core Temp during trial (ΔTco$_{Tot}$, °C)	1.16 (0.08)	1.19 (0.06)	*1.21 (0.07)*[WC]	1.15 (0.06)	1.78 (0.10)	*1.81 (0.14)*[WC]	*1.93 (0.11)*[WC]

Notes: All available data were used for the calculation and analysis of core temperature data. Some loss of data was experience due to core temperature pills that passed early, were affected by water or that otherwise lost communication immediately before or during the study. Those who exited early were included, despite decreased time working in the chamber.

Examination of the interaction between cylinder size and duration of activity did not reveal any significant findings for heart rate or core temperature.

[†] Data reported for P45 conditions are for N-1 subjects, as one subject did not complete the P45 protocol.

[S] Significant SCBA main effect. Significance values presented in text.

[WC] Significant Work Cycle main effect. Significance values presented in text.

Table 3. Self-reported perceptions for each condition (Mean (SE)) (*N* = 30).

						2 Bouts		
		1 Bout				Break between Bouts		Back-to-Back
		S30	S45	S60	P45 (*N* = 29)	S30	S60	S60
Breathing Scale[*]	Pre	1.17 (0.07)	1.10 (0.06)	1.23 (0.09)	1.28 (0.10)	1.10 (0.06)	1.10 (0.06)	1.17 (0.07)
	Post	3.80 (0.13)	3.80 (0.12)	3.77 (0.13)	3.93 (0.10)	4.50 (0.20)	4.47 (0.13)	4.47 (0.16)
Feeling Scale[†]	Pre	3.57 (0.25)	3.43 (0.22)	3.58 (0.20)	3.59 (0.22)	3.50 (0.19)	3.65 (0.18)	3.60 (0.23)
	Post	0.33 (0.35)	0.73 (0.31)	0.97 (0.33)	0.62 (0.34)	−1.17 (0.37)	−1.23 (0.44)	−1.60 (0.40)
Thermal Sensations[‖]	Pre	4.12 (0.07)	4.17 (0.13)	4.27 (0.09)	4.03 (0.14)	4.10 (0.11)	4.05 (0.10)	4.10 (0.13)
	Post	5.92 (0.11)	5.98 (0.10)	6.00 (0.10)	5.91 (0.10)	6.65 (0.12)	6.68 (0.10)	6.85 (0.11)
Perceived Exertion[‡]	Post	15.8 (0.4)	15.8 (0.3)	15.8 (0.3)	16.0 (0.4)	17.9 (0.3)	18.0 (0.3)	18.1 (0.3)

Notes: There was a significant *Time* main effect and significant *Work Cycle* main effect for all perceptual measures. Significance values are presented in the text.

[*] Breathing Scale anchors: (1) 'My Breathing is OK Right Now'; (3) 'I Am Starting to Breathe Hard'; (5) 'I am Not Getting Enough Air' (7) 'I Can't Breathe'.; [†] Feeling Scale anchors: (+5) 'Very Good'; (+3) 'Good'; (+1) 'Fairly Good'; (−1) 'Fairly Bad'; (−3) 'Bad'; (−5) 'Very Bad'.

[‖] Select Thermal Sensation anchors: (0.0) 'Unbearably Cold'; (4.0) 'Comfortable'; (5.0) 'Warm'; (6.0) 'Hot'; (7.0) 'Very Hot' (8.0) 'Unbearably Hot'.

[‡] Select Perceived Exertion anchors: (6) 'No Exertion at All'; (11) 'Light'; (13) 'Somewhat Hard'; (15) 'Hard (Heavy)'; (17) 'Very Hard'; (19) 'Extremely Hard'; (20) 'Maximal Exertion'.

reported breathing harder ($p < 0.001$), feeling worse ($p < 0.001$) and feeling hotter ($p < 0.001$) than prior to completing the activities (*Time* main effect). Subjects also felt they were breathing harder ($p = 0.001$), feeling worse ($p < 0.001$), feeling hotter ($p < 0.001$) and working harder ($p < 0.001$) following S60_2B and S60_BB than after S60_1B (*Work Cycle* main effect), but there were no significant differences between S60_2B and S60_BB.

3.2. Intra-activity parameters – work performed and heart rate per activity

There was no *SCBA* main effect on work output, peak heart rate, $\dot{V}O_2$ or $\dot{V}_E$ when completing a single bout of activity (Table 4). However, a significant *Activity* main effect was detected for peak heart rate, $\dot{V}O_2$ and $\dot{V}_E$ ($p < 0.001$ for all) for the single bout activities with various SCBA. Peak heart rates were significantly lower in the first drill (stair climb) and significantly higher in the final drill (overhaul) ($p < 0.001$ for both). There was no significant difference between the second and third drills (hose advance and search). $\dot{V}_E$ was significantly lower during the stairs activity than the other three activities ($p < 0.001$ for all). $\dot{V}_E$ was significantly lower during the overhaul task than during the hose advance and search ($p = 0.019$ and $p = 0.009$, respectively). On the other hand, $\dot{V}O_2$ was significantly higher during the stair climb than in the hose advance and search activities ($p < 0.001$ and $p = 0.001$, respectively). $\dot{V}O_2$ was significantly lower during the overhaul task than all other activities ($p < 0.001$ for all). There was no statistical difference between the hose advance and search activities.

For the two bout activities completed with the S60 SCBA, there was a significant *Work Cycle Bout* main effect on work output (Table 5 $p = 0.001$ for stairs; $p < 0.001$ for hose advance, search and overhaul) with subjects completing a significantly higher number of repetitions in the

Table 4. Repetitions, peak heart rate, peak oxygen consumption and peak minute ventilation rate during each of the four simulated firefighting activities for single bout activities (Mean (SE)).

		1 Bout			
		S30	S45	S60	P45 (*n* = 29)
Stair climb	Repetitions (#)	40.0 (1.5)	39.5 (1.5)	39.5 (1.4)	39.1 (1.5)
	Peak Heart Rate (HR_{peak}, bpm)^A	163.0 (2.8)	162.5 (2.6)	164.6 (2.7)	160.9 (3.0)
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg)^A	28.4 (0.9)	27.7 (1.1)	27.9 (1.1)	27 (1.1)
	Peak Minute Ventilation ($\dot{V}_E$, l/min)^A	74.5 (5.3)	74.6 (5.7)	75.3 (5.1)	73.4 (5.8)
Hose advance	Repetitions (#)	54.8 (2.0)	54.2 (2.3)	54.5 (2.2)	54.4 (2.2)
	Peak Heart Rate (HR_{peak}, bpm)	176.3 (2.2)	174.7 (2.2)	175.3 (2.2)	172.4 (2.5)
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg)	24.9 (0.7)	23.5 (0.9)	24.4 (1.0)	23.4 (1.0)
	Peak Minute Ventilation ($\dot{V}_E$, l/min)	90.6 (4.1)	89.8 (4.7)	91.9 (4.3)	88.6 (4.7)
Search	Distance (m)	107.5 (5.8)	107.5 (5.6)	107.5 (6.0)	103.8 (5.1)
	Peak Heart Rate (HR_{peak}, bpm)	177.0 (2.3)	175.8 (2.3)	177.6 (2.3)	173.4 (2.2)
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg)	25 (0.8)	24.4 (1.1)	25.2 (0.9)	24.3 (1.0)
	Peak Minute Ventilation ($\dot{V}_E$, l/min)	91.0 (3.8)	93.0 (3.9)	92.7 (3.6)	92.0 (4.0)
Overhaul	Repetitions (#)	56.2 (2.3)	57.8 (2.5)	57.3 (2.4)	56.6 (2.2)
	Peak Heart Rate (HR_{peak}, bpm)^A	180.1 (2.4)	178.8 (2.2)	180.1 (2.2)	177.3 (2.5)
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg)^A	19.8 (0.7)	19.1 (0.8)	20 (0.7)	19.1 (0.8)
	Peak Minute Ventilation ($\dot{V}_E$, l/min)^A	84.1 (4.3)	86.7 (4.9)	87.2 (4.6)	86.8 (4.7)

^{A}Activity main effect. Significance values presented in text.

Table 5. Repetitions, peak heart rate, peak oxygen consumption and peak minute ventilation for each of the four simulated firefighting activities ($N = 19$ unless otherwise noted).

			2 Bouts		Back-to-Back
			S30	S60	S60
Stairs	Repetitions (#)	First Bout	41.8 (2.2)	**40.5 (2.2)**^{B,R}	**40.3 (2.1)**^{B,R}
		Second Bout	38.5 (2.1)	**37.2 (1.9)**^{B,R}	**35.6 (1.7)**^{B,R}
	Peak Heart Rate (HR_{peak}, bpm)	First Bout	160.0 (3.4)	**158.2 (3.4)**^{B}	**158.8 (3.4)**^{B}
		Second Bout	182.2 (2.6)	**181.1 (2.7)**^{B}	**183.2 (2.6)**^{B}
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg) ($N = 18$)	First Bout	27.7 (1.9)	**28.7 (1.4)**^{B}	**28.2 (1.5)**^{B}
		Second Bout	23.7 (1.9)	**24.4 (1.6)**^{B}	**24.9 (1.3)**^{B}
	Peak Minute Ventilation ($\dot{V}_E$, l/min) ($N = 18$)	First Bout	72.7 (8.1)	71.7 (8.1)^{X}	70.0 (7.4)^{X}
		Second Bout	81.6 (9.2)	74.6 (6.5)^{X}	79.2 (6.6)^{X}
Hose Advance	Repetitions (#)	First Bout	55.8 (3.7)	**55.7 (3.5)**^{B}	**55.2 (3.6)**^{B}
		Second Bout	44.7 (3.2)	**45.8 (3.9)**^{B}	**41.5 (3.3)**^{B}
	Peak Heart Rate (HR_{peak}, bpm)	First Bout	171.1 (3.5)	**170.3 (3.0)**^{B}	**170.2 (2.8)**^{B}
		Second Bout	184.0 (2.3)	**182.6 (2.3)**^{B}	**186.5 (2.3)**^{B}
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg) ($N = 18$)	First Bout	22.7 (1.4)	**23.9 (1.2)**^{B}	**23.3 (1.1)**^{B}
		Second Bout	17.3 (1.2)	**19.1 (1.3)**^{B}	**20.4 (1.1)**^{B}
	Peak Minute Ventilation ($\dot{V}_E$, l/min) ($N = 18$)	First Bout	83.7 (6.8)	85.4 (5.7)^{X}	80.9 (6.3)^{X}
		Second Bout	81.4 (7.7)	81.7 (6.9)^{X}	83.3 (6.0)^{X}
Search	Distance (m)	First Bout	117.9 (7.5)	**114.1 (7.0)**^{B}	**111.3 (6.7)**^{B}
		Second Bout	83.6 (5.6)	**83.1 (6.9)**^{B}	**82.7 (5.7)**^{B}
	Peak Heart Rate (HR_{peak}, bpm)	First Bout	171.6 (2.8)	**170.5 (2.9)**^{B}	**170.7 (2.7)**^{B}
		Second Bout	182.5 (2.4)	**181.6 (2.5)**^{B}	**184.1 (2.9)**^{B}
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg) ($N = 18$)	First Bout	22.9 (1.7)	**24.4 (1.2)**^{B}	**23.7 (1.2)**^{B}
		Second Bout	16.8 (1.4)	**17.8 (1.2)**^{B}	**17.9 (1.2)**^{B}
	Peak Minute Ventilation ($\dot{V}_E$, l/min) ($N = 18$)	First Bout	80.8 (6.1)	81.7 (5.2)^{X}	78.0 (4.9)^{X}
		Second Bout	71.5 (6.1)	74.4 (5.8)^{X}	75.2 (5.4)^{X}
Overhaul	Repetitions (#)	First Bout	60.5 (3.6)	**60.0 (3.5)**^{B}	**58.2 (3.7)**^{B}
		Second Bout	49.3 (3.9)	**50.6 (3.8)**^{B}	**47.1 (3.9)**^{B}
	Peak Heart Rate (HR_{peak}, bpm)	First Bout	178.6 (2.9)	**177.1 (3.0)**^{B}	**176.8 (2.8)**^{B}
		Second Bout	187.6 (3.0)	**187.2 (2.8)**^{B}	**189.6 (2.9)**^{B}
	Peak Oxygen Consumption ($\dot{V}O_2$, ml/min/kg) ($N = 18$)	First Bout	18.4 (1.5)	**18.5 (0.9)**^{B}	**18.3 (1.0)**^{B}
		Second Bout	13.6 (1.2)	**14.6 (1.1)**^{B}	**14.6 (1.1)**^{B}
	Peak Minute Ventilation ($\dot{V}_E$, l/min) ($N = 18$)	First Bout	78.5 (6.8)	78.0 (5.4)^{X}	72.1 (5.3)^{X}
		Second Bout	69.5 (6.3)	70.2 (5.3)^{X}	70.2 (4.8)^{X}

^{B}**Work Cycle Bout main effect. Significance values presented in text.**^{R}*Work Cycle Rest main effect. Significance values presented in text.*
^{X}Work Cycle Rest × Work Cycle Bout interaction. Significance values presented in text.

first bout than in the subsequent bout for all four activities. A significant *Work Cycle Rest* main effect on work output was found for the hose advance ($p = 0.006$) and there was nearly a main effect of *Work Cycle Rest* for the stairs and overhaul activities ($p = 0.051$ for both), with a greater number of repetitions completed when subjects were given a five-minute break between bouts. HR_{peak} during each activity was significantly higher in the second bout than the first bout ($p < 0.001$ for all). There were no significant differences in HR_{peak} between S60_BB and S60_2B in any activity (i.e. no *Work Cycle Rest* × *Activity* interaction). $\dot{V}O_2$ was significantly higher in the first bout than the second *Work Cycle Bout* ($p < 0.001$ for all activities). For $\dot{V}_E$ there was a significant *Work Cycle Rest* × *Work Cycle Bout* interaction ($p = 0.042$) indicating that $\dot{V}_E$ did not change between the first and second bouts in the S60_BB condition, whereas $\dot{V}_E$ decreased in the second bout in the S60_2B condition.

3.3. Work cycle completions

All subjects were able to successfully complete the four single-bout activities regardless of SCBA worn. Eleven of the 30 subjects tested were unable to complete at least one of the three two-bout conditions. On average, those subjects who were unable to complete all of the two-bout conditions were heavier (weight 101.8 ± 18.1 kg vs. 85.0 ± 9.4 kg, $p = 0.002$), had higher BMI (30.3 ± 4.1 vs. 25.7 ± 2.6 kg/m^2, $p < 0.001$) and had lower maximum $\dot{V}O_2$ (40.3 ± 7.4 ml/min/kg vs. 45.7 ± 7.4 ml/min/kg, $p = 0.040$) while there were no differences in age, height, maximum heart rate or peak ventilation.

4. Discussion

In the current study we have quantified, in the most complete manner to date, firefighters' significantly higher levels of cardiorespiratory strain and perceived stress as well as significantly reduced work output as a consequence of performing two bouts of simulated firefighting activity compared to a single bout of activity. These data provide the first quantitative assessment of the impact of extended duration SCBA on work performance using a validated simulated firefighting scenario. Notably, 37% of the firefighters participating in this study felt that they were unable to complete a second bout of simulated firefighting activity safely and terminated the firefighting protocol during at least one trial. On average, this group was larger and less fit than the group of firefighters who completed all two-bout scenarios. Interestingly, there were minimal impacts of SCBA size on these same measures, when considering only standard commercially available units (S30, S45 and S60). We did not find any interaction between cylinder size and duration of firefighting activity. These data suggest that the fatigue and physiological stress induced during extended duration firefighting (which is made possible by the additional air supply) is a more significant risk than the added weight and bulk of the larger SCBA itself.

4.1. Effect of SCBA size and design

The various sizes of standard, commercially available cylindrical carbon-fibre wrapped SCBA cylinders used in this study did not significantly affect any of the heart rate, perceptual or work performance variables measured when firefighters completed a single, fixed duration, bout of simulated firefighting activity. The single bout of simulated firefighting in an environmental chamber has been validated against the same activities conducted under live-fire conditions (Horn et al. 2015), therefore we would not expect the sizes of SCBA used in the current study to induce important differences in physiological response or work performance under live-fire conditions. This finding contrasts with previous research by Louhevaara et al. (1995) who suggested that it is important to decrease the mass of SCBA cylinders to improve a firefighter's ability to safely conduct firefighting tasks. Several other research groups have studied the physiological effects of SCBA weight and report conflicting results. For example, Hooper, Crawford, and Thomas (2001) found that lightweight SCBA (15 kg) resulted in lower energy expenditure than conventional SCBA (27 kg) during a submaximal stepping exercise. However, during live firefighting exercises, no difference in heart rate was attained by Manning and Griggs (1983), who also compared light (7 kg) and heavy (15 kg) SCBA cylinders. This latter finding may be due to the near maximal heart rate commonly encountered during firefighting activity (Sothmann et al. 1992; Smith and Petruzzello 1998; Barr, Gregson, and Reilly 2010), or that energy expenditure during live firefighting activities is not reflected solely by the heart rate achieved. However, Manning and Griggs (1983) pointed out that the benefit of lighter SCBA is most likely to be seen as a reduced time to complete a given task as opposed to a reduced physiological load. Like Manning and Griggs (1983), we did not detect a significant difference in heart rate due to operating with different size (and weight) SCBA. We also did not detect an impact on the work performance (in our case, the amount of work completed instead of time to complete a given task) when wearing different size SCBA. Furthermore, the modern, commercially available SCBA utilised in this study are relatively more similar to the 'lightweight' SCBA used by Hooper, Crawford, and Thomas (2001). The maximum weight difference between cylinders in this study was less than 4 kg, while the 'heavy' cylinder used by Hooper et al. (22 kg) was 12 kg heavier than the 'lightweight' cylinder. Hence, a 12 kg difference in load may impact physiology while the 4 kg difference is not significant enough to cause a change.

SCBA design did have a statistically significant impact on peak core temperature, $Tco_{peak,FF}$, and $Tco_{peak,Tot}$ (Table 2). The lower core temperature values measured in the low-profile prototype design (P45_1B) relative to the standard cylinder design (S60_1B) may be attributed to less muscular work being performed to move the SCBA while completing a statistically equivalent amount of external work. Previous work by Coca et al. (2011) suggested that the same prototype SCBA allowed subjects increased range of motion, mobility and comfort relative to the standard SCBA. Subjects may not have been restricted by the prototype SCBA with the increased range of motion, resulting in less effort needed to complete each task. This may account for the lower core temperature observed in the low profile prototype SCBA relative to the traditional single cylinder SCBA of similar size. It is important to note that these differences, while statistically significant, are quite small in magnitude (on average about 0.2 °C).

4.2. *Effect of work cycle*

The design of this study allowed for the ability to quantify the effect of rest prior to a second bout of simulated firefighting activity. As in previous work, during a single bout of simulated firefighting activities, subjects reached near maximal heart rate, with heart rate continuing to increase during subsequent bouts (Smith et al. 1996; Walker et al. 2015; Hostler et al. 2016). Subjects had lower HR_{peak} values when there was a break between bouts (S60_2B) than when no break was provided (S60_BB), likely due to the recovery in heart rate which occurred during the 5-min break between bouts in the 2B condition. While the break may have resulted in lower HR_{peak} values than in back-to-back bouts, these values were still greater than for a single bout of activity (S60_1B).

Rate of core temperature increase in the first bout of the two-bout trials was 0.035 ± 0.023 °C/min. During the second bout the rate of core temperature increase was 0.039 ± 0.014 °C/min in the condition with the five minute rest (S60_2B). However, when there was no break (S60_BB), rate of core temperature increase was notably higher 0.062 ± 0.017 °C/min. While the rest period does appear to reduce the rate of accumulation of heat stress during the work, the 5-min rest period does not provide a significant reduction in total overall core body temperature. Firefighters should be aware that firefighting activity can rapidly lead to elevated core temperature values, and longer work cycles, especially without rest, can result in greater rates of core temperature rise.

The changes in firefighters' self-perceptions were remarkably worse after the two bout activities compared to the single bout of activities (Table 3). Prior to beginning all scenarios, on average, firefighters were able to 'Breathe OK' (1.1–1.3), felt 'Good' (3.4–3.7), and were 'Comfortable' (4.0–4.3). After the single bout activities, firefighters felt as if they were 'Starting to Breathe Hard' (3.8–3.9), felt 'Fairly Good' (0.3–1.0), were 'Hot' (5.9–6.0) and that their exertion was 'Hard' (15.8–16.0). However, after the two bout activities, firefighters felt as if they were almost 'Not Getting Enough Air' (4.5), felt 'Fairly Bad' (−1.2 to −1.6), were 'Very Hot' (6.7–6.9) and that their exertion was 'Very Hard' (17.9–18.1). These perceptual differences mirror physiological changes measured after a second bout of simulated firefighting activity, though these perceptions were unaffected by the 5 min rest (2B) versus no rest (BB).

The increased physiological strain induced by a second round of activity and cumulative fatigue may explain the decreased work output, reduced $\dot{V}O_{2Peak}$ and changes in $\dot{V}_E$ (Table 5). Significant declines in work output were measured in each simulated firefighting activity in the second bout compared to the first bout: −10.4% in stairs, −22.4% in hose advance, −26.8% in search, −18.3% in overhaul. It is apparent that the average firefighter's work capabilities are diminished shortly after beginning work on the second cylinder of air. Despite firefighters reporting that they feel 'fairly good' (~1 on Feeling Scale) after their first cylinder of air, upon returning to work they have an immediate reduction in work output on the stairs. This decline in capabilities was larger in magnitude for the remaining three simulated firefighting activities. Every firefighter was able to complete the stair climb activity during the second bout. However, during the hose advance and subsequent activities, some firefighters began to remove themselves due to fatigue.

The reduction in work output and $\dot{V}O_{2Peak}$ tended to be larger for the second bout of activity in the back-to-back condition than in the trial where the two bouts were separated by a 5 min break.

Importantly, the total amount of work completed during the stair, hose advance and overhaul stations was lower in the back-to-back condition than when a 5-min break was presented between bouts (Table 5). However, there were no significant differences in the peak heart rate for each activity between S60_2B and S60_BB. The fact that work output and oxygen consumption were lower in the trials in which no rest was provided, but peak heart rate was the same highlights the challenge of relying on this easily quantified physiological measure as an index of fatigue. When firefighters are instructed to perform work at 'fireground pace' – especially when activity continues beyond 15 min – they will often be working near their physiological limits. Working at a high percentage of physiological capacity will induce physiologic fatigue, resulting in decreased work output. It should be noted that while more work was completed in the scenario where a 5-min break was provided compared to working without a break, the difference was relatively small and was still significantly less than what could be accomplished in the first bout of activity.

On average, during the simulated firefighting activities, peak $\dot{V}_E$ was approximately 79 L/min, or nearly twice the standard 40 L/min consumption rate that is utilised to estimate duration of SCBA cylinder. Our highest observed peak $\dot{V}_E$ value across all activities and conditions was less than the 103 L/min test level in NFPA 1981. While $\dot{V}O_2$ was significantly lower for all activities in Bout 1 vs. Bout 2, differences in $\dot{V}_E$ were much smaller. Indeed, for the stair climb activity $\dot{V}_E$ increased by 10%, similar to the increases in air consumption reported by Walker et al. (2015), but was not significantly different in any of the other activities. In the second bout of activity, the body was consuming less oxygen as less work was being conducted, yet minute ventilation did not significantly differ between the two bouts. This may reflect the effect of higher body temperature on breathing rate. Combined with the results above, we see that firefighters completing a second bout of activity will consume nearly the same amount of air as their first bout of activity, but will be able to complete less fireground work.

It is critical that fire officers understand that firefighters who are sent back to live-fire activities after a quick air cylinder change for a second 30-min cylinder, or are continuously working through a 60-min air cylinder, may not have the same operational capabilities as those who are just beginning work. NFPA 1584 standards suggest that firefighters should report to an area designated for fireground rehabilitation after completing 2 bouts with a 30-min cylinder or a single bout with a 60-min cylinder (National Fire Protection National Fire Protection Association 2008). However, our data suggest that significant rest and recovery should be provided after the first bout of work if operationally feasible or overall work output may decrease.

4.3. Completion

In addition to the reduction in work output during the second bout of firefighting activity, we also found that more than one-third of the subjects felt that they were too tired, too hot, nauseous, dizzy or otherwise felt it was unsafe to complete at least one of the two bout activities. These 11 subjects had lower fitness levels, were heavier, and higher BMI compared to the 19 subjects who were able to complete both bouts on all conditions. There was no significant difference between the age distributions in each group. The BMI for those able to complete all trials was at the threshold between normal and overweight (BMI = 25 kg/m^2), while the BMI for those unable to complete at least one of these trials was at the threshold between overweight and obese (BMI = 30 kg/m^2) (National Research Council Committee on Diet and Health 1989). Average $\dot{V}O_{2max}$ for all 30 subjects tested was 43.7 ml/min/kg, which is similar to $\dot{V}O_{2max}$ data reported by Barr, Gregson, and Reilly (2010). The average of those who did not complete at least one trial of simulated activity ($\dot{V}O_{2max}$ 40.3 ml/kg/min) is below the NFPA 1582 (National Fire Protection Association 2013a) suggested minimum level of 42 ml/min/kg, while the group who successfully completed all trials had an average $\dot{V}O_{2max}$ of 45.7 ml/min/kg, significantly above this threshold. Poor fitness is associated with lower maximal $\dot{V}O_2$ (Saltin et al. 1968; McGuire et al. 2001). Firefighters are commonly warned about the impacts of high body mass and low fitness on their risks for fireground injury and sudden cardiac events. These data provide compelling evidence that low fitness and excess fat also impair work performance on the fireground.

5. Summary and conclusions

We examined the effects of SCBA size and design, as well as effects of repeated bouts of simulated firefighting activity on firefighter's physiological and cardiorespiratory responses, using realistic firefighter activity simulations in a controlled laboratory environment. Heart rate, core temperature, $\dot{V}O_2$, $\dot{V}_E$, work output and self-reported perceptions were analysed. We found few significant differences in physiological response when wearing commercially available air cylinders of a wide range of size and air capacity (30, 45 and 60) for a single bout of simulated firefighting activity. The one exception was a small (~0.2 °C) but significant difference in maximum core temperature, with core temperature slightly higher when the 60-min cylinder was used relative to the standard 45-min cylinder and the prototype 45-min design.

Extended work cycles, involving a second bout of simulated firefighting activity, resulted in a significantly higher heart rate and core temperature values relative to a single bout, similar to what has been measured during simulated training and fire response. Importantly, the protocol utilised here provided the first opportunity to quantify changes in work output during simulated extended duration firefighting activities. When no rest was provided prior to the second bout, core temperatures increased by more than 0.06 °C/min, and peak heart rates were higher and the reduction in work output was more significant than when a 5 min rest was provide (simulating the work-rest cycle employed for traditional 30 min air cylinders). Overall, subjects completed approximately 20% less work in the second bout of activity than was accomplished in the first bout of simulated firefighting activity. Notably, 11 of the 30 subjects tested were unable to complete all conditions during the second bout. Those who were unable to complete all of the trials involving a second bout of firefighting had lower fitness levels and larger body mass index than those who were able to complete all activities.

The use of extended duration SCBA cylinder should be approached by the fire service with a holistic view of potential impacts. This study found minimal differences in physiological parameters caused by increasing weight of extended duration SCBA when a single 14-min bout of simulated firefighting activity was performed (a timeframe that was traditionally necessitated by '30 min SCBA'). However, we found significant decreases in work output and increases in physiological strain when performing longer activities. This finding is exacerbated when no break is provided between bouts of activity, an option that is only possible with extended duration SCBA cylinders. These findings suggest that extended activity leads to impaired work performance and potentially increases the risk of injury on the fireground. Importantly, fire officers need to understand that a firefighter who is sent back to live-fire activities after a quick air cylinder change for a 30-min cylinder, or is continuously working through a 60-min air cylinder, may not have the same operational capabilities as those who are just beginning work.

Disclosure statement

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