Effect of SCBA Design and Firefighting Induced Fatigue on Balance, Gait and Safety of Movement

ILLINOIS FIRE SERVICE INSTITUTE

IFSI RESEARCH

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

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1 Acknowledgements

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3 Terms and Abbreviations

STF – Slip, trip and fall
SCBA – Self-contained breathing apparatus
O/E – Overexertion and strain
EOSTI – End of Service Time Indicator
PPE – Personal Protective Equipment
GRF – ground reaction force
COM – center of mass
BMI – Body Mass Index (weight (kg)/(height (m)2))
HR – Heart rate
VO2 – Oxygen Consumption
PVT – Psychomotor vigilance test
Tco – Core Temperature
FAS – Firefighter Activities Station
FBT – Functional balance test
RPE – Rating of perceived exertion

4 Abstract

Here we presented a report for the Fire Service documenting an examination of the effect of SCBA and firefighting induced fatigue on firefighters' gait, balance, and safety of movement. More detailed, peer-reviewed scientific reports can be found in academic literature and are available at the Illinois Fire Service Institute.

Fireground operations are inherently dangerous, with overexertion/strain and slips, trips, and falls being the two leading causes of injury. 26.5% of fireground injuries are a result of overexertion or strain, conditions which may be accelerated by the fact that firefighting activities can induce near maximal heart rates and elevated core temperatures. The high levels of effort and exertion needed to complete such activities may be made worse by the firefighter's turnout gear and self-contained breathing apparatus (SCBA).

Anecdotal evidence suggests a trend in the Fire Service toward extended duration SCBA (greater than 30-min), which may further increase the physical demand on the firefighter.

Further, nearly 23% of fireground injuries are the result of a slip, trip, and/or fall. These injuries often occur while or following firefighting activities, and may often be a result of the fatigue those activities have induced in the firefighter. Extended duration SCBA are typically heavier and may reduce the time before the firefighter becomes fatigued.

Thirty firefighters were recruited to take part in repeated-measures study to examine the effects of SCBAs and duration of work cycle have on physiological strain, balance, gait, and safety of movement. Firefighters completed seven different conditions with various SCBA (30, 45, and 60-minute standard cylindrical SCBA and a low-profile 45-min prototype) and durations of simulated firefighting (one or two bouts) in a heated environmental chamber (117°F (47°C)). Four activities were performed (stair climb, hose advance, secondary search, and overhaul) on two-minute work-rest cycles. Subjects also completed an obstacle course designed to test their gait and functional balance prior to, and immediately after the simulated firefighting activities.

Following firefighting activity firefighters had elevated heart rates and core temperatures. The firefighters also generally performed worse in the obstacle course. The size of the SCBA had a minimal impact on the firefighters, though it did decrease the performance on a Functional Balance Test. The low-profile prototype SCBA impacted the firefighters in a similar manner as the traditional cylindrical SCBA, though firefighters generally took longer to pass through a 16-inch on-center stud space.

When firefighters completed multiple bouts of simulated firefighting activity heart rates and core temperatures were elevated relative to a single bout while the number of repetitions performed during each activity decreased. Performance during the obstacle course was also more negatively impacted following a second bout of activity than after a single bout.

5 Background

5.1 Motivation

5.1.1 Injuries and Safety of Movement

In 2013 there were 65,880 total firefighter injuries. While this number has been steadily decreasing over the past 30 years and is the lowest since analysis began in 1981 (down from 103,340 injuries in 1981), the rate of injuries has remained relatively constant at about 23 injuries per 1000 fires [1]. The two leading causes of firefighter injury on the fireground are overexertion/strain and slips/trips/falls (Figure 1).

Slip, trip, and fall (STF) injuries are the second leading cause of minor injuries and the leading cause of firefighters' moderate to severe injuries; respectively accounting for 20% and 28% of all fireground injuries from 2005-2009 [2]. Further, STF injuries are the only causes of injury which have a higher percentage of moderate to severe injuries than minor injuries [2]. Icy, slippery, and uneven surfaces account for the greatest numbers of severe and moderate STF injuries at nearly 44% (over 12% of all moderate and severe injuries) [2]. Results from a 2008 survey of 148 firefighters indicated icy, wet, and uneven terrain accounted for three of the top four causes of slips, trips, and falls while equipment (including hose, apparatus, self-contained breathing apparatus (SCBA), and other objects) contributed to four of the top ten causes [3]. Stairs were involved in nearly 10% of fireground injuries, the fifth most prevalent cause [3].

Accidents due to STFs resulted in the longest work absences for firefighters [4]. In an analysis completed in 2003, the average total worker's compensation claim per STF injury was $8,662, which is well above the mean of all claims - $5,168 [5]. These statistics indicate that changes in safety of movement (gait, balance, and situational awareness) have significant implications for personnel and insurance costs. Despite the high rate and cost of STF events, there has been relatively little scientific study on changes in safety of movement due to firefighting activities while wearing structural firefighting protective equipment (PPE). Two studies have focused on the effect of each component of firefighter's PPE on mobility, both of which determined that the firefighters' SCBA has the most detrimental effect on functional balance [6] and restriction to movement [7].

Firefighting activities involve inherently physical tasks, many of which are made more demanding by the environment the work is conducted in along with the tools and equipment needed to complete the tasks and protect the firefighter. The increased restriction in movement caused by firefighting SCBA is likely to be a significant contributor to overexertion (O/E) injuries in part as a result of increased effort and exertion (metabolic stress) needed to move while wearing an SCBA. The bulk of O/E injuries on the fireground are attributed to handling a hoseline and during overhaul operations [8], both of which require significant upper body movement that can be restricted by the weight and design of the SCBA. These operations require moving a moderate amount of weight for a relatively long time, which increases metabolic stress and may lead to fatigue re-

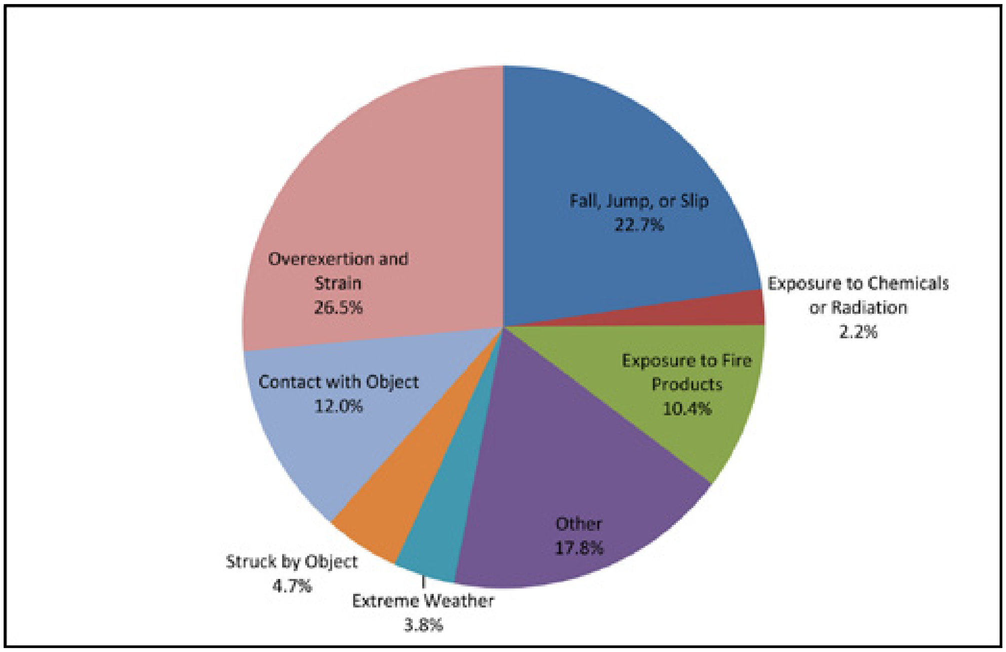


Figure 1. Fireground injuries by cause in 2013.
22.7% of all injuries were the result of a fall, jump, or slip [1].

lated injuries. Furthermore, high environmental temperatures increase heat stress which hastens the onset of muscular fatigue, causes dehydration, increases cardiovascular strain, and interferes with cognitive function [e.g. 9, 10]. These factors all can contribute to overexertion/strain injuries, can effect movement biomechanics and reduce an individual's ability to maintain situational awareness of the surrounding physical space.

This report examines the impact of SCBA size and design on firefighters' safety of movement (gait, balance, and situational awareness) before and after bouts of simulated firefighting activity in an effort to further educate firefighters about the risks and potential causes of STF and O/E injuries on the fireground.

5.1.2 SCBA Trends in the Fire Service

Anecdotal evidence suggests that there has recently been a significant increase in the purchase and utilization of extended duration ("45 minute" or "60 minute") air cylinders in the Fire Service, which is suggested to be partially driven by the recent change in the end of service time indicator (EOSTI) from 25% to 33% capacity in NFPA 1981 [11]. This trend is also driven by specific departmental needs such as in rapid intervention team (RIT) scenarios and HAZMAT operations, as well as in departments performing significant high-rise operations. Increased usage of extended duration SCBA has also been attributed to concerns with running out of air, which may result in smoke exposure and risk of asphyxiation. However, with the increased work time allowed by extended duration SCBA, firefighters may move further into the structure and may require longer egress times, possibly working longer and experiencing a higher level of fatigue.

Karter reported that between 2003 and 2006, on average 8,715 firefighters suffered an injury from STFs while an additional 9,235 firefighters were injured by overexertion, yet only 910 firefighters were injured by exposure to fumes, gases or smoke [8]. Examination of three NIOSH line of duty death investigations over the last 8 years which specifically cite firefighters running out of air also generally involve firefighters becoming lost, trapped, or disoriented [12-14]. In New York in 2010, a lieutenant was trapped when the floor collapsed under him, and a firefighter also became trapped trying to rescue the lieutenant. Both were found with their masks off and empty 30-min SCBA [12]. In 2006 and 2012, firefighters became disoriented after the low-air alarm sounded and were unable to exit the structure before running out of air [13, 14]. Examples such as these are commonly cited for the need to employ extended duration SCBA, but it is unclear if such a change would have resulted in a different outcome.

While the utility of the additional air volume from extended duration air cylinders has not been proven operationally, researchers have found that most of the physiological strain caused by firefighting SCBA can be attributed to weight [15], which would increase with the use of longer duration SCBA cylinders. In recent studies, we have shown that heavier SCBA bottles significantly impact firefighter gait performance [16] and balance [17, 18]. At the same time, conducting firefighting activities with a heavier load is likely to increase the rate of fatigue development, and by working for a longer period of time, the demands on the body's systems (level of metabolic stress) and overall fatigue may increase. There have been no previous scientific studies on the interaction between firefighting activity and SCBA size and design on firefighter balance, gait, situational awareness, and metabolic stress.

5.2 Background Literature Review

5.2.1 Effect of Personal Protective Equipment on Physiology and Biomechanics

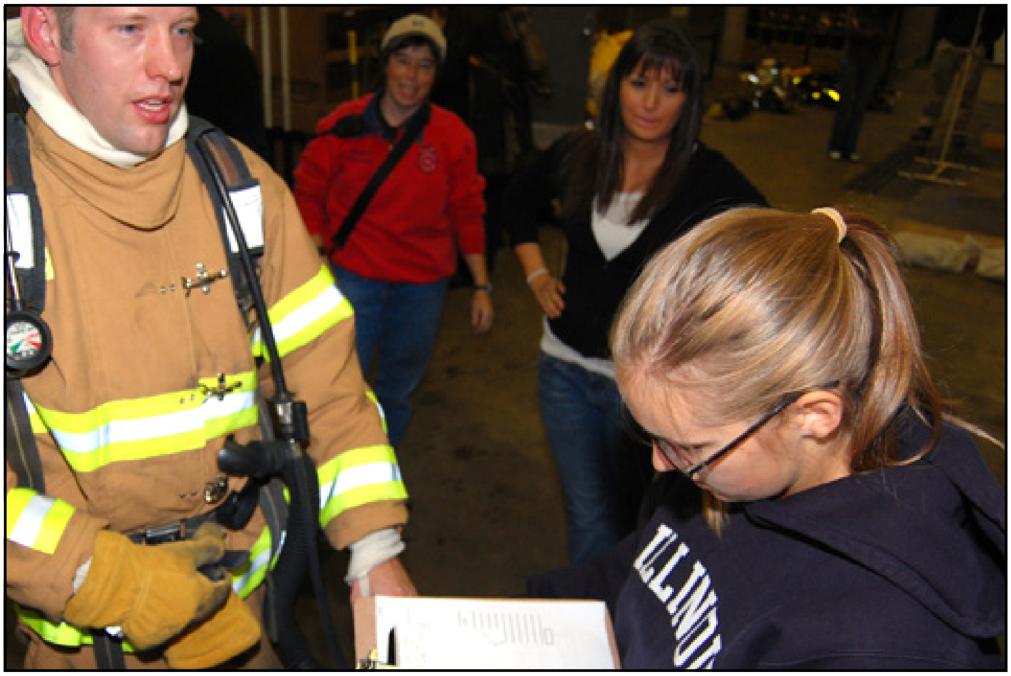
Data indicate that slip, trip, and fall injuries (STFs) are a serious problem among firefighters on the fireground [2], however there is limited research examining how firefighters movement is affected by working in structural firefighting personal protective equipment (PPE). There are changes in balance due to wearing different types of PPE, which has been quantified by measuring the sway of the body during standing balance tests (postural sway) [6, 17, 19, 20]. The results of these studies are varied, as two studies have found increased sway when wearing heavier PPE [6, 17], and another study reported a reduction in sway after donning PPE [20]. The effects of wearing PPE on gait and functional balance (the balance required to complete a movement, similar to body control) are more clear, with PPE decreasing uphill walking speed and endurance [21] and causing more errors and slower speed when performing a functional balance test [18, 22]. Additionally, wearing PPE while walking on a slippery laboratory surface significantly increases fall risk compared to walking on the same surface without PPE [23]. We have found an increase in trip risk when stepping over an obstacle while wearing firefighting PPE compared to station blues [24]. The increased risk for STF injuries may be attributed in part to reduced mobility from wearing PPE [7, 25] and changes in a firefighter's center of mass (COM) caused by the additional weight and its distribution on the body [17, 26].

PPE also adds to the physiological stress (higher heart rate and greater core temperature change) experienced while completing a task, and reduces heat dissipation because the PPE encapsulates the firefighter, reducing the exchange of body heat between the firefighter and outside environment. Thus, wearing PPE compounds issues related to heat stress and fatigue when working in a hot environment [27-30]. The specific design of firefighting PPE (bunker-style gear versus traditional long coat style PPE) can influence thermal and cardiovascular strain in a laboratory setting [30] and the time needed to complete a firefighting task during a live-fire training evolution [29]. Attempts to redesign current bunker-style gear to reduce heat stress have not been successful [31]. Other studies have investigated the effects of specific elements of modern firefighting PPE. Two studies have found that increased boot weight and less flexible designs increase the metabolic demand on the firefighter and reduce clearance when stepping over obstacles [32, 33]. Another group of studies examined the conventional versus chemical/biological prototype PPE and found the prototype gear to be less comfortable and have no significant cooling effects, with no improvement in the firefighters' ability to move with the gear on [34, 35].

5.2.2 Effect of SCBA on Physiology and Biomechanics

Wearing SCBA has been found to negatively impact physical performance [6, 7, 21, 36-38]. The addition of SCBA to other PPE increases fatigue [36], restricts movement [7], reduces maximal exercising time and maximal inclined walking speed [21], decreases balance [6], increases breathing resistance [37] and is significantly associated with fall occurrences among firefighters [38].

Decreasing the mass of SCBA has been suggested as the most important factor toward improving a firefighter's ability to safely conduct firefighting tasks [21]. Several groups have studied the physiological effects of SCBA weight, showing that lightweight SCBA resulted in lower energy expenditure during submaximal exercise [39]. However in other studies utilizing live firefighting exercises, lightweight SCBA had no impact on heart rate [40]. This latter finding may be due to the near maximal heart rates commonly encountered during firefighting activity, or that energy expenditure during live firefighting activities may not be reflected by the heart rate achieved. However, it has been suggested 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 on the firefighter [40]. We have studied the effect of SCBA design (carbon fiber versus



aluminum 30-minute cylinders) and found that lighter designs result in lower ground reaction forces (GRF, the force exerted by the ground equal but opposite to the force of the firefighter stepping down) in both the anterior-posterior (front-back) and vertical directions, indicating the firefighter does not step down or push forward/backward as hard with the lighter designs. Further, when using lighter SCBA, subjects made contact with a 30-cm tall obstacle fewer times during trials which required stepping over an obstacle. This suggests that lighter weight SCBA may reduce risk for slips and trips on the fireground [16]. We have also measured increased sway during standing balance tests with heavier SCBA cylinders compared to lighter SCBA [17]. Decreased functional balance abilities caused by donning SCBA has also been documented, specifically in those firefighters who do not engage in regular resistance training [22].

5.2.3 Effect of Load Carriage on Physiology and Biomechanics

Several studies have investigated the effect of load-carriage on the postural stability of military personnel, adults, and children. In all cases, stability while walking has been found to be influenced by the weight of the load carried [41-45]. Load-carriage has been shown to cause changes in biomechanical parameters (increased body sway and larger ground reaction forces) indicating that adding a load on the back deteriorates postural stability [41, 44]. In general, studies on gait and load carriage have shown that walking velocity decreases and double support time (time with both feet in contact with the ground) increases when individuals carry heavier loads [42]. More specifically, increasing the amount of weight carried by soldiers challenged their stability [44] and posture may be affected by changing the center of mass (COM) of a backpack. One study has shown that placing the backpack COM close to the body COM minimized energy cost [45].

Additionally, carrying weight on the back in a backpack has been shown to result in significant physiological strain including increased heart rate, breathing rate, and oxygen consumption during submaximal exercise [15, 26, 46-48]. Generalizing these studies to firefighting SCBA suggests that designs which bring the COM closer to the firefighter's core have potential to reduce the physiological strain (heart rate, breathing rate, and oxygen consumption) experienced during structural firefighting activities and thus improve the firefighter's safety, though Park et al. [16] has shown that these changes to COM do not affect the firefighters biomechanics during obstacle crossing.

5.2.4 Effect of Fatigue on Gait, Stair Crossing, and Obstacle Crossing

While fighting a fire, heat stress and the resulting rise in body temperature and heart rate have a variety of effects including: accelerating the onset of muscular fatigue and dehydration, increasing cardiovascular strain, and interfering with cognitive function [9, 10]. The onset of muscular fatigue may be a contributing factor to slips, trips, and falls as well as overexertion injuries by impacting firefighters' biomechanics. Thus, it is necessary to understand how physiological strain due to firefighting activity combined with PPE design affects mobility and slip, trip, and fall risk.

Numerous studies in athletes and the general population have shown that fatigue can cause significant postural instability which may lead to injury [49-61]. For example, athletes may be at increased risk after competition [49] or training [50]. This risk can also apply to firefighters who must function after or during strenuous activities in which the firefighter can reach near maximal heart rates and energy expenditures have been estimated as high as 12 METs [62] (12 times the energy used by the body during rest). Unfortunately, the general fitness level of many firefighters may not match that of trained athletes. It is apparent that acute fatigue can result in muscular strains [59] as well as alterations in coordination [60] that can lead to injuries. Further, more mental effort is needed to control balance even after mild fatigue [61]. This increased mental demand may lessen the ability to make safe decisions on the fireground.

The intensity of the exercise (amount of metabolic stress demanded) determines the extent to which fatigue affects stability [50-52]. For example, after young healthy adults completed strenuous physical exercise on a treadmill or bicycle, body sway was found to increase, but if this exercise was performed below the individual's estimated anaerobic threshold the effects were minimal [51]. Furthermore, the amount of time over which fatigue affects balance and gait varies significantly. Researchers have induced fatigue to the whole body through a maximal treadmill protocol, but the resulting decrease in postural stability was relatively short lived, with effects lasting six minutes following the completion of exercise [53]. Athletes performing 65ft shuttle runs in a different study returned to baseline levels of postural control within approximately 13 minutes from the end of exercise [50], which is similar to other reported recovery times [51]. On the other hand, another group of researchers measured impairments in postural control that lasted at least 30 minutes post-fatigue, regardless of whether the fatigue was localized to specific lower body joints (ankle/knee flexion and extension), or the lower body as a whole (repeated squat jumps) [56].

Two experimental protocols have investigated the effects of conducting simulated firefighting activities in PPE on gait characteristics. For example, a treadmill exercise protocol in a heated room showed increased gait variability after exercise [63], while we have measured a significant reduction in obstacle clearance distance and obstacle crossing errors after an 18 minute bout of live fire activities [24].

6 Specific Aims

The primary aims of this study were:

- To better understand the impact of SCBA design on
  a) metabolic stress (oxygen consumption, core temperature and heart rate) and
  b) safety of movement (gait and balance) of firefighters on the fireground.

We investigated the effect of bottle design by comparing conventional cylinder designs with a prototype low profile design and the interaction of these designs with firefighting induced metabolic stress.

- To quantify the effect of extended duration SCBA on
  a) firefighters' safety of movement pre- and post-firefighting and
  b) metabolic stress generated during simulated firefighting activities,
  c) with particular interest on the interaction between safety of movement with firefighting induced fatigue.

We tested the effects of extended duration bottles by examining several different conventional cylinder designs (30-min, 45-min, and 60-min) over different durations of simulated firefighting activity (1-bout and 2-bout).

7 Procedure

7.1 Study Design

Thirty subjects participated in this study, which included one baseline visit and seven different trials using various combinations of SCBA configurations and durations of simulated firefighting activities. During the initial baseline visit participants were fully informed of the purposes of the study and provided informed written consent indicating that they understood and voluntarily accepted the risks and benefits of participation. This study was approved by the University of Illinois Institutional Review Board.

Each participant's age, height, weight, chest depth, and leg length were recorded and body mass index (BMI) was calculated at the baseline visit. Participants were asked to complete 1) a health history inventory, 2) Physical Activity Readiness Questionnaire (PAR-Q), 3) a personality assessment, and 4) an Epworth Sleepiness Scale (ESS). A maximal exertion treadmill test (Figure 2) was conducted to determine maximal oxygen consumption (VO2,max) and heart rate (HRmax) using the following protocol:

- Begin the test by walking at 3.0 mph, 0% grade for 3 minutes.
- Speed was then increased to 4.5mph.
- Every 1 minute afterward speed and grade were alternately increased by 0.5mph or 2% grade until the participant voluntarily ended the test or became too fatigued to continue.

For each data collection session, all participants followed the timeline depicted in Figure 3. Six to 12 hours prior to arrival participants ingested a core temperature monitoring pill. Upon arrival participants completed a Fatigue Severity Scale (FSS) and sleep diary. Participants then completed the Psychomotor Vigilance Test (PVT) (Section 7.2.4.1) and were fit with a physiological status monitor and donned PPE and SCBA. Next, participants completed two laps on the obstacle course (Section 7.2.3). Following the obstacle course subjects rated their thermal comfort, breathing, and overall feeling (Section 7.2.2). They then donned their SCBA facepiece and hood, and entered the environmental chamber. Inside the chamber the firefighter was fit with a metabolic monitoring tool to measure oxygen consumption. Next the participant completed the assigned firefighting activities (1-bout, 2-bouts with break, or 2-bouts back-to-back). After exiting the environmental chamber, they removed their facepiece and hood, and again rated their thermal comfort, breathing, and overall feeling. They also expressed their rating of perceived exertion (RPE) during the completed tasks. Participants were then asked to complete the obstacle course two more times. Following the obstacle course, subjects doffed their SCBA and completed the PVT. They then removed their PPE and rehabbed for a minimum of ten minutes. Following rehab, subjects completed a questionnaire of the task difficulty (Task Load Index) (Section 7.2.4.2).

Figure 2. Maximal exertion treadmill test used to determine maximal oxygen consumption and heart rate.

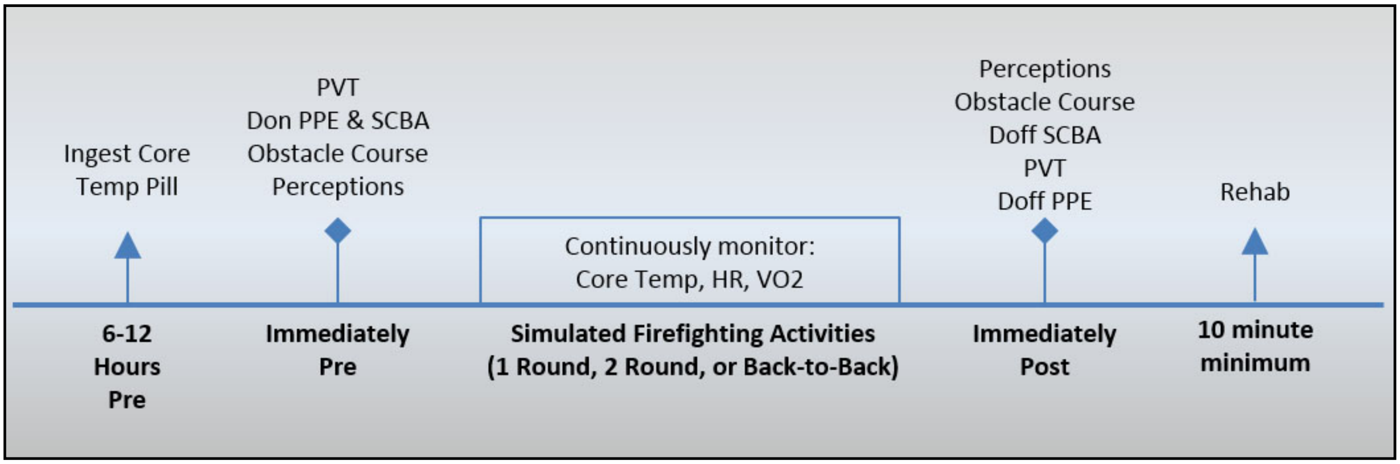


Figure 3. Schematic of timeline followed for all test sessions.

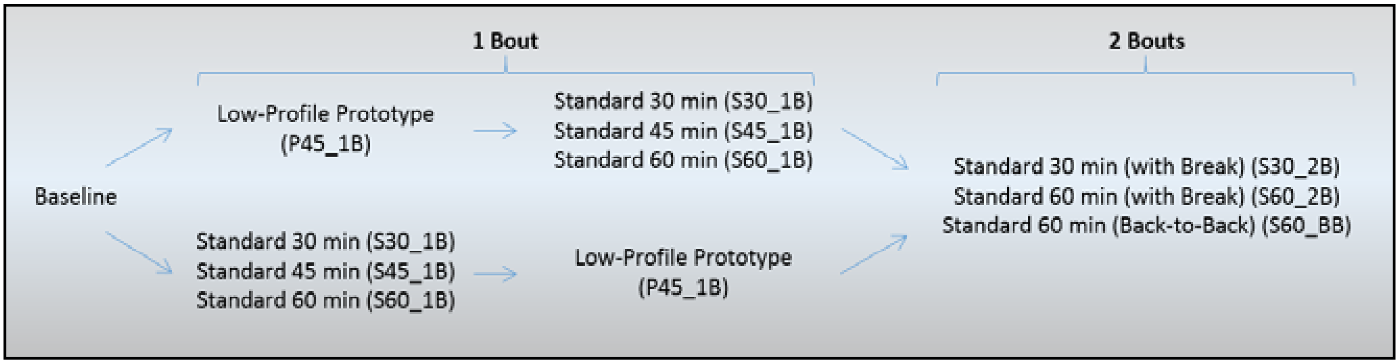
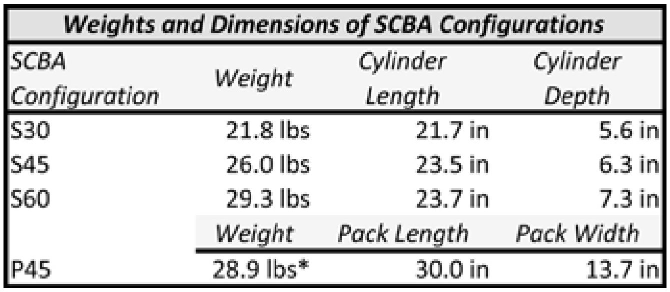


Figure 4. Schematic of trial order. Half of subjects performed a trial with the low-profile SCBA first, followed by the standard single bout trials in a counter-balanced order. Multiple bout trials were always performed last, also in a counter-balanced order.

The order in which simulated firefighting activities were introduced is described in Figure 4. A baseline trial was always performed first during which subjects were allowed to familiarize with the firefighting activities simulator and the obstacle course. The simulated firefighting activity scenarios included firefighters wearing either traditional, single-cylinder carbon fiber SCBA with durations rated for 30, 45, and 60 minutes (identified as S30, S45, S60 in this report) or a prototype low-profile 45-minute SCBA (P45). Physical characteristics of the SCBA are shown in Table 1 and Figure 5. Firefighters completed the activities outlined in Section 7.3.2 in a single bout (each activity only once) with each of these single-cylinder SCBA in a counter-balanced order so that each condition was presented second, third, and fourth an equal number of times. Half of the subjects completed the P45 trial following single-cylinder trials, while the other half completed P45 trial first. Three additional trials were then completed with firefighters wearing the 1) S30 SCBA and completing 2 bouts of activity with rest in between bouts, 2) S60 SCBA with 2 bouts of activity and rest in between bouts, and 3) S60 SCBA with 2 bouts of activity back-to-back. These three conditions were also introduced in counterbalanced order. Conditions were presented in this order to minimize effects of learning or familiarization with the tasks. Each trial was separated by a minimum of 24 hours.



Weights and Dimensions of SCBA Configurations

SCBA Configuration	*Weight*	*Cylinder Length*	*Cylinder Depth*
S30	21.8 lbs	21.7 in	5.6 in
S45	26.0 lbs	23.5 in	6.3 in
S60	29.3 lbs	23.7 in	7.3 in
	Weight	*Pack Length*	*Pack Width*
P45	28.9 lbs*	30.0 in	13.7 in

Table 1. Weight and size of SCBA.
****Measurements of the P45 were taken with pack empty.***

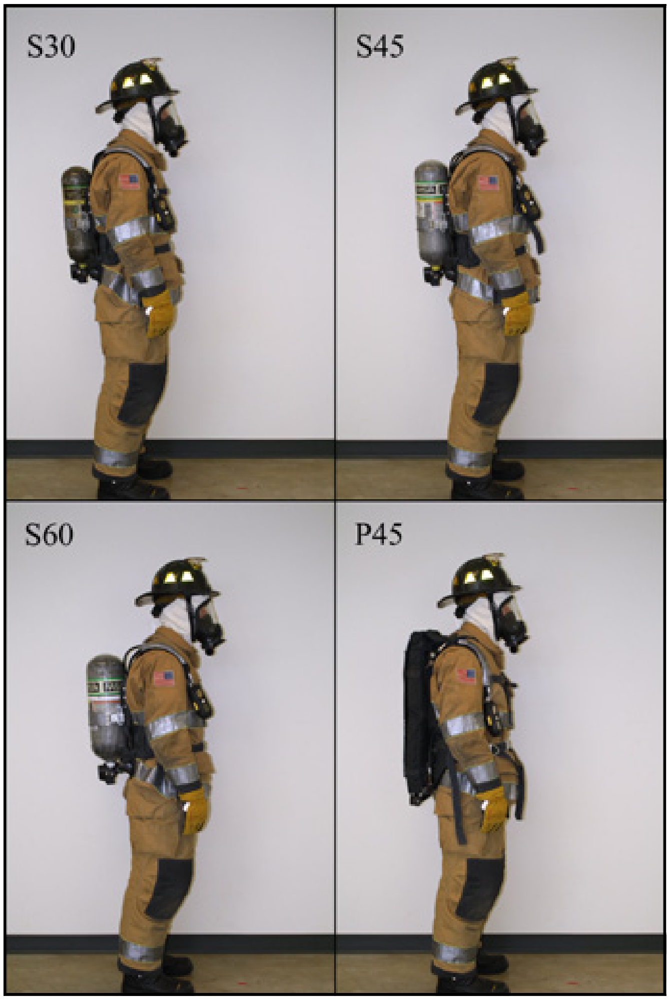


Figure 5. Side profile of various SCBA.

7.2 Measurement Techniques

7.2.1 Physiological Monitoring

Heart rate and core body temperature were continuously measured throughout all data collection sessions. Prior to completing each of the seven exercise protocols, participants were instrumented with a physiological status monitor (Equivital, Phillips Respironics, Andover, MD) worn on the chest to measure heart rate and communicate with and record data from the core temperature pill (Figure 6). Participants swallowed a small disposable core temperature sensor capsule (the size of a multivitamin), which passes through the body and is eliminated within ~24 hours. While the sensor was in the GI tract it transmits temperature information to the remote recording device.

Figure 6. Equivital and cheststrap with core temperature pill.

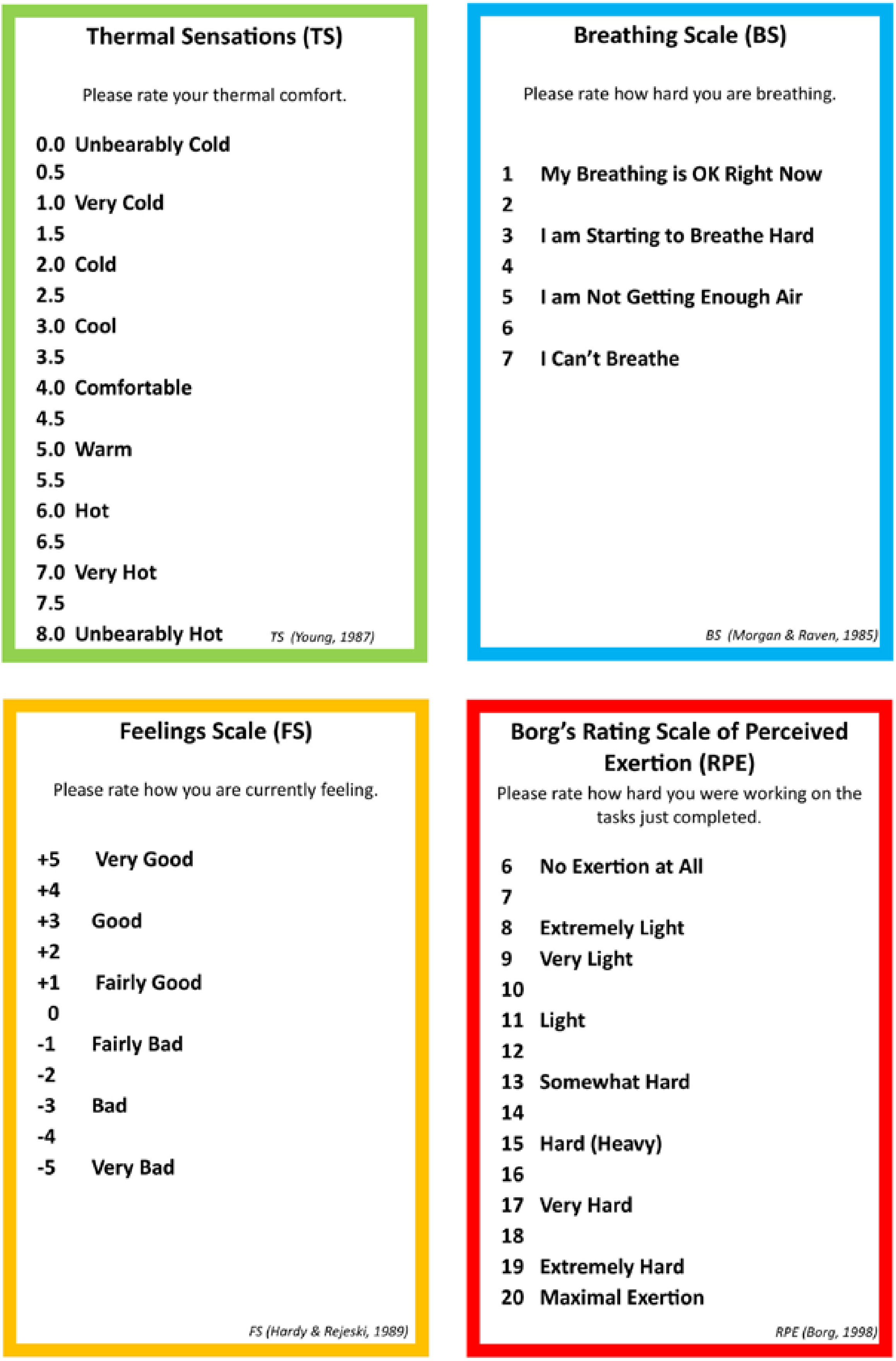
During the simulated firefighting activities participants wore a modified SCBA facepiece [64] which interfaced with a metabolic data collection tool (Cosmed K4b^2) to allow collection of metabolic data, specifically oxygen consumption (Figure 7).

Figure 7. Cosmed K4b2 and custom facepiece used to measure oxygen consumption.

While the participant was completing the simulated firefighting activities heart rate (HR), core temperature (T_{co}), and oxygen consumption (VO_2) were measured continuously, but the following measures were recorded to describe the activities: the maximum heart rate achieved (HR_{max}), the average heart rate during the activity (HR_{ave}), the maximum core temperature measured during the entire simulated firefighting activity ($T_{coMax,FF}$), the change in core temperature during the simulated firefighting activity ($\Delta T_{coMax,FF}$).

7.2.2 Self-Perceptions

In order to determine firefighter self-perceptions of their physical conditions before and at the end of the simulated firefighting activities, several self-response measures were collected (Figure 8). Perception of respiratory distress was assessed using the 7-point scale developed by Morgan and Raven [65]. Odd numbers on the scale are anchored with descriptions (e.g. "My breathing is okay right now," "I can't breathe," etc.). Perceptions of thermal sensations, ranging from "unbearably cold" to "unbearably hot" were assessed using the rating scale developed by Young [66]. Firefighters reported their overall feeling with the Feeling Scale developed by Hardy and Rejeski [67]. For this 11-point scale, anchors are provided at 0 (neutral) and at odd integers, ranging from -5 (very bad) to +5 (very good). Finally, a rating of perceived exertion was recorded immediately after the activity was completed using the 15-point, 6-20 Borg scale [68]. To complete this assessment, firefighters were asked to rate how hard they were working during the activity on a scale that ranges between 6 ("no exertion at all") and 20 ("maximal exertion"). Firefighters verbally responded to the questions for each scale and pointed to their level of exertion on a posted scale, which was verified and recorded by an investigator.



Thermal Sensations (TS)

Please rate your thermal comfort.

0.0	Unbearably Cold
0.5	
1.0	Very Cold
1.5	
2.0	Cold
2.5	
3.0	Cool
3.5	
4.0	Comfortable
4.5	
5.0	Warm
5.5	
6.0	Hot
6.5	
7.0	Very Hot
7.5	
8.0	Unbearably Hot

TS (Young, 1987)

Breathing Scale (BS)

Please rate how hard you are breathing.

1	My Breathing is OK Right Now
2	
3	I am Starting to Breathe Hard
4	
5	I am Not Getting Enough Air
6	
7	I Can't Breathe

BS (Morgan & Raven, 1985)

Feelings Scale (FS)

Please rate how you are currently feeling.

+5	Very Good
+4	
+3	Good
+2	
+1	Fairly Good
0	
-1	Fairly Bad
-2	
-3	Bad
-4	
-5	Very Bad

FS (Hardy & Rejeski, 1989)

Borg's Rating Scale of Perceived Exertion (RPE)

Please rate how hard you were working on the tasks just completed.

6	No Exertion at All
7	
8	Extremely Light
9	Very Light
10	
11	Light
12	
13	Somewhat Hard
14	
15	Hard (Heavy)
16	
17	Very Hard
18	
19	Extremely Hard
20	Maximal Exertion

RPE (Borg, 1998)

Figure 8. Self-reported perception scales.

7.2.3 Safety of Movement – Biomechanics Assessment Obstacle Course

Immediately before and after the simulated firefighting activities, participants passed through a biomechanics assessment obstacle course two times at "fireground pace." The course was designed to simulate movements/obstacles which are commonly encountered on the fireground (Figure 9). Throughout the obstacle course firefighters' boots were tracked using 3-dimensional motion capture cameras so that the research staff could determine the exact location of the firefighter. Further, time to complete each task and any errors committed at each station were recorded.

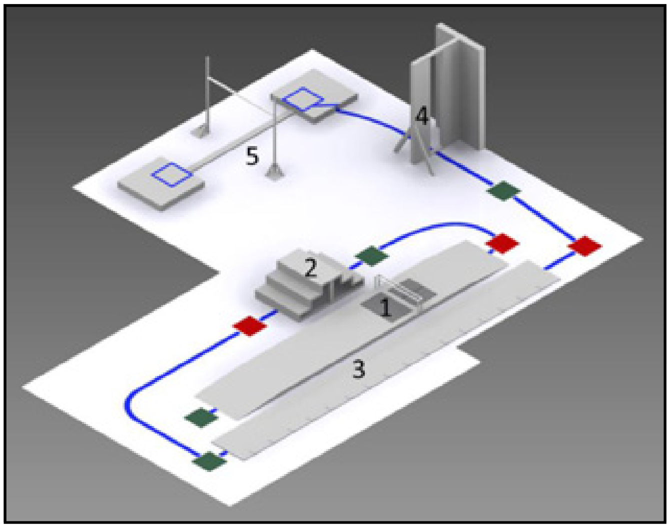


Figure 9. Three dimensional sketch of biomechanics assessment obstacle course.

7.2.3.1 Walkway

The first station involved walking along a straight path in which the firefighter must pass over an obstacle that is relatively challenging but short enough to walk over, such as a charged supply line on the fireground. A movable stick-figure frame obstacle (constructed from 0.6 in (1.5 cm) diameter polyvinylchloride (PVC) pipe), 11.8 in (30 cm) high by 47 in (120 cm) wide by 5 in (12 cm) deep) was placed in the walkway. Immediately before the obstacle, a large embedded force was placed to measure trailing foot (second foot over the obstacle) ground reaction force (GRF) data. Immediately after the obstacle, two smaller force plates were placed side-by-side to measure lead foot (first foot over the obstacle) GRF data. The clearances of the firefighter's boots over the obstacle (Figure 10 and Figure 11) as well as the number of times the firefighters contacted the obstacle were also examined. The ground reaction forces recorded are the forces the ground applies on the firefighter's foot

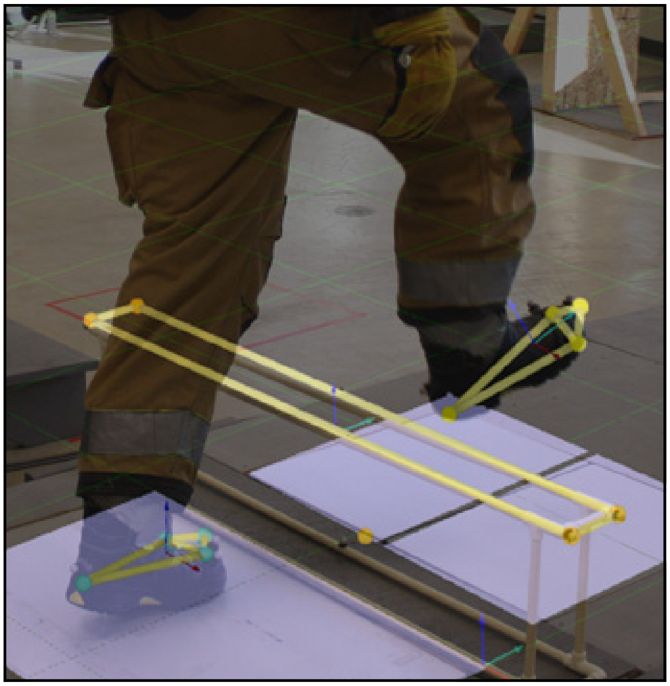


Figure 10. 3-dimensional computer recreation of firefighter stepping over obstacle using motion capture technology.

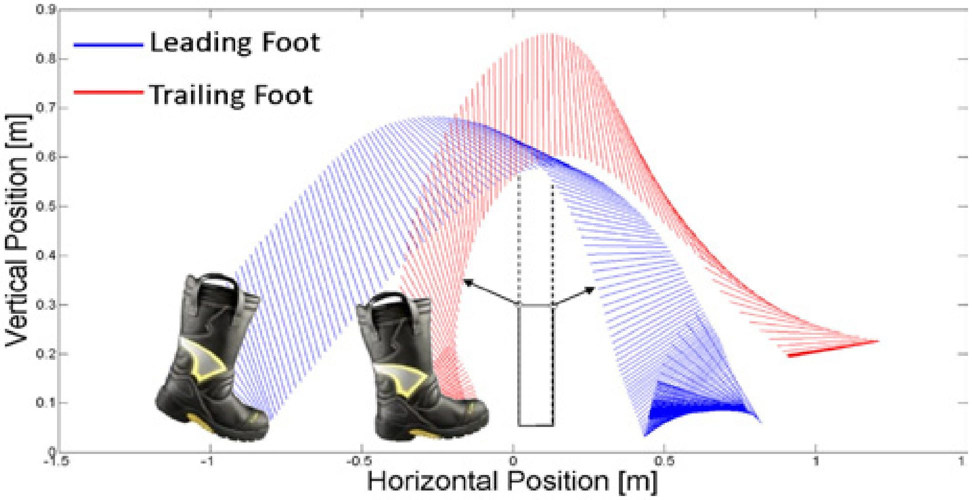


Figure 11. Trace of the boots over the obstacle. Minimum clearance between the boots and obstacle was examined.

in reaction to the firefighter stepping down. GRF forces can be broken down into the three directions the force acts (vertical, front/back, side to side). Both the vertical and front/back (also called anterior/posterior or AP) are comprised of early and late segments. Early stance is when the firefighter is landing on the ground while late stance is when the firefighter is pushing off the ground to start the next step.

7.2.3.2 Stairs

The second station involved walking up, over, and down a short staircase simulating the typical front steps a firefighter might navigate entering and exiting a single family home. The minimum clearance between the toe of the boot and the stair edge during ascent and between the boot heel and stair edge during descent were analyzed (Figure 12). At this station, subjects crossed a three step tall wooden-frame staircase (48 in (1.2 m) wide, 7.1 in (17.9 cm) rise, 10.9 in (27.7 cm) run) where the subject ascended one side and descended the opposite, always facing forward. The top surface was 22 in (56 cm) deep. A start box was placed 24 in (61 cm) from the start of the staircase and a stop box was placed 36 in (91 cm) from the final step.

Figure 12. Firefighter crossing stair obstacle.

7.2.3.3 Gait Mat

For the third station, subjects proceeded down a 26 ft (7.9 m) gait mat (GAITRite Platinum, CIR Systems Inc.). The mat consists of 80,000 one centimeter square force sensors which measure traditional gait parameters such as stride length (distance between the heels of the same foot), step width (distance between opposite feet), stride velocity (the speed of one stride), single support time (time only one foot is on the ground), and double support time (time with two feet on the ground) (Figure 13). To compare these gait parameters, the percent change between pre- and post-simulated firefighting activities was computed. Understanding the changes in gait parameters found following simulated firefighting activity may lead to safer movements on the fireground and a reduction in slip, trip, and fall injuries.

7.2.3.4 Standard Stud Space Opening

The fourth station was a fixed wall opening based on standard building practices (studs placed at 16-inches on-center) which a firefighter may need to pass through in an emergency situation (Figure 14). Different sizes and designs of SCBA can impact the way firefighters move through confined spaces on the fireground. This station allowed investigators to record the time necessary to pass through a standard stud space in various conditions in order to determine the impact of the SCBA size and design on the firefighter's speed through a confined space that may be encountered on the fireground. Firefighters were allowed to pass through the obstacle using any technique they desired, and allowed to shift or dump the pack if necessary.

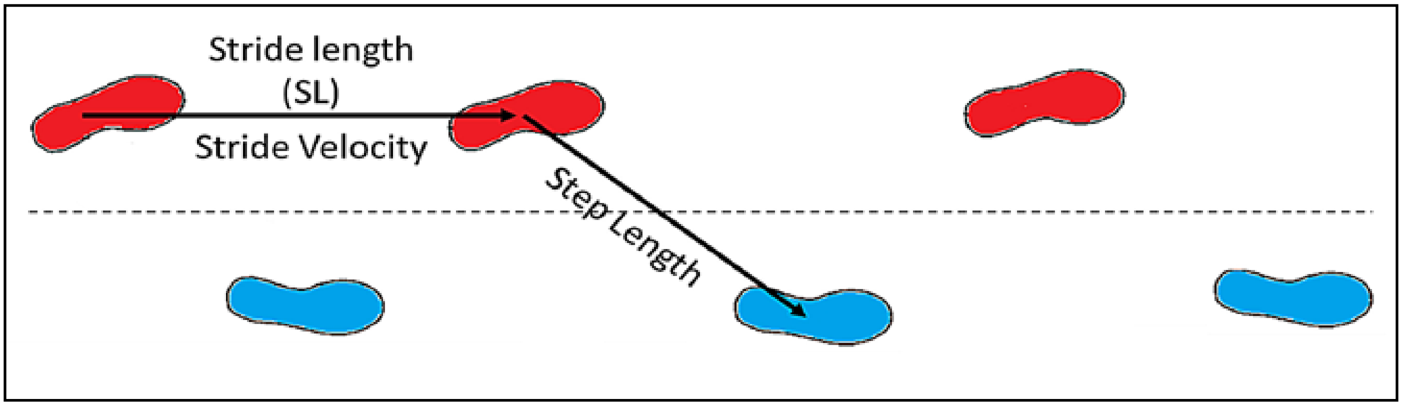


Figure 13. Gait parameters measured while firefighters walked on gait mat.

7.2.3.5 Functional Balance Test

The fifth and final station was a Functional Balance Test [18] (Figure 15). Subjects stepped from an elevated platform (6 in (15 cm) high) and crossed on a narrow beam (5.5 in (14 cm) wide, 10 feet (244 cm) long). Subjects then stepped up to another elevated platform, turned within a defined space (24 in x 24 in (61 cm x 61 cm)), and returned back to the original platform (Figure 15 and Figure 16). A second trial was repeated with a bar placed at 75% of the participant's height supported by posts 70 in (180 cm) apart. Errors were counted for placing a foot or hand on the ground, not turning within the defined space, or contacting the obstacle and time to complete the entire obstacle was kept. This obstacle was developed to assess firefighter's body control and functional balance while encountering obstacles which are more applicable to fireground conditions.

Figure 14. Firefighter passing through stud space.

7.2.4 Human Factors

7.2.4.1 Psychomotor Vigilance Test

To quantify changes in reaction time following each of the exercise protocols, each subject participated in a Psychomotor Vigilance Test (PVT) pre and post activity. The PVT is an attention and reaction time based test. Using a hand held device, participants pushed a designated button as quickly as possible after a target appeared on the device screen (Figure 17). The target appeared randomly every few seconds during the three minute test.

The PVT is typically used to predict decreases in performance caused by fatigue. The PVT provides an objective measure of alertness determined through simple response time on a track-

Figure 15. Firefighter completing Functional Balance Test.

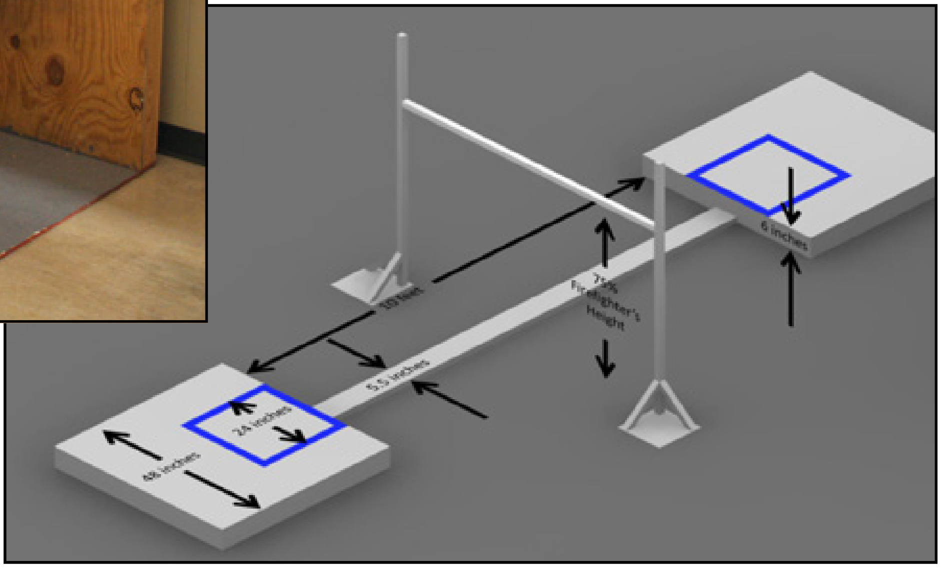


Figure 16. Schematic of Functional Balance Test (FBT).

ing test, that can be associated with sleep loss, extended work shifts or periods of wakefulness, and/or time on task [69, 70]. The traditional PVT test is 10 minutes long, though that length makes it impractical in applied settings [71, 72]. Accordingly, a 3-minute version was chosen for this study to reduce the time before the firefighter was able to cool down and rehydrate.

7.2.4.2 Task Load Index

The Task Load Index (TLX) was completed by the firefighter as they checked-out from the study each day (i.e. all activity and rehabilitation periods were completed) [73, 74]. The firefighter reported what he/she felt the physical and mental demands of the task were, the level of effort needed throughout activity, the frustration he or she experienced, and how he/she judged his/her overall performance. These different areas are weighted and averaged and a single Index (0-100) is reported.

7.3 Firefighting Drills

7.3.1 Environment

All simulated firefighting activities in this study were conducted in an environmental chamber adjacent to the obstacle course. The chamber was at 117°F (47°C) and 30% relative humidity. The environmental chamber measures approximately 9.5 ft (2.9 m) x 11 ft (3.4 m) x 9 ft (2.7 m).

7.3.2 Firefighter Activities Station (FAS)

Simulated firefighting activities conducted for this study were comprised of four activities completed on a two-minute work-rest cycle, similar to the legacy live-fire activities that have been conducted at IFSI for several decades [24, 27, 29, 31]. In order to replicate these activities in a controlled environmental chamber that has a smaller footprint than the IFSI burn buildings, the research team designed and built a compact Firefighting Activities Station (FAS). We conducted a detailed study of the FAS to ensure that firefighters who completed activities in the laboratory based environmental chamber would experience similar physiological responses as the simulated firefighting activities conducted in a live-fire structure to provide confidence in the ability of laboratory based studies to replicate more realistic live-fire scenarios. A model of the structure of the room can be seen in Figure 18 and photographic images of its use are shown Figure 19. The activities consisted of: (1) a stair climb in which the subject climbed to the second step on a three-step staircase (47 in (120 cm) wide, 7 in (18 cm) rise, 11 in (28 cm) run)), touched both feet to the second step, then stepped backward down the steps to ground level; (2) a simulated hose advance from the kneeling position, in which a section of hose was fixed to the low pulley of a modified gym exercise machine with 20 lb (9.1 kg) resistance during forward movement; (3) a simulated search, which included crawling around the perimeter of the room on hands and knees performing hand movements to locate victims and exits; and (4) a simulated overhaul task in which a pike pole was attached to the high pulley of the same modified gym exercise machine that required pulling weight of 20 lb (9.1 kg) from overhead. During the hose and overhaul tasks, one repetition was counted as beginning with the weight stack at rest, touching the end of the tool (either hose or pole) to a target located 70 in (1.8 m) from the first stair edge, and returning the weight stack to the resting position. Subjects performed these tasks with a self-selected technique, as long as they completed the full movement of the tool. Firefighters were instructed to perform all activities at a self-selected pace that simulated their effort on a fireground and were allowed to modify their technique or to rest at any time throughout the activity.

Walter Reed
Army Institute of Research
Psychomotor Vigilance Test

When each stimulus appears, press the side button as fast as you can to see your time in 100ths of a sec. Do not 'jump the gun'.

Press center UP button to start. (DOWN button to select User)

User: John Doe

Figure 17. The Psychomotor Vigilance Test measures reaction time and alertness. Subjects reacted as quickly as possible to a target appearing on the screen.

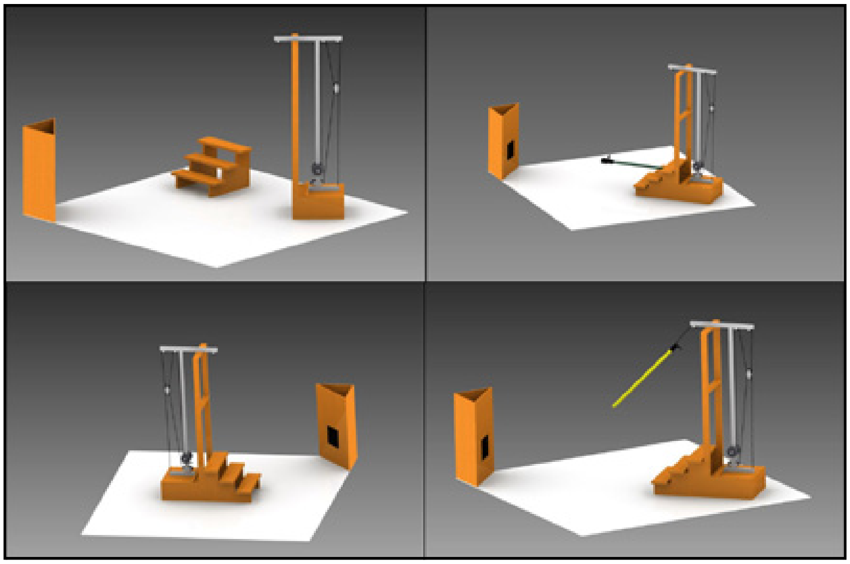


Figure 18. Firefighting Activities Simulator computer model. Clockwise from top-left: Stair climb, hose advance, overhaul, and search.

7.4 Location of Simulated Firefighting Activities

For decades, research to quantify the effects of firefighting activities and personal protective equipment on physiology and biomechanics has been conducted in a variety of testing environments. As discussed previously, a novel Firefighter Activities Station (FAS), which simulates four common fireground tasks, was recently developed to allow firefighting activities to be performed in an environmental chamber in a controlled laboratory setting.

To validate the FAS in the environmental chamber as a suitable surrogate for live fire structures, nineteen firefighters completed three different exercise protocols in two different environments [75]. Simulated firefighting activities conducted in an environmental chamber or live-fire structures elicited similar physiological responses (max heart rate: 190.1 vs 188.0 bpm, core temperature response: (0.08 vs 0.08°F/min (0.047 vs 0.043°C/min)) and body movement counts. At the same time, the response to a treadmill protocol commonly used in laboratory settings resulted in significantly lower heart rate (178.4 vs 188.0 bpm), core temperature response (0.07 vs 0.08°F/min (0.037 vs 0.043°C/min)) and physical activity counts compared with firefighting activities. This study effectively showed that the FAS in an environmental chamber was a valid experimental setup for simulating live-fire activities to study firefighters.

Figure 19. Firefighting Activities Simulator in use. Clockwise from top-left: Stair climb, hose advance, overhaul, and search.

8 Results and Discussion

8.1 Statistical Analysis

While firefighters completed 7 trials with varying SCBA size, design, and duration of simulated firefighting, four specific comparisons (Figure 20) were made to examine the effects of SCBA size (red), SCBA design (purple), bouts of simulated firefighting (green), and any interaction between SCBA size and bouts of simulated firefighting (blue). Each of the variables examined in this study were compared using these groupings.

8.2 Descriptives

8.2.1 Anthropometrics

Overall, the 30 firefighters who participated in this study were young (30.4±8.3 years, average ± standard deviation) and healthy, with no cardiovascular or movement disorders. 14 were career firefighters, 14 were volunteer, and 2 were both career and volunteer. The average experience was 8.2 years for the career firefighters and 5.6 years for the volunteers. These firefighters had an average height 6.0±0.2ft (1.82±0.07 meters) and weight of 201.0±34.0lb (91.2±15.4 kg).

40% (12/30) of the firefighters had a BMI classifying them as overweight (Body Mass Index 25-30 kg/m^2), while more than 23% (7/30) were classified as obese (BMI > 30 kg/m^2). The remaining 11 firefighters were classified as having a normal BMI (20-25 kg/m^2).

The population of firefighters who volunteered for this study had an average maximum oxygen consumption rate (VO$_2$) of 12.5 METS (43.7 ml/kg/min). NFPA 1582 [62] states that a VO$_2$ of 12 METS is required to safely perform essential job tasks. 13 of the firefighters in this study were below the 12 MET recommendation while 17 were above the minimum. Being unable to achieve the 12 METs may put firefighters at risk on the fireground as they may be required to push themselves beyond their own capacities in order to complete fireground tasks. All 30 firefighters successfully completed the first 4 conditions (1 bout of simulated firefighting activity), however, 11 firefighters were unable to complete at least one of the conditions with multiple bouts of simulated firefighting activity (Table 2). The 11 unable to complete all three conditions were generally heavier (102 vs 85 kg), had higher BMIs (30.3 vs 25.7kg/m^2), and had lower maximum oxygen consumption levels (11.5 vs 13.1 METS) (Table 3). Two firefighters were unable to complete any of the conditions with multiple bouts of simulated firefighting activity while three firefighters were able to finish one condition and six firefighters completed two out of the three multiple bout conditions.

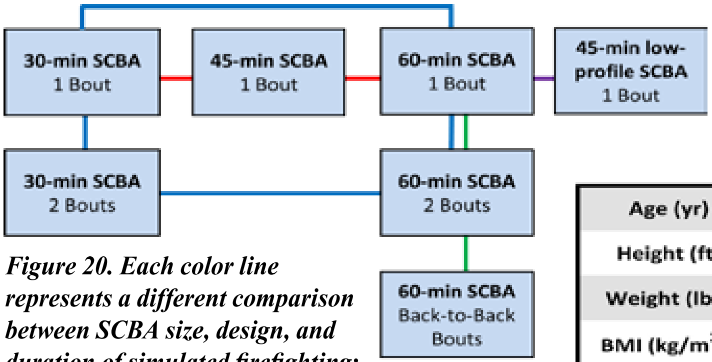


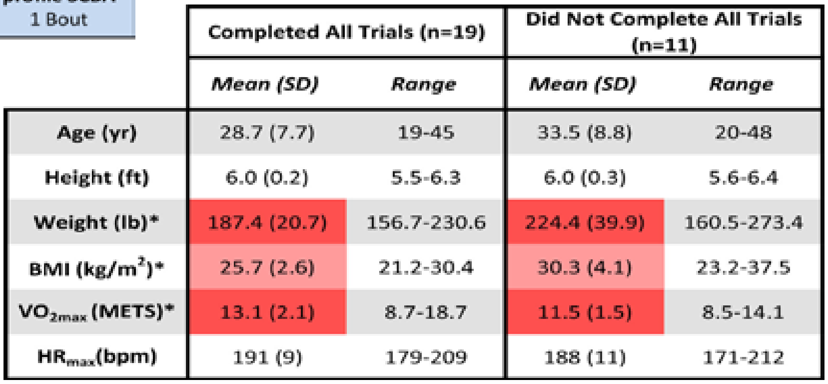
Figure 20. Each color line represents a different comparison between SCBA size, design, and duration of simulated firefighting: SCBA size (red), SCBA design (purple) bouts of simulated firefighting (green), and the interaction between SCBA size and bouts of simulated firefighting (blue).

Number of multiple bout conditions successfully completed	Number of firefighters
0	2
1	3
2	6
3	19

Table 2. Completion numbers for multiple bouts of simulated firefighting activity.

Of the six who completed two out of the three, three firefighters were unable to complete the first condition they faced, but successfully completed the following two conditions. This may be due to the fact that following the first condition the firefighter recognized that she/he could push further or that they became better acclimatized to the more stressful conditions, leading to successful completion of the final two conditions.

Firefighters unable to complete a particular condition typically reported that it was either too hot, or they were too fatigued to continue. Firefighters were then escorted out of the environmental chamber and given a chance to rest (~4 minutes) before continuing to the obstacle course.



	Completed All Trials (n=19)		Did Not Complete All Trials (n=11)	
	Mean (SD)	*Range*	*Mean (SD)*	*Range*
Age (yr)	28.7 (7.7)	19-45	33.5 (8.8)	20-48
Height (ft)	6.0 (0.2)	5.5-6.3	6.0 (0.3)	5.6-6.4
Weight (lb)*	🟥 187.4 (20.7)	156.7-230.6	🟥 224.4 (39.9)	160.5-273.4
BMI (kg/m^2)*	🟥 25.7 (2.6)	21.2-30.4	🟥 30.3 (4.1)	23.2-37.5
VO$_{2max}$ (METS)*	🟥 13.1 (2.1)	8.7-18.7	🟥 11.5 (1.5)	8.5-14.1
HR$_{max}$(bpm)	191 (9)	179-209	188 (11)	171-212

Table 3. Comparison of firefighters who completed all multi-bout trials versus those who did not complete at least one trial. Red cells indicate significant differences between the groups.

8.3 Physiological Measurements

Physiological measurements were collected throughout each visit. The parameters reported in this section are provided to describe effort during the firefighting activities (maximum and average heart rate, maximum and change in core temperature while conducting activities (FF)) and total change in core temperature values obtained over the entire visit (Tot) (Table 4).

8.3.1 Heart Rate

When comparing different size SCBA (30, 45, and 60-min) during one round of activity, no significant differences were found in the max HR attained or the average HR during firefighting. This suggests that the difference in size between packs may not increase the cardiovascular demands on the firefighter for the single bout of firefighting tasks. No significant differences in HR_{max} or HR_{ave} were found between the standard 60-min SCBA and the prototype 45-min SCBA indicating that during one bout of simulated firefighting activity the design of the pack did not have a significant impact on the firefighter's heart rate.

When the various bouts of simulated firefighting activity (1 bout, 2 bouts with a break, 2 bouts back-to-back) were analyzed, significant differences were found in both the HR_{max} and HR_{ave}. HR_{max} was increased significantly in conditions with the second bout of activity ($p<0.001$), and was highest in the back-to-back condition (Figure 21). Further, HR_{ave} was significantly higher in the back-to-back condition than in the 2 bout and 1 bout conditions ($p=0.003$), although there was no difference between the 2 bout and 1 bout conditions. The lack of difference between 2 bout and 1 bout conditions may be because the 2 bout condition includes the time firefighter rested outside the chamber between bouts.

8.3.2 Core Temperature

The firefighters' core temperature rose drastically during the-firefighting activities. Maximum core temperatures ($T_{co,max}$) and maximum change in core temperature (ΔT_{co}) over specific portions of the visit are shown in Table 4 and maximum core temperature is shown in Figure 22.

Analysis of the various SCBA sizes with one bout of simulated firefighting activity showed significant differences for Tco,max with core temperatures during the 60-min SCBA trial significantly higher than the standard 45-min and 30-min SCBA ($p=0.02$) during the simulated firefighting activities. No differences were found between the 30-min and 45-min SCBA. ΔT_{co} was not significantly different between any of the three conditions.

When the standard 60-min SCBA was compared to the prototype 45-min SCBA, $T_{co,FF}$ was significantly higher with the 60-min SCBA ($p=0.046$). ΔT_{co} was higher with the 60-min SCBA, but these changes were not statistically significant. If an increased number of firefighters had been tested, this trend may have become significant. These SCBA were similar in weight, indicating that the design differences between the two SCBA may cause less of a rise in core temperature with the prototype 45-min SCBA than with the standard 60-min SCBA. However, it should be noted that these differences are still relatively small.

	1 Bout				2 Bouts		Back to Back
	S30	S45	S60	P45	S30	S60	S60
HR_{max} (bpm)	182.5 (12.9)	181.8 (11.8)	182.0 (12.1)	180.2 (13.8)	189.2 (13.1)	186.8 (12.7)	189.0 (12.4)
HR_{ave} (bpm)	151.2 (13.8)	150.7 (13.0)	151.5 (14.5)	148.7 (17.2)	154.5 (12.8)	151.5 (14.2)	156.2 (14.0)
$T_{coMax,FF}$ (°F)	100.0 (0.6)	100.0 (0.5)	100.4 (0.7)	100.0 (0.7)	101.4 (0.8)	101.2 (1.0)	101.5 (1.0)
$\Delta T_{co,FF}$ (°F)	1.1 (0.8)	1.0 (0.1)	1.1 (0.4)	1.0 (0.4)	2.2 (0.8)	2.3 (0.9)	2.5 (0.9)
$T_{coMax,Tot}$ (°F)	101.0 (0.7)	100.9 (0.5)	101.3 (0.6)	100.9 (0.7)	102.0 (0.7)	102.0 (1.1)	102.3 (0.9)
$\Delta T_{co,Tot}$ (°F)	2.1 (0.6)	2.1 (0.5)	2.2 (0.5)	2.1 (0.5)	3.2 (0.8)	3.3 (1.0)	3.5 (0.9)

Table 4. Heart rate and core temperature parameters measured during simulated firefighting activities (max, ave, and FF tot) as well as core temperature from the beginning to the end of the study (Tot).

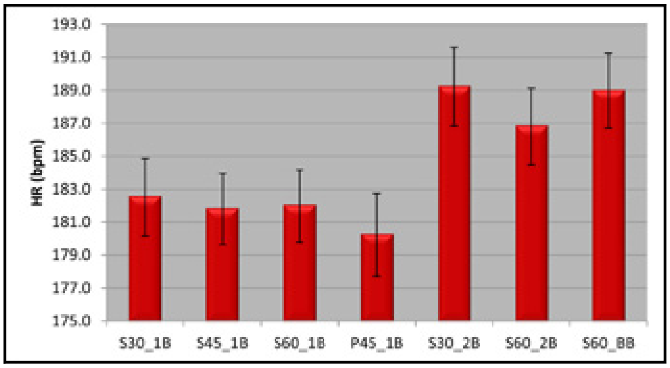


Figure 21. Maximum heart rate achieved by condition.

As expected, $T_{co,max,FF}$ was significantly higher in both of the conditions involving multiple bouts of simulated firefighting activities with the 60-min SCBA when compared to the single bout of activity with the 60 min-SCBA ($p<0.001$). $\Delta T_{CO,FF}$ was also significantly higher in the multi-bout conditions ($p=0.004$). The increased maximum core temperature and higher total change in core temperature observed in the multi-bout conditions are likely the result of increased exposure time to the hot ambient air in the chamber, as well as an extended length of work resulting in more metabolic energy being converted to heat and raising the firefighters' core temperature.

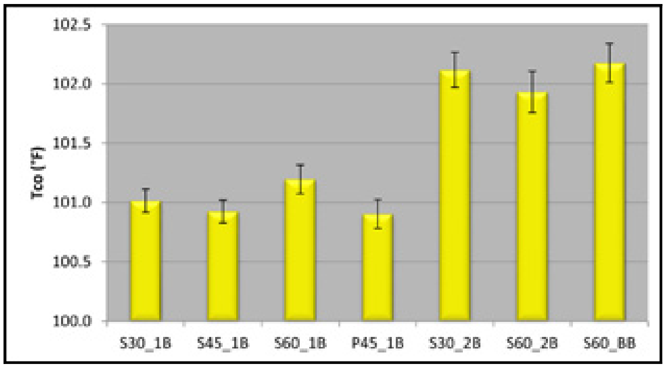


Figure 22. Maximum core temperature achieved by condition.

8.4 Work Expenditure (Heart Rate and Repetitions)

During each of the four simulated firefighting activities work expenditure was measured by recording the number of repetitions completed and the maximum heart rate achieved.

8.4.1 Activity Counts and Max Heart Rate during Firefighting

There were no significant differences between the number of repetitions (or distance in the search activity) completed during each 1 bout (1B) drill with the S30, S45 and S60 SCBA. The maximum HR achieved by the firefighters during each of these drills were not significantly different from each other. This suggests that the different size SCBA had a minimal effect on max HR of firefighters during a single bout of simulated firefighting activity.

Comparison between the prototype 45-min SCBA and the standard 60-min SCBA showed minimal differences in completion of activities (though on average, firefighters searched about 13 feet (4 meters) less when the prototype SCBA was utilized), yet significantly lower max HR's when the prototype SCBA was used ($p=0.036$).

Analysis of the 22 firefighters who completed all 3 of the trials with the 60-min SCBA (1 bout, 2 bouts with a break, 2 bouts back-to-back) revealed significant decreases in the number of repetitions performed and increases in max HR (Figure 23 and Figure 24) in the second bout of the multiple bout conditions. In fact, only 10% of the firefighters who participated in this study were able to maintain the same work level in the second bout as the first. For the stairs and hose advance activities, max HR was lowest in the 1 bout condition, higher in the second bout following a break, and highest in the back-to-back condition ($p<0.001$). Repetitions followed the opposite pattern, with firefighters completing the most repetitions in the 1 bout conditions, less in the second bout following the break, and the least in the back-to-back condition. For the search, distance in the multiple bout conditions was significantly lower than in the single bout ($p<0.001$), but there was no difference between having the break and back-to-back conditions. Max HR was significantly lower in the single bout than the back-to-back bouts ($p=0.024$) but no other differences were detected. During the overhaul activity, repetitions and max HR in the single bout were less than both two-bout conditions ($p<0.001$), but there was no difference between having the break and back-to-back conditions. The initial improvement in heart rate response due to the rest noted after the first two stations is no longer present in the later firefighting activities.

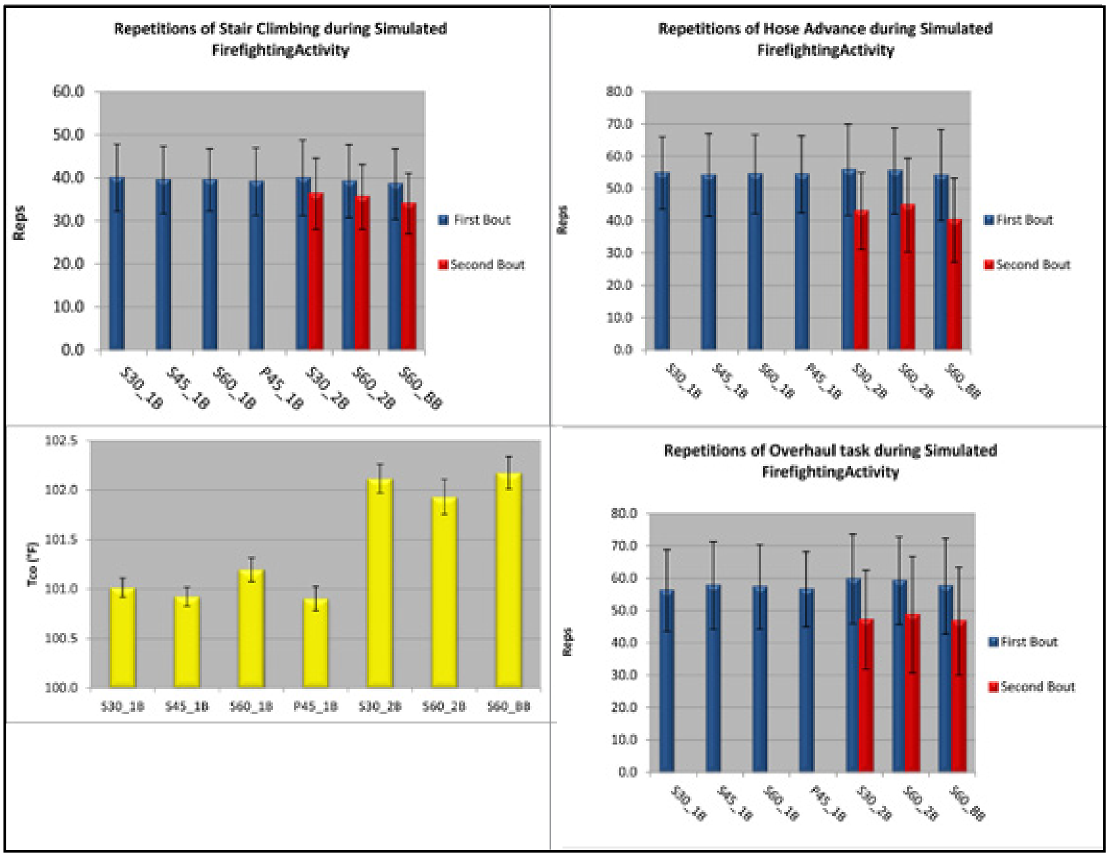


Figure 23. Number or repetitions (or distance) for each firefighting activity.

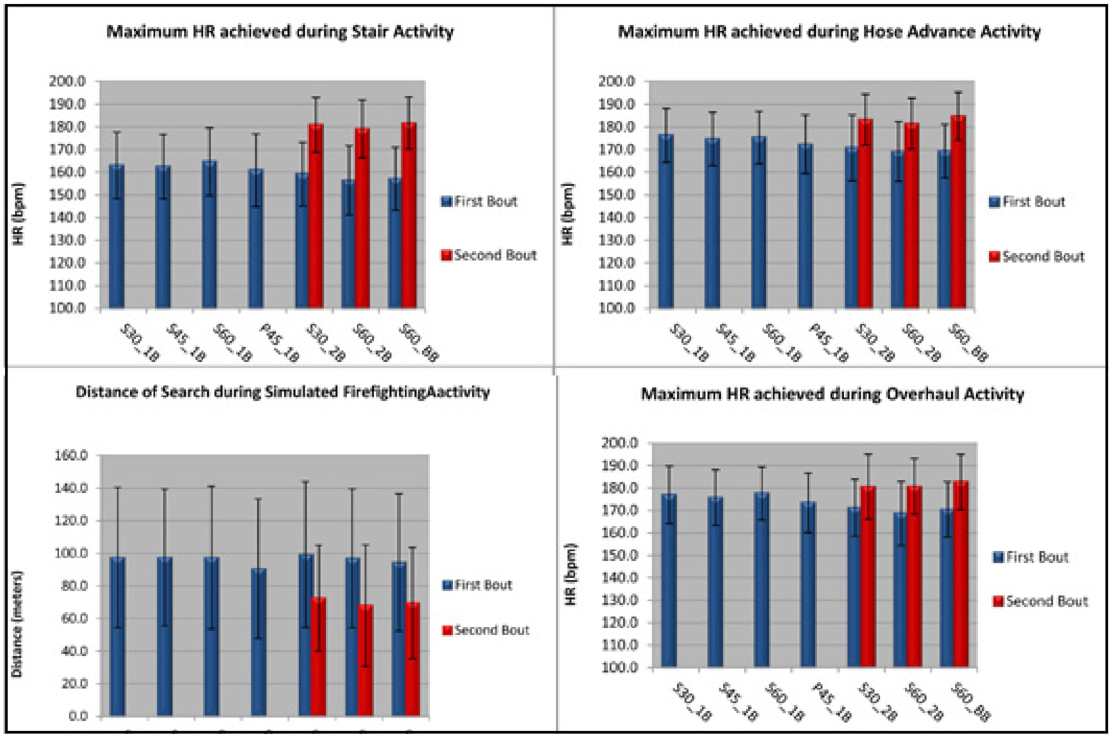


Figure 24. Maximum heart rate during each simulated firefighting activity.

8.5 Self-Assessment

Self-reported perceptual measures (Breathing, Feeling, Thermal Sensation) were significantly worse after performing the simulated firefighting activities in all of the conditions involving a single bout of firefighting (p<0.001) (Figure 25). Prior to the simulated firefighting activities, firefighters reported they were breathing "…OK right now" (~1.2), that they were feeling between "Good" and "Very Good" (~3.5), and were comfortable (~4.2). Post-activity the firefighters were breathing harder (~3.8), feeling worse (~0.6), and felt hotter (~6.0). The rating of perceived exertion was not significantly different between any of the conditions with a single bout of firefighting (Figure 26). These results suggest that neither the size, nor the design, independently affected the way the firefighters felt or how hard they perceived they were working during one bout of simulated firefighting activity.

Prior to all three simulated firefighting activities with the 60-min SCBA, firefighters reported breathing OK (~1.2), feeling between "Good" and "Very Good" (~3.6), and feeling comfortable (~4.1). Firefighters were breathing harder after the two bout conditions than after the one bout condition (4.5 vs. 3.8, p=0.001). They were also feeling worse (p<0.001), as they still felt "Fairly Good" (~1.0) following a single bout, but felt between "Fairly Bad" and "Bad" (~-1.4) following both two bout conditions. Further, the firefighters reported feeling "Hot" (~6.0) after one bout of activity, but were "Very Hot" (~6.8) after both of the two bout conditions (p<0.001). They also reported that they worked significantly harder (p<0.001) after performing two bouts of simulated firefighting activities (~18.5, between "Very Hard" and "Extremely Hard") than they did after one bout of activity (~15.8, between "Hard" and "Very Hard"). No differences were found in any of the self-reported measures (Breathing, Feeling, Thermal Sensation, or RPE) between the two bouts with a break or back-to-back conditions.

Anecdotal evidence from the firefighters following the multi-bout sessions revealed that some firefighters preferred to have the break while others felt they relaxed and had a difficult time resuming activity following the break.

Firefighters responded that they were breathing easier (~3.4), feeling better (~1.3), and were less hot (~5.6) following the first round of the S30_2B and S60_2B conditions than at the completion of the single bout of activity with the same SCBA (breathing (~3.8), feeling (~0.6), and thermal (~6.0), p<0.001). This finding may be the result of familiarization with the environment and test procedures, as the multi-bout firefighting condition were all performed after the four single bouts had been completed.

As expected, the self-reported levels of breathing, feeling, and thermal sensations of firefighters were significantly decreased following simulated firefighting. The changes increased in magnitude when multiple bouts of simulated firefighting were performed. No differences were found between the various size SCBA or between the standard and prototype SCBA. Further, no differences were found between the two bout conditions with the 60-min SCBA.

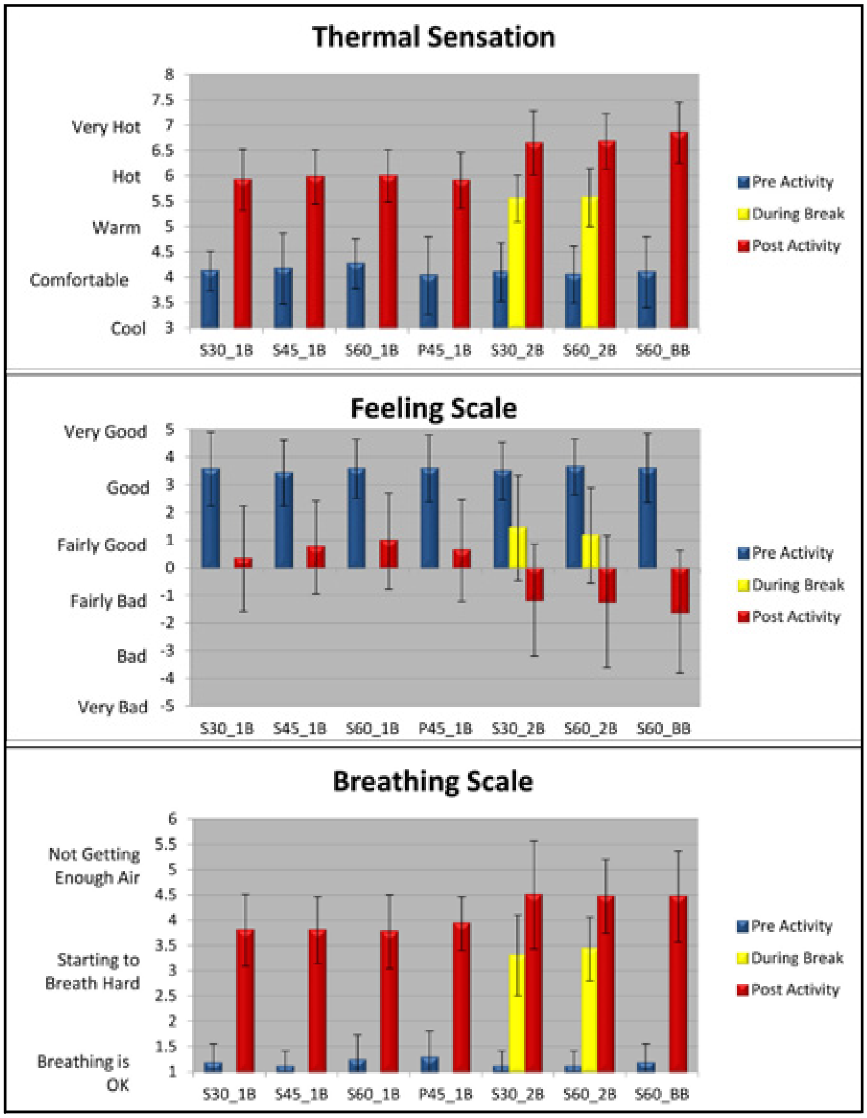


Figure 25. Thermal Sensation, Feeling Scale, and Breathing Scale responses by firefighters.

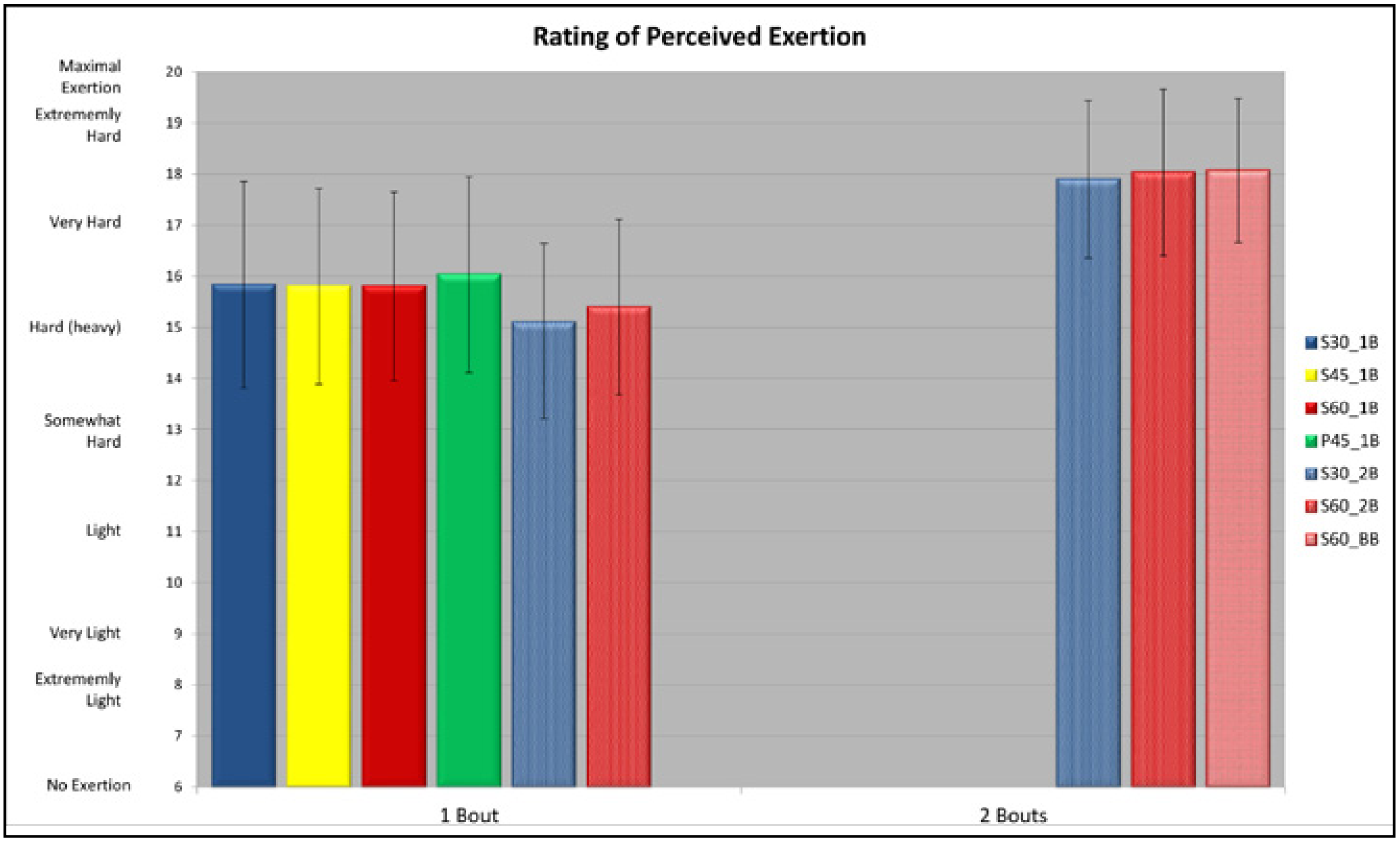


Figure 26. Ratings of Perceived Exertion (RPE) by firefighters following simulated firefighting activities.

8.6 Slips, Trips, and Falls (Biomechanics)

Before and after activities firefighters completed the obstacle course designed to replicate challenges which would be encountered on the fireground. Throughout the course biomechanical measurements were collected.

8.6.1 Walkway

Following simulated firefighting activities, on average, firefighters' walkway obstacle clearance with the lead foot increased significantly. This could possibly be attributed to the firefighter recognizing that tripping over the obstacle was an increased threat, and taking more precautions to avoid contact. However, significantly more contacts occurred following activity than before (31 before to 52 after, Figure 27).

When stepping over the obstacle, firefighters tended to land with more force and push-off with less force in both the vertical and front-back directions following simulated firefighting activity. For the trailing leg, these changes were more significant following multiple bouts of simulated firefighting than following a single bout. The increase in landing force may put the firefighter at an increased risk of slipping. An extreme example would be stomping on ice as opposed to cautiously walking across it, the more force that is in the front-to-back direction the greater the risk of a slip. The decrease in push-off force when stepping over the obstacle could result in a risk of contacting the obstacle and tripping.

During the walkway station firefighters made contact with the obstacle a similar number of times with the 30-min and 60-min SCBA (9 and 10 contacts). Significantly more contacts were made with the obstacle during trials with the 45-min SCBA (16, including 10 pre-activity contacts). It is not clear what caused this significant rise in pre-firefighting contacts in S45 and should be interpreted cautiously. The majority of these errors were minor (where the obstacle was contacted but did not fall over, 88.6%) and with the trailing foot (the second foot over the obstacle, 90.3%).

Clearances of the firefighters boots over the obstacle did not appear to be affected by SCBA size, though these findings contradict the work by Park [16] who found decreased foot clearance with heavier SCBA configurations. However, Park compared heavier aluminum SCBA to carbon fiber SCBA and may have seen a larger effect due to the greater difference in SCBA weight. SCBA size did not significantly affect any of the ground reaction force variables.

Fewer total contact errors were committed during tests using the prototype 45-min SCBA both pre and post exercise than with the 60-min SCBA (7 vs. 10), although the design of the SCBA did not have an effect on the clearances of the foot over the obstacle. The trailing foot late stance vertical peak GRF (how hard the firefighter pushed up as the trailing limb was

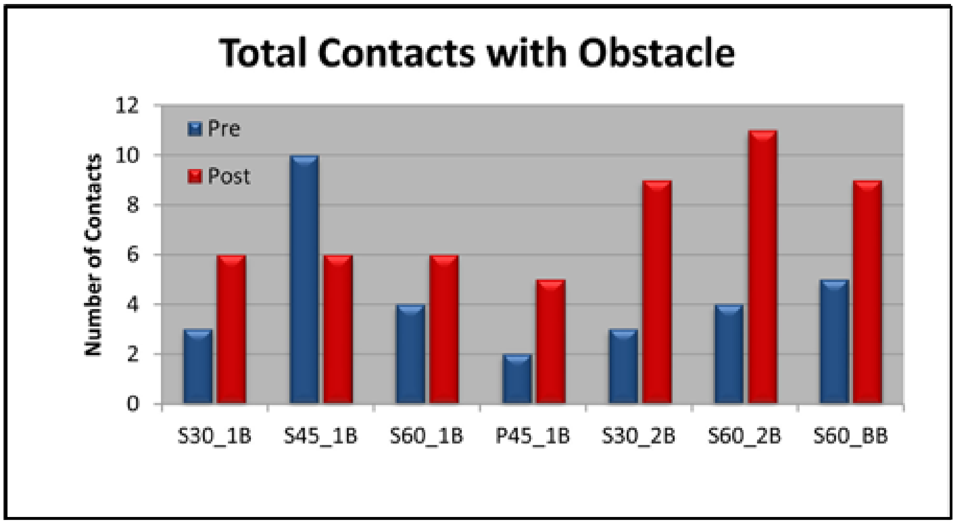


Figure 27. Contacts with Obstacle during Walkway

being lifted to clear the obstacle) was the only variable significantly different between SCBA design (p=0.046) and was greater on average for trials involving the 60-min SCBA compared to the prototype 45-min SCBA by 2.7%.

The number of times the firefighters contacted the obstacle appeared to be related to number of bouts of simulated firefighting activities performed. There were more contact errors following the 2B and BB activity (11 and 9) than in following a single bout of activity with the S60 SCBA (6). Minimum clearance of the trailing leg was significantly lower for the 2B and BB protocols than for the 1B protocol (p=0.046) by about 1.4cm, but having a break (2B) did not result in any improvement in clearance over not having one (BB).

In general, there were decreases in peak GRFs when more than one bout of activity was performed. The vertical and forward push-off forces of the trailing leg were about 7% and 6% less following multi-bout sessions than single bout sessions. Vertical push-off force with the lead foot was lower when two bouts were performed, but there was no difference between one bout and two bouts with the break indicating that the firefighter may have struggled to propel upward following two bouts of activity without a break.

8.6.2 Stairs

Completing the simulated firefighting activities significantly impacted the clearance of the firefighters' boots over the edges of the stair obstacles. Clearances on the ascending side of the stairs decreased regardless of SCBA worn or bouts of activity completed, while clearances on the descending side actually increased (Figure 28). This may be because the firefighter may have had less body control following activity, and was carried into the stairs on the way up, and away from the stairs on the way down by his/her momentum.

Firefighters' foot clearances when landing on the first step were 15% greater (p=0.028) during S60_1B trials than S60_BB trials. For the passing leg over stair 1, S60_1B clearances were 6% greater than both S60_2B and S60_BB (p=0.001). While statistically these differences are significant, the magnitudes of the differences are only 4mm and 8mm.

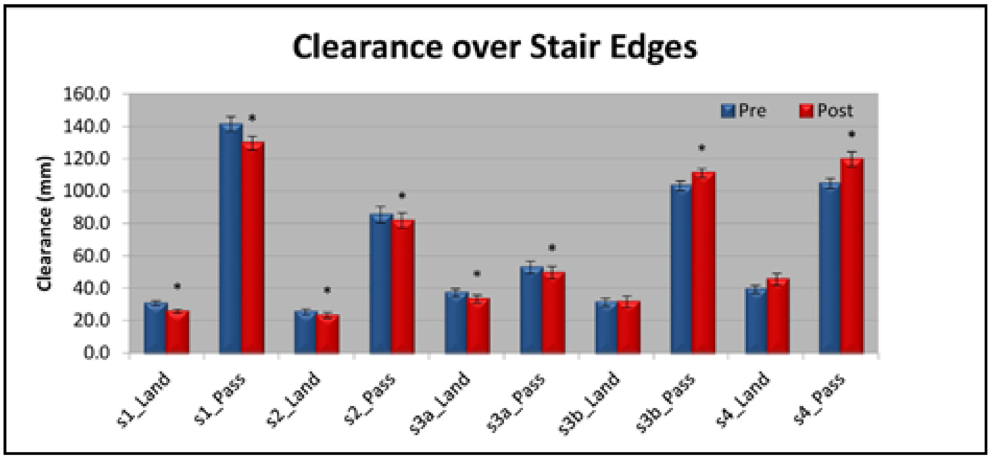


Figure 28. Average clearance over stair edgfes from all conditions. Significant differences between pre and post are indicated with an asterisk (*).

8.6.3 Gait Mat

The gait of firefighters was significantly affected by both the weight of the SCBA and the duration of exercise.

When firefighters wore the 30-min SCBA, the double-support time (time spent with both feet on the ground) was significantly less than the 45-min and 60-min SCBA. No other gait parameters showed significant differences between the three standard sized SCBA. This finding suggests that increased SCBA size may require the firefighter to keep both feet in contact with the ground longer, increasing the double-support time. No significant differences were found in any of the other walking parameters between the 60-min and prototype 45-min SCBA. These results suggest that SCBA design may have minimal effect on gait and agree with previous research which has shown that SCBA weight, but not size or distribution of load, affects walking parameters.

The impact of simulated firefighting on gait parameters was much less apparent when only one bout of simulated firefighting activity was performed compared to completion of two bouts (Figure 29). Compared to the single bout, multiple bouts of simulated firefighting activities (2B and BB) resulted in longer double-support time ($p<0.001$ for both), longer single-support times ($p=0.009$ and $p<0.001$, respectively), shorter stride length ($p=0.003$ and $p=0.001$, respectively), shorter step width ($p=0.003$ and $p=0.001$, respectively), and smaller stride velocity ($p<0.001$ for both). There were no differences between two bouts with a break between them and two bouts back-to-back. These results suggest that with simulated firefighting activity beyond a typical "30-minute bout" firefighters adopt more conservative, slower, and more controlled gait, and a 5-minute rehabilitation break between bouts of firefighting may not prevent the biomechanical changes caused by a second bout of firefighting.

No combined effects of SCBA size and bouts of firefighting were found, but both increased SCBA size and repeated bouts of simulated firefighting activities independently result in firefighters adopting more conservative gait. However, these size and repeated bouts do not appear to produce a combined interaction effect.

The results suggest that heavier SCBA and multiple bouts of exercise may independently cause firefighters to adopt more conservative gait, while profile may a have minimal effect, if any.

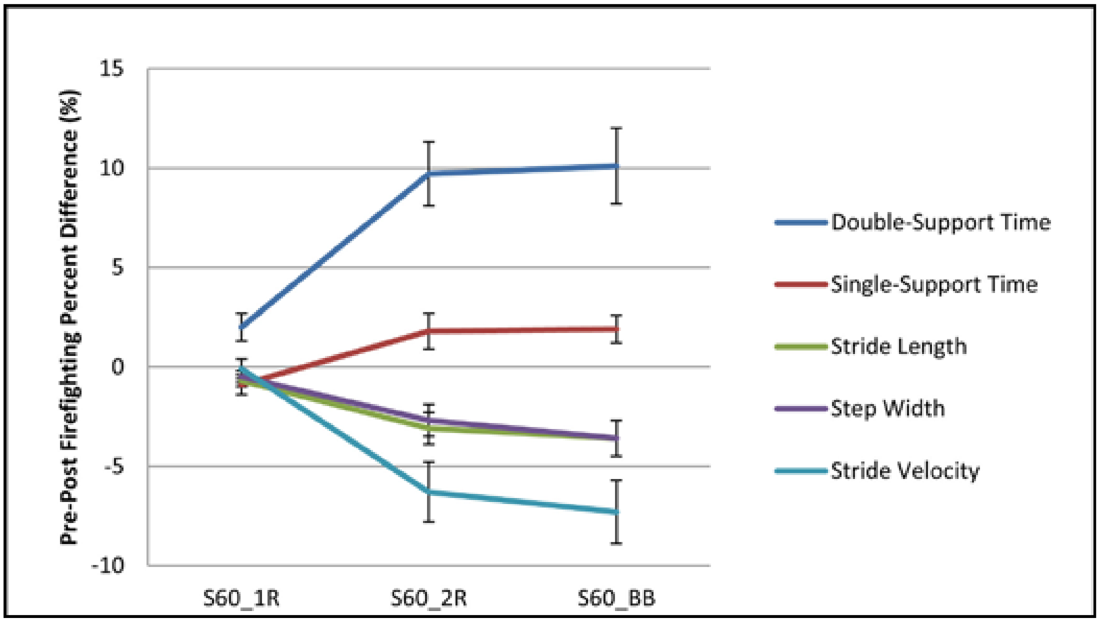
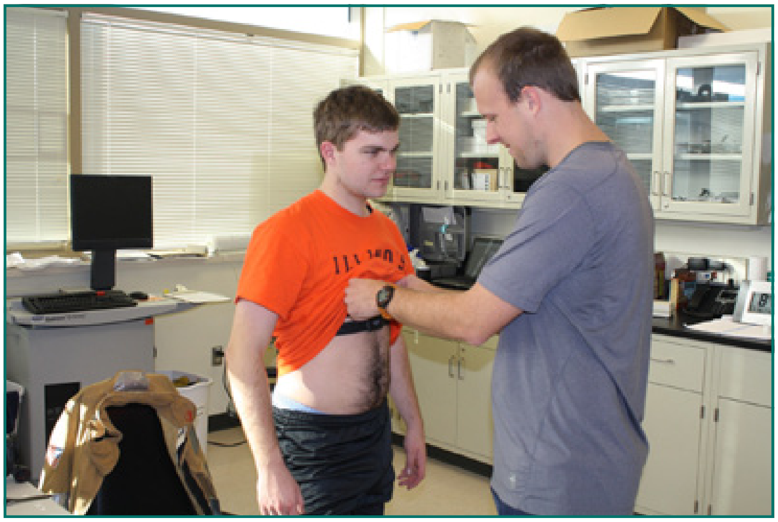


Figure 29. Estimated marginal means for the percent difference between PRE and POST trials. Positive percent difference indicates a positive change.



8.6.4 Standard Stud Space Opening

Firefighters' time to pass through the 16-inch on-center stud space task was similar pre- and post- completion of simulated bouts of firefighting. Further, neither the size of the SCBA, nor the number of bouts performed impacted completion time difference from pre- to post-firefighting. SCBA size and design, however, did play an important role in the total time it took to complete the task. On average, firefighters took 3.8 seconds longer to pass through the opening with the prototype 45-min SCBA (Figure 30). Many firefighters passed through this obstacle by turning sideways, placing the standard cylindrical SCBA against the wall, and "rolling" their shoulders and body through the opening. The rectangular prototype pack doesn't allow the firefighter to perform this strategy due to its increased width. It is possible that additional time spent training with the prototype design may allow firefighters to learn different techniques necessary to move through obstacles such as the standard stud space more efficiently.

Following two bouts of exercise, firefighters' total completion times were 0.5 seconds longer with the 60-min SCBA than with the 30-min SCBA. This difference was not found after firefighters completed just one bout of activity, which may suggest that the additional energy expenditure during the two bouts of activity had a more significant impact.

Overall, the design of the low-profile SCBA slowed the firefighters down the most, though fatigue following simulated firefighting did result in longer times to pass through the obstacle.

8.6.5 Functional Balance Test

During the functional balance test subjects completed the task an average of 0.2 seconds faster (p=0.022) following a single bout of simulated firefighting activity than pre-firefighting (Figure 31). There were no differences in completion time between the two designs of SCBA (cylindrical 60-min and prototype low-profile 45-min) and no differences between the different size SCBA (30-, 45-, and 60-min) when a single bout of simulated firefighting was completed. When firefighters completed a second bout of simulated firefighting activities, regardless of getting rest or not, the time to complete the task was 0.4 seconds longer (p=0.004) than after a single bout of activity with the S60. Further, firefighters committed more errors after two bouts of simulated firefighting activity than pre-activity (p=0.004) (Figure 32).

When the overhead obstacle was placed on the FBT, firefighters completed the task quicker with smaller SCBA. The average completion time was 9.8 seconds, but with the 30-min SCBA firefighters completed the FBT 0.4 seconds quicker than with the 45-min SCBA and 0.8 seconds quicker than with the 60-min SCBA. Firefighters had more errors after the activity than before activity regardless of SCBA worn (p=0.039). Design had minimal effect on the performance through the FBT, with no significant difference in completion time or errors between the cylindrical 60-min SCBA and the prototype low-profile 45-min SCBA. Firefighters also completed the task 0.7 seconds slower (p<0.001) and committed almost twice as many errors per trial (p<0.001) with the 60-min than the 30-min SCBA when both single (1B) and double bouts (2B) of simulated activity were combined.

Multiple bouts of simulated firefighting activity resulted in much slower completion times following simulated firefighting activities. When firefighters were given a five minute break between bouts, completion time with the overhead obstacle was 0.7 seconds slower than before activity. When bouts were completed back to back completion time was 1.0 second slower. However, when only 1 bout was done, there was no change in the completion time.

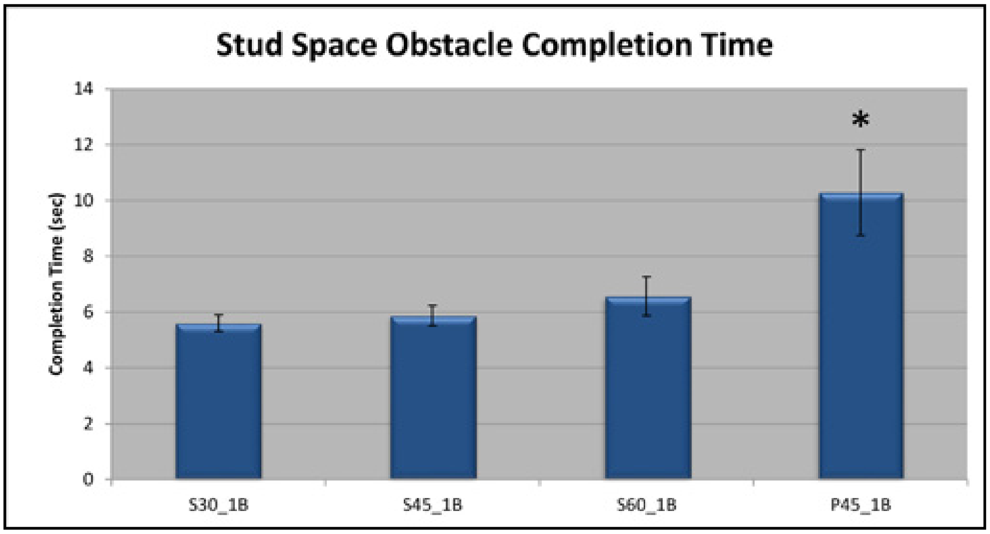


Figure 30. Time to complete stud space obstacle.

Extended duration SCBA resulted in significantly decreased completion speed of the FBT when firefighters had to duck under an overhead obstacle, possibly because firefighters had to duck lower with larger SCBA. However, the lack of difference between the 60-min and prototype 45-min SCBA suggests that weight, not dimensional size, impacts performance. On trials without the obstacle, neither different size nor design of the SCBA affected completion time. Completing a second bout of simulated firefighting activities increased completion time and resulted in more errors both with and without the overhead obstacle. Taking a five minute break between bouts resulted in slightly faster completion times than not having the break, but without the obstacle there were no differences.

8.7 Human Factors

Response time was recorded and the firefighters reported a Task Load Index. These values were used to characterize the impact of the simulated firefighting on the firefighter's reaction time and overall perceptions.

8.7.1 Psychomotor Vigilance Test (PVT)

When viewed together, the mean Response Time (RT) of all participants across conditions in the study remains fairly consistent at ~297ms, though there is some variation among the participants. When averaged and viewed as a whole, there are no statistically significant differences between the pre- and post-simulated firefighting activity conditions. When firefighters completed multiple bouts of simulated firefighting the average reaction time slowed from 291 milliseconds pre-activity to 304 milliseconds post-activity (p=0.007).

8.7.2 Task Load Index

Firefighters reported experiencing higher demands and workload after performing two bouts of simulated firefighting activity versus performing a single bout. Specifically, firefighters felt that the trials involving two bouts of activity were more demanding (mentally, physically and temporally) and more frustrating. Despite these changes, there was no difference in how the firefighters felt they performed in the single or double bout conditions.

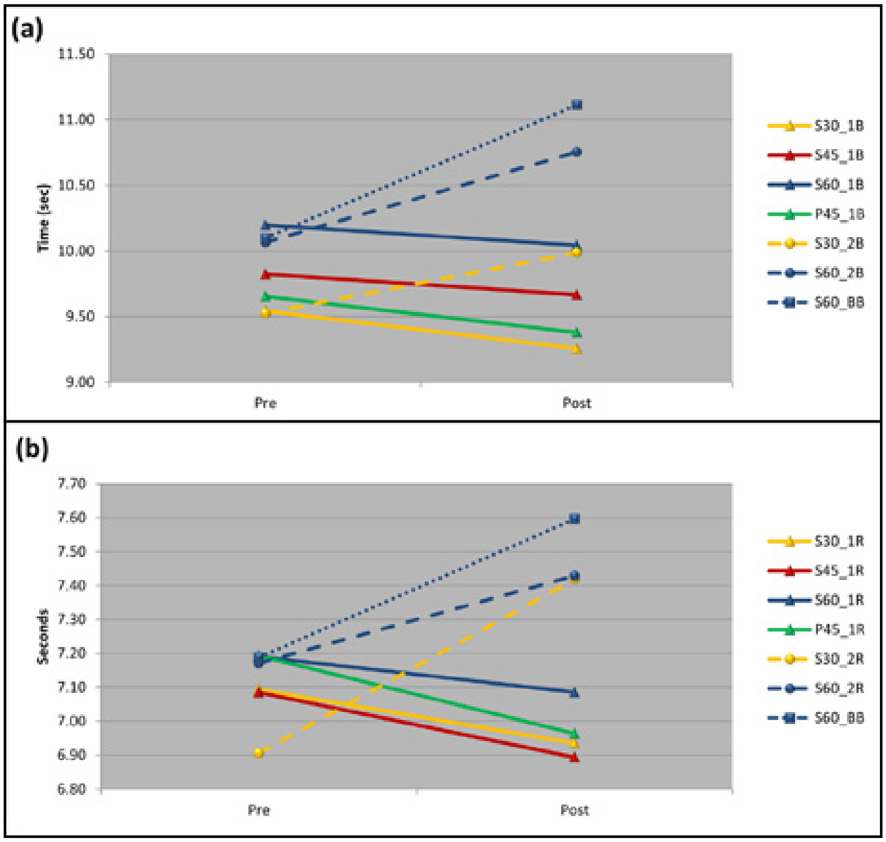


Figure 31. Time to complete functional balance test (a) with and (b) without an overhead obstacle.

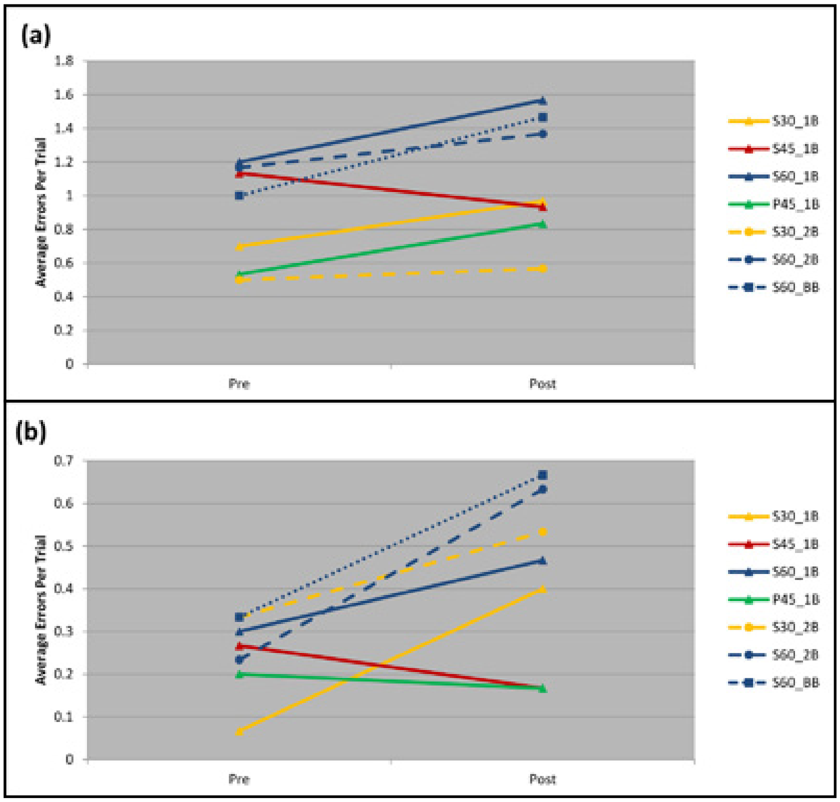


Figure 32. Average errors per trial during Functional Balance Test (a) with and (b) without an overhead obstacle.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9 Summary & Recommendations

9.1 Summary

A visual summary of the major findings of this study are presented in Table 5 with details of these outcomes described below.

9.1.1 Effects of Performing Single Bouts of Simulated Firefighting Activities (Pre- vs Post-Firefighting)

Performing simulated firefighting activities resulted in elevated heart rates (greater than 180 bpm) and core temperatures (0.5°F increase).

Firefighters reported breathing harder, feeling worse, and feeling hotter after completion of the simulated firefighting activities

Firefighters increased the clearance of the lead foot over the walkway obstacle but decreased clearance when ascending stairs. The clearance during stair descent then increased. Firefighters also adopted more conservative gait following activity. All of four of these changes may be the result of decreased postural control following simulated firefighting activities.

After a single bout of firefighting, time to completion on the functional balance test improved, but firefighters committed more errors.

9.1.2 Effects of SCBA Size (S30 v S45 v S60)

SCBA size had few effects across the three conditions before and after a single bout of firefighting activity. The largest SCBA (S60) resulted in firefighters having a significantly higher core temperature across all of the single-bout conditions. The 30-min SCBA did result in less time spent in double support (both feet in contact with the ground) during walking and allowed firefighters to complete the functional balance test with an overhead obstacle in the fastest time. Firefighters completed the functional balance test slower and committed almost twice as many errors per trial with the S60 SCBA than the S30 SCBA

	Pre- vs Post-FF (1 Bout)	S30 v S45 v S60 (SCBA Size)	S60 v P45 (SCBA Design)	S60_1B v S60_2B v S60_BB (Bouts of Activity)
Heart Rate	⬆	—	↓	⬆
Core Temperature	⬆	↑	↓	⬆
Activity Counts	Not Applicable	—	—	⬇
Perceptions	⬇	—	—	⬇
Obstacle Crossing - Clearance	↑	—	—	⬇
Obstacle Crossing - Errors	⬆	—	⬇	⬆
Stair crossing	⬇	—	—	—
Gait	⬇	↓	—	⬇
Stud opening	—	—	⬇	↓
Functional Balance - Time	↓	⬆	—	⬆
Functional Balance - Errors	⬆	—	—	⬆

Table 5. Summary of findings. Red arrows indicate a negative change, while green arrows indicate a positive change. The magnitude of the change is reflected by the arrow's size. Black bars indicate no significant differences.

when both single and double bouts of simulated activity were combined and analyzed together.

9.1.3 Effects of SCBA Design (S60 v P45)

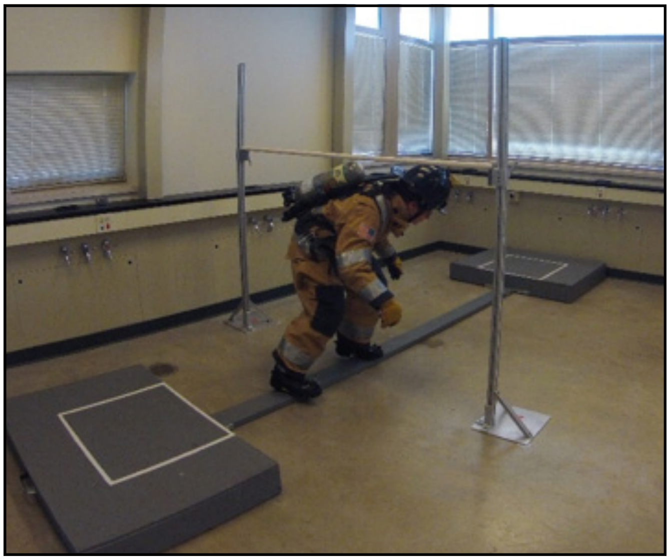
SCBA design again had minimal effects throughout the study, but firefighters did achieve significantly lower maximum heart rates during the search with the prototype low-profile 45-min SCBA. Firefighters made less contact errors on the walkway, though they passed through the standard stud space opening slower with the low-profile 45-min SCBA. This is possibly a result of an inability to perform a popular rolling motion used with cylindrical SCBA to navigate the opening.

9.1.4 Effects of Multiple Bouts of Activity (S60_1B v S60_2B v S60_BB)

The factors which most affected the firefighter across all of the variables tested were the number of bouts the firefighter completed and whether the firefighter had a five minute rehabilitation period between the rounds.

Firefighters had higher heart rates and core temperatures when multiple bouts of firefighting where completed, with the highest heart rates occurring in the trials were no break was given between bouts. Further, the amount of work completed during each activity significantly decreased when firefighters performed a second bout of firefighting activities; most noticeably in trials where the firefighter did not have a break. The work completed decreased more in trials were the firefight did not have a break. Firefighters not only felt worse, were breathing harder, were more hot, and felt there was more demand, but they also had higher landing forces when crossing an obstacle, committed more contact errors, and had slower reaction times following a double bout of simulated firefighting activity than they did after completing single bouts.

Multiple bouts of simulated firefighting activities also resulted in lower boot clearances when stepping over obstacles and slower, more controlled gait. Firefighters walked slower, taking longer for each step, and had shorter, narrow steps. They took longer to pass through the stud space and had more errors during and took longer to complete the functional balance test, with the longest completion time occurring after trials in which the firefighter did not get a break between bouts of activity.



9.2 Recommendations

9.2.1 Fireground Operations Recommendations

Results of this study suggest that completing only a single bout of firefighting typical of that which can be conducted with a 30-min SCBA puts the firefighter at less risk than if the firefighter were to complete multiple bouts of firefighting. Using a single 60-min SCBA bottle allows the firefighter to work longer without having to swap bottles, and is commonly equated to two bouts with a 30-min SCBA per NFPA 1584: *Standard on the Rehabilitation Process for Members during Emergency Operations and Training Exercises* [76]. Recognizing that the job at hand and staffing may demand that firefighters work through more than a single cylinder of air, the risk of slip, trip, and fall injuries could be decreased by rehydrating and taking a short break (approximately 5 minutes) prior to completing a second bout of firefighting with the 30-min SCBA, and enforcing the same work-rest cycle when utilizing a larger SCBA (45- or 60-min). Following the second bout of firefighting, it is recommended that firefighters take a longer rehabilitation period per NFPA 1584.

Recommendation 1

When possible, it is recommended that staffing and/or mutual aid provide enough manpower at the scene to limit the workload on firefighters to a single bout of activity. It is important to recognize the reduced capability of many firefighters when operating on their second cylinder of air in a 30 minute bottle (or second half of air in a 60 minute bottle) even when a 5 minute rest and rehydration break is provided.

Recommendation 2

Firefighters should follow NFPA 1584 and allow for a minimum of 20 minutes of rehabilitation following extended fireground activity such as two bouts with a 30-min SCBA or a single bout of activity with a 45- or 60-min SCBA. After the second bout of activity, nearly all firefighters had reached near maximal heart rates, core temperatures increased more than 2°F and their overall self-perceptions of heat, breathing and general feelings as well as perceived exertion levels suggest that such a break would be beneficial. It is important to remember however, we have shown previously that a 20 minute break will not return the firefighter to their pre-firefighting condition and additional work after this period will likely begin at elevated heart rates and core temperatures.

9.2.2 Fireground Equipment Recommendations

When wearing the 30-min SCBA used in this study, firefighters were able to complete the functional balance test more quickly than when wearing the larger SCBA and may have given the firefighters increased confidence when walking as they spent less time with both feet on the ground. Further, the 60-min SCBA resulted in higher core temperatures than those recorded while the firefighters wore smaller SCBA.

Recommendation 3

Transitioning from the traditional 30-minute SCBA to extended duration SCBA should be done with a full evaluation of the consequences. While the 30-min SCBA has been shown to be sufficient for use in many firefighting operations, extended duration SCBA may be better suited for high-rise or HAZMAT operations. The additional weight and bulk does have some important impacts on the biomechanics of movement and extended work time can further exacerbate these concerns. If extended duration SCBA are to be utilized, it is recommended that the work-rest cycles typical of the 30-minute SCBA still be followed (and the extra air be considered reserve) instead of relying on the End of Service Time Indicator to indicate time to exit the structure.

Recommendation 4

It is essential that firefighters remain aware of their surroundings on the fireground particularly after completing a strenuous bout of firefighting activity. Slip, trip, and fall injuries are often the result of contact with equipment and obstacles on the fireground. The PPE and SCBA that firefighters wear restrict the range of motion and change a firefighter's center of mass and make it difficult to recover from obstacle contacts.

9.2.3 Pre Firefighting Recommendations

To prepare for the demands of firefighting, firefighters need to take measures to protect themselves prior to responding to a fire. Per NFPA 1582: Standard on Comprehensive Occupational Medical Program for Fire Departments [62], all firefighters should have a medical evaluation prior to joining the fire service and annual fitness evaluations. At aerobic capacity levels below 12 METs it is suggested that the firefighter be counseled to improve his/her fitness and below 8 METs the firefighter be prescribed a fitness program and restricted from many essential job tasks including wearing PPE and SCBA and performing firefighting tasks (hoseline operations, ventilation, rescue operations, etc.).

Recommendation 5

Firefighters should follow exercise programs with the goal of achieving the 12 MET requirements in order to perform essential job tasks. Of the 30 firefighters who participated in this study, 11 were unable to complete all of the 2 bout firefighting scenarios. On average, these 11 were able to achieve 11.5 METS, while the 19 who did complete all of the scenarios were able to achieve 13.1 METS (on average).

Recommendation 6

Firefighters should follow an exercise program and a healthy diet to maintain a healthy weight and normal BMI (20-25 kg/m^2). Firefighters' BMI should be calculated and monitored annually as recommended. On average, the 11 firefighters who were unable to complete 2 bouts had a BMI of 30.3 kg/m^2, while the 19 who did complete all of the scenarios had a BMI of 25.7 kg/m^2 (on average).

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