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Physiological demand on firefighters crawling during a search exercise

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ABSTRACT

This study was an investigation into the physiologic demands of crawling for firefighter trainees performing the search portion of a 'search and rescue' (SAR) exercise. A total of twenty-five male subjects participated in the exercise, each of whom provided demographic data, body part discomfort before and after the exercise, and air consumption data from their self-contained breathing apparatus (SCBA) during the exercise. A subset ($n = 14$) of these subjects also wore heart rate monitors during the search exercise, which involved crawling in full turnout gear. Results demonstrated a dramatic increase in heart rates during crawling activities. The maximum heart rate during crawling averaged 174 beats per minute (bpm) (~88% of their mean age-predicted maximum heart rate), about 97 bpm higher than their standing resting heart rate. The duration of the crawling search exercise ranged from 14.4 to 21.0 min. The volume of air consumed from the SCBA's averaged 52.9 L/Min (SD = 10.1). Five subjects (20%) exhausted their air before completing the exercise, and an additional sixteen subjects (64%) finished with critically low levels of reserve air. Crawling was observed to be a mode of locomotion that required extremely high cardiorespiratory demands, even in the absence of the thermal load that would be experienced in an actual fire event. The high cardiac load associated with crawling in turnout gear may increase the risks of heat-related illnesses and cardiac events during firefighter search and rescue activities.

Relevance to industry: The findings in this paper can help Fire Department Training Officers appreciate the magnitude of cardiac loading associated with firefighter crawling exercises in Bunker Gear. This awareness, coupled with commercially available physiological monitoring equipment and the minimization of exercise duration and intensity, has the potential to lower the risk associated with such physically demanding training exercises.

1. Introduction

Firefighters regularly contend with hazardous environments that require the use of protective ensembles (turnout gear) and necessitate the use of awkward postures for locomotion and task performance. A major issue in highly-involved structural fires is that the smoke is toxic, blocks vision, and impedes navigation. The tendency of smoke and soot to rise toward the ceiling requires firefighters (and others trying to escape) to stay low to the ground, forcing them to crawl beneath the smoke, sometimes for extended distances and durations.

Previous research has demonstrated that crawling is a physically demanding method of locomotion, even without the additional burden imposed by wearing turnout gear (Morrissey et al., 1985; Davis, 2011). Firefighters perform many tasks in the course of their duties that have also been reported as heavy workloads. Dreger and Petersen, 2007, reported an average VO_2 of 34.1 ml/kg/min (~9.7 MET) for simulated firefighting tasks, with Holmér and Gavhed, 2007 reporting an average VO_2 of 33.9 ml/kg/min (~9.7 MET), with the most stressful task at 43.8 ml/kg/min (~12.5 MET). The increased metabolic demand associated with crawling (compared to walking) is partially due to the recruitment of the arm musculature which supports the weight of the upper body, and also contributes to propelling the body forward when crawling. Despite the additional physiological demands incurred, the maximum speed attainable when crawling is greatly reduced compared to walking (Babic et al., 2001; Bajd et al., 1995; Kady and Davis, 2009a,b; Muhdi et al., 2006; Patrick et al., 2009). It has also been shown that the stride length associated with crawling is dramatically reduced compared to walking, and the stride rate associated with crawling cannot compensate for the reduction in stride length (Gallagher et al., 2011).

Turnout gear has been shown to reduce mobility, increase muscular strain, as well as increase heat load experienced by firefighters (Coca et al., 2010). Standard turnout gear restricts evaporative heat loss through decreased water vapor permeability, which

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may lead to serious heat stress issues (McClellan and Selkirk, 2006). Decreased water vapor permeability severely inhibits evaporative heat loss from the skin due to sweating when the evaporative heat loss required to maintain thermal steady state (E_{req}), exceeds the maximum capacity of the environment to accept water vapor (E_{max}). This may lead to a condition of uncompensable heat stress. The primary cause of the increased heat load is the trapped metabolic heat produced by working muscles, in addition to any heat gained from the ambient environment. The vasodilation that occurs in the periphery in an attempt to respond to the thermal strain imposed on the body creates increased cardiovascular demands (which may be significant when performing metabolically demanding tasks) and may place firefighters at increased risk of succumbing to hyperthermia, heat illness, or heart attack (leading cause of firefighter fatalities) (Washburn et al., 1998).

Besides the tragic loss of life and impact to firefighters families and communities, firefighter injuries and fatalities have been shown to result in significant economic costs. According to a recent publication by the Firefighter Safety Research Institute (2010), the average cost per firefighter injury has been estimated at $63,300 and the average cost per firefighter fatality is $7.3 million. It is well established that the number one cause of firefighter deaths is heart attack (Washburn et al., 1998). An analysis of the NIOSH Fire Fighter Fatality Investigation Reports database (NIOSH, 2013) indicates that approximately 40% of the 540 firefighter fatalities over the period studied (1998–2012) were the result of cardiac events.

A review of the literature indicates that the physiological demands associated with crawling in firefighter turnout gear have not been evaluated. Accordingly, the purpose of the present investigation was to measure the physiological demands experienced by career firefighters when crawling in turnout gear during a search exercise.

2. Methodology

As with previous studies that investigated crawling behavior (Muhdi et al., 2006; Kady and Davis, 2009a,b; Nagai et al., 2006) the present study was conducted in a field environment. In this case, the field environment was an abandoned industrial building used by fire departments for firefighter training exercises.

3. Subjects

Twenty-five healthy, active male subjects volunteered to participate and provided informed consent. Subject demographic data included height ($\bar{x}$=180.6 cm, SD = 5.1), weight ($\bar{x}$=86.6 kg, SD = 11.4), BMI ($\bar{x}$=26.6, SD = 3.1), and age ($\bar{x}$=23.2 years, SD = 6.5). All subjects were experienced in the use of turnout gear and reported that they had previously crawled in such gear numerous times. The protective ensembles worn by the subjects included undergarments and uniform, turnout pants, turnout jacket, boots, hood, helmet, SCBA, and gloves. Each trainee firefighter had been hired into a full-time position which commenced upon successful completion of the State mandated course.

4. Dependent measures

The amount of air consumed during the search exercise was calculated from the pre- and post-exercise SCBA regulator readings in pressure per square inch (PSI). Garmin Forerunner 110 monitors (Garmin International, Olathe, KS) were used to collect heart rate data. To assess the physical effects of crawling for extended periods, subjects were asked to complete a body part discomfort survey both pre- and post-exercise.

5. Procedure

Subjects were briefed on what data would be collected and how the heart rate monitors were to be worn, provided demographic data, and also completed the pre-exercise body part discomfort survey and were asked to provide information regarding existence of significant previous injuries or surgeries.

6. Protocol

All twenty-five subjects were assigned to teams of two or three firefighters by the training officers. Three 3-person teams and three 2-person teams were designated by the training officers to wear the HR monitors. Some firefighters ($n = 15$) voluntarily wore knee pads in addition to the padding provided in turnout pants, to reduce stress on their knees. Hand protection was provided by the use of heavy leather firefighter gloves, which contained some degree of built-in padding on the palms. After being briefed by the Incident Scene Commander (details about the layout of the building, expectation of occupants/survivors, and that fire conditions would require them to crawl), search teams entered the building, one team at a time. Each team was accompanied by a senior fire department training officer who observed their performance, served as a safety monitor, and provided additional scenario information as required. A researcher accompanied each group to videotape the exercise with an infrared camera.

Firefighters performed a 'right-hand-sweep' technique to systematically search while crawling in a completely dark, abandoned two-story building, examining both upper and lower floors. Each team crawled a total distance of approximately 830 feet, including 16 stairs which were crawled up to get to the second floor and back down to return to the first floor. The firefighters were required to provide a comprehensive and thorough search of each of the numerous spaces involved, Fig. 1. After finishing the exercise, firefighters stood up, turned off their SCBA, were debriefed on their performance by the training officer, and doffed most of their turnout gear. They were asked to stand for an additional few minutes to monitor HR recovery and then complete the post-exercise body part discomfort survey. Researchers then recorded the regulator readings on the SCBA tanks. Video footage was used to provide a detailed accounting of the duration of each team's trial and provided a means of recording communications between the search team members.

At the conclusion of the exercise, researchers entered the building with flashlights, measuring all distances and room sizes, noting the presence of obstacles and stairs. These observations and measurements were used to recreate the layout of the facility (Fig. 1).

7. Data analysis

Descriptive statistics were performed on all physiological variables (HR, Air Consumption, and Body Part Discomfort). Data were evaluated for outliers using the 1.5 inter-quartile-range (IQR) procedure. Though all twenty-five subjects provided demographic, air usage, and body part discomfort data, crawling times are only reported for those subjects wearing the HR monitoring equipment. Additionally, HR data for one subject was not reliable, hence the number of subjects changed to $n = 14$ for this analysis. HR_{max} was calculated using the standard formula $HR_{max} = 220 - Age$. Percent HR_{max} = [Task (crawling) maximum observed HR]/[age adjusted HR_{max}].

8. Results

Subject demographic data for trainees monitored for HR included height ($\bar{x}$=183.1 cm, SD = 7.4), weight ($\bar{x}$=87.4 kg,