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The thermal ergonomics of firefighting reviewed

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A B S T R A C T

The occupation of firefighting is one that has repeatedly attracted the research interests of ergonomics. Among the activities encountered are attention to live fires, performing search and rescue of victims, and dealing with emergencies. The scientific literature is reviewed to highlight the investigative models used to contribute to the knowledge base about the ergonomics of firefighting, in particular to establish the multi-variate demands of the job and the attributes and capabilities of operators to cope with these demands. The job requires individuals to be competent in aerobic and anaerobic power and capacity, muscle strength, and have an appropriate body composition. It is still difficult to set down thresholds for values in all the areas in concert. Physiological demands are reflected in metabolic, circulatory, and thermoregulatory responses and hydration status, whilst psychological strain can be partially reflected in heart rate and endocrine measures. Research models have comprised of studying live fires, but more commonly in simulations in training facilities or treadmills and other ergometers. Wearing protective clothing adds to the physiological burden, raising oxygen consumption and body temperature, and reducing the time to fatigue. More sophisticated models of cognitive function compatible with decision-making in a fire-fighting context need to be developed. Recovery methods following a fire-fighting event have focused on accelerating the restoration towards homeostasis. The effectiveness of different recovery strategies is considered, ranging from passive cooling and wearing of cooling jackets to immersions in cold water and combinations of methods. Rehydration is also relevant in securing the safety of fire-fighters prior to returning for the next event in their work shift.

1. Introduction

Firefighting is an occupation characterised by prolonged periods of low-intensity work and occasional bouts of moderate to high-intensity efforts (Bos et al., 2004; Scott, 1988). In some instances, firefighters may also perform strenuous work for periods of an unpredictable duration under conditions of high environmental heat strain (Romet and Frim, 1987; Rossi, 2003; Smith et al. 1997, 2001). The tasks associated with firefighting place high physical demands upon those engaged. Carrying equipment, operating in protective clothing, and dealing with the tasks in hand entail a large outlay of energy expenditure (Bilzon et al., 2001; Gledhill and Jamnik, 1992; Lemon and Hermiston, 1977; von Heimburg et al., 2006). In order to complete such tasks successfully the firefighters must possess certain physiological characteristics. Successful completion of fire-fighting activities requires high levels of contribution from both aerobic and anaerobic energy systems (Bilzon et al., 2001; Gledhill and Jamnik, 1992) and is associated with high levels of muscular strength and endurance. In an occupational setting such as firefighting, protective clothing is required to shield the individual from hazards (e.g. fires and chemical substances) that may be encountered during work. The protective clothing worn by firefighters is typically heavy, thick with multiple layers, and also encapsulates the head. The reduced water-vapour permeability across the clothing layers also limits the rate of evaporative heat exchange with the environmental conditions increasing the degree of physiological strain (Cheung et al., 2000; Nunneley, 1989). The combined effects of strenuous exercise, protective clothing, and high ambient temperatures under which firefighters are frequently required to operate may lead to high levels of cardiovascular and thermoregulatory strain. Such physiological alterations are frequently associated with decrements in work capacity (Hancock and Vasmatzidis, 2003) and heat-induced exhaustion (Cheung et al., 2000).

In this review we will summarise the available literature on the physical demands of fire-fighting activities and the physical attributes required for successful performance of such tasks. The physiological responses during fire-fighting simulations, the metabolic effects of protective clothing, and its impact on heat production and heat loss will also be described. The final section

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will focus on research into interventions for reducing the physiological strain.

2. Physiological profile of the firefighter

The tasks associated with fire suppression and search and rescue activities impose a high physical burden on those engaged. Carrying equipment, operating in protective clothing, and dealing with the prevailing tasks entail a large outlay of energy expenditure. Given that firefighters are exposed to such stressors regularly, it is important that they possess certain physiological characteristics to allow for rapid and successful execution of fire-fighting activities. High levels of aerobic fitness, in combination with muscular strength and endurance in both the upper and lower body, flexibility, and a favourable body composition, are essential for meeting the demands associated with firefighting, maintaining the health and safety of the firefighter, and preserving public safety. Ability to perform such tasks quickly and effectively may lessen the amount of casualties and human suffering, and significantly reduce financial loss.

2.1. Aerobic fitness

Tasks such as search and rescue of victims, climbing ladders and stairs, and charging a hose when performed in full fire-fighting protective clothing and self-contained breathing apparatus can have an energy cost corresponding to 80–100% of a firefighter's $\dot{V}O_{2max}$ (Lemon and Hermiston, 1977; O'Connell et al., 1986; Bilzon et al., 2001; von Heimburg et al., 2006; Holmer and Gahved, 2007; Elsner and Kolkhorst, 2008). The findings from these studies have led to a variety of recommendations for aerobic power levels that provide an adequate safety margin for firefighters when performing fire-fighting activities.

Maximal oxygen uptake values of firefighters from various countries are shown in Table 1. With no standard test for assessing $\dot{V}O_{2max}$ it is difficult to draw comparisons between brigades as a number of studies from many different countries have reported $\dot{V}O_{2max}$ values with some measured during maximal exercise tests and others estimated using submaximal exercise protocols, multi-stage fitness test or even a questionnaire, and in some cases no indication of how $\dot{V}O_{2max}$ was assessed. The studies in Table 1 indicate that firefighters have a mean aerobic power ranging from 39.6 to 61 $ml \cdot kg^{-1} \cdot min^{-1}$; with some individual values ranging from 31.5 to 73.3 $ml \cdot kg^{-1} \cdot min^{-1}$. The firefighters at the lower end of the scale would not be able to perform successful execution of fire-fighting activities.

Elsner and Kilkhorst (2008) shied away from prescribing a definite threshold for firefighters whilst emphasising its importance, reporting that those firefighters with the lower levels for $\dot{V}O_{2max}$ tended to complete a simulation that averaged 11.65 ± 2.21 min more slowly than counterparts with higher levels of $\dot{V}O_{2max}$. Moreover, the latter group members were able to operate at a higher proportion of $\dot{V}O_{2max}$ than the former group. In a study by Sothmann et al. (1990), seven from a group of 32 firefighters voluntarily quit a protocol involving fire-fighting activities due to excessive fatigue; five of the firefighters had $\dot{V}O_{2max}$ values between 26 and 33.5 $ml \cdot kg^{-1} \cdot min^{-1}$ and the remaining two had $\dot{V}O_{2max}$ values below 35 $ml \cdot kg^{-1} \cdot min^{-1}$. As a result of these findings the authors proposed an aerobic power value of 33.5 $ml \cdot kg^{-1} \cdot min^{-1}$ as the minimum acceptable level for performing fire-fighting activities. Another important finding from this study was that performance time of the fire-fighting simulation increased with advancing age even when subjects were matched for $\dot{V}O_{2max}$. This finding and the fact that both cross-sectional and longitudinal studies have indicated a decline in maximal aerobic power at a rate of around 5 $ml \cdot kg^{-1} \cdot min^{-1}$ per decade after the age of 30 years in both endurance-trained and untrained individuals (Buskirk and Hodgson, 1987; Wilson and Tanaka, 2000) and firefighters (Kilbom, 1980; Saupe et al., 1991) have implications for firefighters of advancing age, as the required demands for successful completion of fire-fighting activities remain the same regardless of age.

In a study of UK firefighters, Scott et al. (1988) reported that over 93% of firefighters rated themselves as having average or above-average fitness levels compared to the general population. The mean $\dot{V}O_{2max}$ of the firefighters in this study was 43.7 $ml \cdot kg^{-1} \cdot min^{-1}$. Peate et al. (2002) also reported a lack of association between self-perception and actual aerobic fitness in US firefighters. From a group of firefighters in this study who rated themselves as having high fitness levels, 29% had a $\dot{V}O_{2max}$ value

Table 1
Summary of studies reporting aerobic capacity for firefighters.

Author/year	Origin	Number	Age/range	$\dot{V}O_{2max}$/range	Method
Davis et al., 1982	USA	100 males	33.1 ± 7.6/21–57	39.6 ± 6.42	Balke Treadmill protocol
Skoldstrom, 1987	Sweden	8 males	35 ± 4/30–42	49 ± 7/45–54	Astrand protocol
Faff and Tutak, 1989	Poland	18 males	29 ± 7	41.4 ± 8.8	Cycle ergometer
Gahved and Holmer, 1989	Sweden volunteer and professional firefighters	2 x 12 males	V, 33 ± 5/ P, 34 ± 3	V, 47 ± 7.2/P,47.5 ± 5.7	
Ilmarinen et al., 1997	Finish firefighting instructors	8 males	38 (31–44)	51.6/ 46-60	Not stated
Smith and Petruzzello, 1998	USA	10 males	34.5 ± 5/ 28-42	44.8 ± 4.7/37–53	Estimated from 1.5 mile run
Carter et al., 1999	Canada	12 males	31.8 ± 6.7	61 ± 3.9	Cycle ergometer
Weafer, 1999	UK Petro-chemical plant fire response group	14 males	28.5 ± 1.8	48.75 ± 4.96	Bruce Protocol Treadmill
Budd, 2001	Australian bush firefighters	28 males	26 /18–45	47/31–63	Not stated
Hooper et al., 2001	U.K	21 males,1 female	35 ± 8/21–54	43.7 ± 6/34.3–57.8	Stepping exercises
Bilzon et al., 2001	UK Royal Navy firefighters	34 males, 15 females	26 ± 7 m/26 ± 6	54.6 ± 5 m/43 ± 8.1 f	Treadmill $\dot{V}O_{2max}$ test
Peate et al., 2002	USA	96 males, 5 females	32 ± 8/20–58	41.8 ± 8	Bruce Protocol Treadmill
Clark et al., 2002	USA	168 males	33.5 ± 8.6/18–58	44.6 ± 5/31.5–58	Bruce Protocol Treadmill
Eglin et al., 2004	UK firefighting instructors	13 males	37.5 ± 3.3	43.1 ± 7.7	Submaximal step test
McLellan and Selkirk, 2004	Canada	24 males	39 ± 0.7	51.2 ± 1	Treadmill $\dot{V}O_{2max}$ test
Eglin et al., 2004	UK firefighting instructors	10 males	38.2 ± 4.8	42.4 ± 7.5	Predicted (Astrand et al 2003
Smith et al., 2005	USA	11 males	31.8 ± 6/24–38	43.4 ± 5.7/35–54	Estimated from 1.5 mile run
Selkirk et al., 2004	Canada	15 males	41 ± 1	45.7 ± 1.4	Treadmill $\dot{V}O_{2max}$ test
von Heimburg et al., 2006	Norway	14 males	38 ± 9/26–54	53 ± 5/41–63	Graded treadmill test
Ilmarinen et al., 2004	Finland	12 males	32.1/26–46	46.9 ± 9.5/33.4–73.3	Not stated
Carter et al., 2007	UK	10 males	33.3 ± 4.2	50.9 ± 7.0	Treadmill $\dot{V}O_{2max}$ test
Barr et al., 2008	UK Firefighters	12 males	40.63 ± 7.9/28.2–49.8	43.54 ± 3.92/50.5	Bruce Protocol Treadmill
Barr et al., 2009	UK Firefighters	9 males	41.92 ± 6.7/28.2–52	43.32 ± 5.4/33.4–51.13	Bruce Protocol Treadmill