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Relationship between novel design modifications and heat stress relief in structural firefighters' protective clothing

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ABSTRACT

The purpose of this study was to investigate design modifications in structural firefighter turnout suits for their ability to reduce heat stress during firefighting activities. A secondary aim of this research established a benchmark for the manikin heat loss value necessary to achieve significant improvements in physiological comfort. Eight professional firefighters participated in five simulated exercise sessions wearing a control turnout suit and one of four turnout prototypes: Single Layer, Vented, Stretch, and Revolutionary. Physiological responses (internal core body temperature, skin temperature, physiological strain, heart rate, and sweat loss) were measured when wearing each turnout suit prototype. Results demonstrated a significant increase in work time and significant reductions in heat stress (core temperature, skin temperature, and physiological strain) when participants wore the Single Layer, Vented, and Revolutionary prototypes. An estimated garment heat loss value of 150 W/m^2 was determined in order to achieve a significant reduction in heat stress.

1. Introduction

The profession of firefighting is one of the most dangerous occupations in the world. Firefighting results in an average of 80,000 occupational injuries per year (Park et al., 2011), with over half of those due to heat stress and cardiovascular strain (Rossi, 2001). Firefighters face numerous hazards, especially those of heat, flame, and high temperature exposure. Other concerns include liquid protection (from water and steam), chemical protection (from carcinogen causing contaminants), trips and falls, impact penetration resistance (to avoid punctures from sharp objects), and fatigue. While the majority of these hazards come from the external environment, others are a direct or indirect result of the portable clothing environment itself (Coca et al., 2010; Park et al., 2015; Watkins, 1984), such as the heat stress caused by the inability to dissipate heat from the clothing microclimate to the external environment.

Working in a hot, humid environment and performing substantial physical activity, with the addition of protective clothing, adds to the heat load on the body, (Havenith, 1999; McLellan and Selkirk, 2005). The human body is constantly working to achieve thermal homeostasis in which a balance between heat production and heat dissipation is required (Holmér, 2006). When restrictions to heat transfer are imposed, such as heavier and bulkier garments, physical work requires more energy and produces greater metabolic heat (Holmér, 2006). For the body to maintain thermal homeostasis it must dispel the gain in metabolic heat. Clothing layers create both thermal and evaporative heat resistance, further hindering heat loss. The inability of the body to maintain its proper heat balance can lead to heat illnesses such as fatigue, exhaustion, stroke, and even fatality. Heat strain occurs when the body can no longer regulate core temperature at the necessary level (D S Moran et al., 1998a,b). For healthy participants, the body's thermostat for intestinal core temperature is set around 37 °C (Cabanac, 1981). Heat exhaustion, however, begins to occur between 38 °C and 40 °C. To reduce the risk of heat strain, and improve the physiological comfort of structural firefighter turnout garments, more research to improve heat loss through the clothing system needs to be conducted.

Protection requirements often exacerbate thermoregulation issues as they contradict the need for heat dissipation. For example, additional protection from thermal exposure for firefighters has been achieved, in recent decades, by adding thicker layers and more of them to the design of the turnout suit. This increase in fabric thickness and overall material layers creates a heavier ensemble and decreases the air and moisture transfer necessary for sufficient heat loss to occur (Rossi, 2001). Extra thickness and garment bulk add to the amount of energy expended during physical activity and reduce the time it takes to reach fatigue (Barr et al., 2010; Dorman and Havenith, 2009; Duggan, 1988). This method of improving thermal protection also makes it more difficult to perform the work and leads to a greater risk of overheating (Dorman

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Abbreviations

THL	Total Heat Loss
IRB	International Review Board
USAR	Urban Search and Rescue
PBI	Polybenzimidazole, PTFE Polytetrafluoroethylene, SCBA Self-Contained Breathing Apparatus
Tsk	Skin temperature
PSI	Physiological Strain Index
ANOVA	Analysis of variance
NFPA	National Fire Protection Association

and Havenith, 2009; Duggan, 1988).

The approach of protecting firefighters from the worst case flashover scenario 100% of their working time is unnecessary. Firefighters only spend, on average, 10–20% of their working time in or around a structural fire, leading to excessive clothing insulation between 80 and 90% of a firefighter's working time (Den Hartog, 2010; Rossi, 2001), which creates a negative impact on wearer comfort. Therefore, better optimization between protection and comfort is needed in order to reduce heat stress during normal working conditions (i.e. goodwill calls, vehicle accidents, extrications, urban search and rescue (USAR), and emergency medical responses), which make up the majority of a firefighter's on-duty work time.

Previous studies have explored reducing the thermal burden of structural firefighter turnout suits by using a thermal manikin and through virtual modeling methodologies, as it is not always feasible to conduct human wear trials (Ellison et al., 2006; Li et al., 2007; McQuerry et al., 2016b, 2016c; Ross et al., 2012). McQuerry et al. (2016b) found that removing inner liner layers (moisture barrier and thermal liner) for specific firefighting work conditions where these layers are not essential significantly improved heat transfer on the garment level. These findings support a modular or adaptive layering approach to the design of turnouts to reduce heat strain. A modular systems approach can be defined as strategic layering of the clothing ensemble for specific working conditions. For example, single layer USAR suits and two-layer vehicle extrication suits currently exist on the market today, constructed using the same layers and materials that already exist in the traditional three-layer turnout suit. Due to budgetary reasons, purchasing multiple suits for different activities is not feasible; nor is this option practical, as the garment layers needed for these activities already exist in the required turnout suit. As simple as this clothing modification may sound, modularity has not been explored before on the human wear level in a structural firefighter turnout suit application.

The same researchers also measured significant improvements in heat loss when ventilation designs were strategically fabricated into structural turnout suits (McQuerry et al., 2016c). The practical application of such ventilation openings would be during the 80–90% of the firefighter's working time when they are not exposed to direct heat or flame. Activities such as responding to a vehicle accident on a hot and humid summer day or working emergency medical operations at an outdoor event are examples of when such a heat stress relieving clothing modification may be deployed. It should be noted that the majority of the clothing modifications explored in this study would be intended for implementation during non-structural firefighting activities.

A third potential modification to be explored is the strategic reduction of layers in isolated locations, as opposed to whole garment layers. Recent literature supports the removal of additional reinforcements in specific areas without a sacrifice in required thermal protection, per the National Fire Protection Association (NFPA) standards (McQuerry et al., 2015; National Fire Protection Association, 2013). In this study, we explored the isolated reduction of thermal liner batting layers in the torso region in combination with the firefighter's base layers, which are not considered part of the protective ensemble in current NFPA standards. Pilot data indicated no decrease in thermal protective performance (TPP) when removing these layers.

The purpose of this study was to investigate clothing design modifications for their ability to reduce heat strain experienced by firefighters. Four individual design modifications were evaluated in a structural firefighter protective clothing application. These designs included: garment ventilation openings, strategic reduction of fabric layers, systems modularity, and air gap volume reduction. This research also investigated the relationship between the heat loss properties of each clothing modification and its ability to effectively reduce heat strain when worn on the human body during simulated exercise.

A secondary goal of this study was to establish a benchmark for the amount of heat loss necessary to produce a significant reduction in heat

Fig. 1. Control turnout suit and developed prototype designs: single layer USAR system, Vented prototype, Stretch prototype, and Revolutionary prototype with combined designs.