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Effect of base layer materials on physiological and perceptual responses to exercise in personal protective equipment

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ABSTRACT

Ten men (non-firefighters) completed a 110 min walking/recovery protocol (three 20-min exercise bouts, with recovery periods of 10, 20, and 20 min following successive bouts) in a thermoneutral laboratory while wearing firefighting personal protective equipment over one of four base layers: cotton, modacrylic, wool, and phase change material. There were no significant differences in changes in heart rate, core temperature, rating of perceived exertion, thermal discomfort, and thermal strain among base layers. Sticking to skin, coolness/hotness, and clothing humidity sensation were more favorable ($p < 0.05$) for wool compared with cotton; no significant differences were identified for the other 7 clothing sensations assessed. Separate materials performance testing of the individual base layers and firefighting ensembles (base layer + turnout gear) indicated differences in thermal protective performance and total heat loss among the base layers and among ensembles; however, differences in heat dissipation did not correspond with physiological responses during exercise or recovery.

1. Introduction

The personal protective equipment (PPE) worn by firefighters is designed to protect against thermal injuries, products of combustion, scrapes and abrasions and falling objects. The personal protective clothing (PPC), or turnout (TO) gear, is specifically designed to protect against thermal injury and includes a thermal layer and a moisture barrier layer to prevent hot water passing through the material to the firefighter. The turnout gear that firefighters wear is typically manufactured to meet specific industry standards (NFPA, 2006) for thermal protection and evaporative heat transfer. Paradoxically, the equipment designed to afford protection also contributes to the physiological and perceptual strain experienced by the firefighter. The increased physiological strain associated with working in PPE is well documented (Cheung et al., 2010; Duncan et al., 1979; Nunneley, 1989; Sköldström, 1987; Smith and Petruzzello, 1998; Smith et al., 1995), with both the added mass of the gear, and the gear's insulating and encapsulating properties, and the positioning of the added mass contributing to the strain (Haisman, 1988).

Current standards for thermal protection and moisture transfer of firefighting clothing only apply to the turnout gear worn by the firefighters. However, the entire clothing ensemble, including the base layer or undergarment, would be expected to influence both thermal protection afforded and the transfer of moisture through the garment. Furthermore, some newly developed technical textiles are designed to wick moisture away from the skin and enhance evaporative cooling, whereas others may attenuate increases in temperature through the absorption of heat using phase change materials (Mondal, 2008). In addition to physiological and perceptual benefits, it is possible that different base layer textiles may be sensed as being more comfortable than standard fabrics.

The performance of different base layers under protective gear has been examined by several researchers. Wickwire et al. (2007) determined that a snug-fitting synthetic shirt with moisture-wicking properties worn under a bulletproof vest did not enhance cooling compared with a 100% cotton shirt. Similarly, van den Heuvel et al. (2010) observed no differences in measures of physiological or perceived strain among five different base layer configurations when worn under a standard combat uniform and body armor. Under a combat uniform alone, Fogarty et al. (2009) detected no differences in core temperature (T_{co}), skin temperature (T_{sk}), heart rate (HR) or psychophysical variables between a 100% cotton t-shirt and polyester shirt.

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Previous studies (Fogarty et al., 2009; van den Heuvel et al., 2010) that investigated the effect of a base layer worn under PPE have relied on continuous workloads where the participants wore the ensembles throughout the protocol. We are unaware of any data on the effect of different base layers on physiological and perceptual measures when the wearer is able to doff the protective clothing during planned recovery cycles. This is particularly relevant for firefighting because firefighters are encouraged or mandated to take breaks that include doffing their PPC during "rehabilitation" with the goal of reducing heat strain and hastening physiological recovery. If base layers could facilitate cardiovascular, thermal or perceptual recovery during planned cooling periods, the cumulative strain experienced by a firefighter over a specific time period could be lessened or the firefighter might be able to extend their time to fatigue.

The aims of this study were to evaluate the effect of different base layers worn under firefighting PPE on physiological and perceptual strain during an alternating work/recovery exercise protocol, to describe individual sensations to different base layers, and to assess the materials performance of the base layers individually and with turnout gear.

2. Methods

2.1. Participants

Ten healthy, physically active men from the college community were recruited for this study. The study was approved by the Institutional Review Board of Skidmore College and all participants provided written informed consent prior to testing. Additionally, each participant underwent a medical evaluation and received clearance to participate.

2.2. Clothing

Clothing ensembles were comprised of full firefighting PPE and one of four base layers: cotton (COT), modacrylic (MOD), wool blend (WOOL) or phase change material (PCM). The PCM consisted of a proprietary blend of modacrylic, rayon, *p*-aramid and spandex. Material characteristics of the base layers are presented in Table 1. All base layer shirts were loose fitting, athletic style t-shirts that had been washed and dried three times on normal cycles prior to wear. Participants and testers were blinded to the fabric in the shirts. Firefighting PPE included flash hood, gloves, boots, helmet, turnout pants and coat (G-Xtreme; Globe Manufacturing Co, LLC, Pittsfield, NH), and self-contained breathing apparatus (SCBA) (Fig. 1). The fabric weight of the turnout coat was 697 g m^{-2} and the thickness was 2.1 mm. Average mass of the PPE, including SCBA, was 19.2 kg. Nomex station pants (Topps Safety Apparel, Rochester, NY) were worn in all trials over boxers made of the same material as the t-shirt worn that day.

2.3. Study design

In order to test the physiological and perceptual responses to intermittent exercise, the study employed a repeated measures

Table 1
Base layer properties.

Textile	Weight (g m^{-2})	Thickness (mm)	Properties
Cotton	231	0.56	High regain
Modacrylic	193	0.43	Moderate wicking, resilient
Wool blend	158	0.43	Resilient, high regain, self-extinguishing
Phase change material	186	0.46	Ability to absorb, store, release heat

Note: all textiles other than cotton were flame resistant.

Fig. 1. During treadmill walking the participant wore the base layer (in this case cotton) under personal protective equipment, which included self-contained breathing apparatus.

design. Participants completed four experimental trials consisting of a 110-min alternating work/recovery protocol on a treadmill while wearing a different clothing ensemble. In each trial, participants wore full firefighting PPE (see Section 2.2) over a different base layer giving the following ensembles: COT + TO, MOD + TO, WOOL + TO, PCM + TO. Ensembles were presented in random order. All exercise testing was conducted in a thermoneutral laboratory (21.1 °C; 58.6% relative humidity [RH]).

2.4. Experimental protocol

Participants underwent 6 days of progressive acclimation in firefighting PPE prior to the start of the experimental protocol. The 110-min alternating work/recovery protocol consisted of three 20-min bouts of exercise, with bouts followed by successive seated recovery periods of 10, 20 and 20 min. Participants walked at a 5% grade on a treadmill and the speed was varied to maintain a constant relative intensity of 70–75% maximal HR on each of the 6 days. The treadmill speed achieved at the end of the acclimation period was used to establish the workload for the participant during the subsequent experimental protocol. During recovery periods, some (Recovery 1) or all (Recovery 2 and 3) PPE was doffed and fluid ingestion was standardized.

For the experimental trials, all participants consumed a standardized meal (EAS Myoplex drink, EAS, Columbus, Ohio) 1 h prior