The oxygen cost of wearing firefighters' personal protective equipment: Ralph was right!

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THE OXYGEN COST OF WEARING FIREFIGHTERS' PERSONAL PROTECTIVE EQUIPMENT: RALPH WAS RIGHT!

Nigel A.S. Taylor, Michael C. Lewis, Sean R. Notley and Gregory E. Peoples

INTRODUCTION

For firefighters, the personal protective equipment (PPE) includes thermal protective clothing, breathing apparatus, and protective head, hand and footwear. Whilst this equipment is designed to increase safety when working in hazardous conditions, it can limit work efficiency and performance. Indeed, an escalating physiological burden on the wearer will increase physiological and psychophysical strain (Gavhed & Holmér, 1989; Smith et al., 1998; Kerry et al., 2009), potentially leading to decrements in physical and cognitive performance (Hancock & Vasmatzidis, 2003; Caldwell et al., 2006).

In a parallel communication (Taylor et al., 2011), work-related injuries to firefighters were reported, revealing that increased injuries within older firefighters appeared to occur in parallel with improved protection provided by this protective equipment, and with some equipment becoming heavier. Thus, while subtle design changes were minimal, the combined load of the total ensemble may have compromised safety for some less-fit individuals. In this project, that possibility was evaluated, and the oxygen cost of each piece of protective equipment used by Australian firefighters was evaluated.

METHODS

This experiment was comprise of 12 steady-state and two maximal exercise trials. Each phase involved 20 healthy adults (20-56 years), with of equal numbers of males and females recruited into three stature classifications (tall, medium, short), each of whom provided written, informed consent to procedures approved by the Human Research Ethics Committee (University of Wollongong).

Subjects first participated in steady-state exercise treadmill walking (4.8 km.h⁻¹) and low bench stepping (20 cm at 40 steps.min⁻¹) in an air-conditioned laboratory. The former task was designed to represent realistic, but not rushed walking speeds that may be observed at a fire. The latter was considered to be an important exercise mode, since stair climbing is frequently performed by firefighters. The cadence of stepping was designed to achieve a steady-state heart rate approximately equivalent to that observed during walking. Each trial lasted 15 min to ensure the attainment of an adequate steady-state, with subjects resting at least 5 min between subsequent trials performed on the same day. Every subject performed 12, 15-min trials; six walking and six stepping trials. In addition, baseline data (5 min) were collected for seated rest and standing rest. The only variations among trials within each exercise mode involved the nature of the clothing and personal protective equipment (ensembles) worn, and these ensembles were tested in a balanced order: (a) Ensemble one (control): minimal clothing (t-shirt, shorts, sports shoes); (b) Ensemble two: underclothing plus all personal protective equipment; (c) Ensemble three: minimal clothing plus helmet; (d) Ensemble four: minimal clothing plus breathing apparatus; (e)
Ensemble five: minimal clothing, but with boots replacing sports shoes; (f)
Ensemble six: underclothing, sports shoes plus station-wear (long-sleeved
shirt, long trousers) and all thermal protective clothing.

Subjects then participated in two incremental exercise trials to voluntary
exhaustion. One test was performed with minimal clothing (control: ensemble
one above) and the second was undertaken with subjects wearing the
complete personal protective equipment ensemble (experimental: ensemble
two above). The control trial was always administered first to ensure that test
familiarity did not adversely affect performance in the experimental state.
Tests commenced with standing rest, followed by easy walking (10 min at 4.8
km.h\(^{-1}\), 0% gradient). These were baseline states used to derive physiological
reserves. In all control trials, treadmill speed was then elevated in stages over
5 min until the desired final running speed was achieved (least fit: 7.0 km.h\(^{-1}\),
moderate fitness: 8.0 km.h\(^{-1}\), most fit: 10.0 km.h\(^{-1}\)), but the treadmill gradient
(slope) was not changed. From the sixth minute, running speed was held
constant whilst the gradient was increased by 1% every minute until volitional
exhaustion was achieved. In the experimental (protective equipment) trials,
the same protocol was used, with every subject reaching the same peak
running speed that was obtained within the control trial.

In both trials, oxygen consumption and carbon dioxide production were
computed (TrueOne 2400 metabolic measurement system, ParvoMedics Inc.,
Utah, USA). Heart rate data were obtained from ventricular depolarisation
(Advantage, Polar Electro Sport Tester, Finland). All data were sampled at 15-
sec intervals.

RESULTS

Under steady-state, but not dynamic phases, oxygen consumption and
carbon dioxide production provide a valid approximation of metabolic rate. For
the walking and bench-stepping experiments, the comparison between the
control and full protective ensembles revealed respective elevations in steady-
state metabolic rate of 47% and 36% (P<0.05).

The impact of each component of the protective equipment was isolated by
first subtracting the seated resting data from each of the physiological
responses. The quiet standing data were similarly measured and subtracted
to quantify the demand placed on postural muscles. Thirdly, data from the
control trial (ensemble one), which represented the least loaded state (minus
sitting and standing rest), were subtracted from each of the other five trials
(within exercise modes). This step permitted isolation of the physiological
burden of each component of the personal protective ensemble.

In the control state, seated rest represented 30.3% of the steady-state
oxygen consumption observed when walking, while standing accounted for a
further 1-2% increase. Together, seated rest, standing and unloaded walking
contributed to 68% of the total metabolic burden, and 74% of the heart rate
response observed when wearing all of this protective equipment. For bench
stepping, these values were 73% and 76%. Thus, the impact of wearing the
protective equipment was approximately 30% of the overall effect during
these modes of exercise.

The breathing apparatus, which was greater than four times the mass of the
boots, and more than twice that of the clothing, imposed a metabolic
burden significantly less than the boots for walking ($P<0.05$), but not during stepping. In that mode, the breathing apparatus, boots and clothing had equivalent influences ($P>0.05$). Previously, Soule and Goldman (1969) reported that the oxygen cost of walking, normalised to body mass, was 12.8 mL.kg$^{-1}$.min$^{-1}$. When loads were added to the head, the burden was 13.4 mL.kg$^{-1}$.min$^{-1}$ for each additional kilogram, while for the feet, this increased to 73.6 mL.kg$^{-1}$.min$^{-1}$. Current derivations resulted in 12.94, 13.67 and 88.75 mL.kg$^{-1}$.min$^{-1}$ (respectively); *Ralph was right!* Thus, footwear not only exerted the greatest absolute burden during walking, but when normalised to the load carried, its affect was 8.7 times greater than that of the breathing apparatus. The corresponding data during stair climbing showed the boots to be 6.4 times more powerful than the breathing apparatus.

Maximal testing often has little relevance to real-world scenarios. However, firefighters do work maximally in some situations, so evaluating the physiological reserve is directly relevant to the first 5-15 minutes at an incident, and to search and rescue operations involving injured or unconscious people. The complete protective ensemble reduced exercise tolerance time by 55.9% across subjects ($P<0.05$), with women experiencing a slightly, but not significantly greater performance decrement ($P>0.05$). However, whilst the maximal absolute values for each of the key physiological variables were not significantly affected by wearing this equipment ($P>0.05$), subjects reached exhaustion significantly earlier ($P<0.05$), and at a significantly lower work rate ($P<0.05$), when wearing the protective ensemble.

Oxygen consumption data were normalised to the total mass (body mass plus equipment mass). Since the absolute oxygen consumption did not differ between trials, then normalisation highlights the impact of the protective equipment, with the relative peak oxygen consumption being reduced ($P<0.05$). This means that more oxygen was used to support the load carried, leaving less energy available for locomotion. This was reflected in a 14.5% reduction in relative aerobic power during the experimental trial ($P<0.05$).

Thus, the combined affects of an elevation in the baseline metabolic load, and a reduction in the maximal ability to exercise, will independently limit the range of exercise tolerance, thereby reducing the physiological (ambulatory) reserve. Across all subjects, the mean oxygen consumption reserve was reduced by 30.7% ($P<0.05$) by wearing the complete ensemble of personal protective equipment. Based upon evidence from these steady-state trials, it would be reasonable to assume that the boots provided a significant, and quite possibly the largest absolute and relative contribution to the load-related limits for maximal exercise.

It was anticipated that the female subjects would have been more adversely affected by this equipment. However, the opposite occurred, and it is speculated that this was perhaps associated with gender-related training history differences. Accordingly, it is suggested that the greater performance decrements in the males may have been a function of their ability to push themselves to much higher levels of strain within the control state.

**CONCLUSION**

From these observations, it may be concluded that the most efficient way to reduce the metabolic burden for firefighters wearing their full protective
ensemble would be to reduce the mass of their boots, of their clothing or of both components. For instance, removing 100 g from each boot would be metabolically equivalent to reducing the mass of the breathing apparatus by 1.74 kg during walking, or by 1.27 kg for stair climbing.

REFERENCES


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239