
International Journal of Occupational Safety and Ergonomics

ISSN: 1080-3548 (Print) 2376-9130 (Online) Journal homepage: https://www.tandfonline.com/loi/tose20

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**To cite this article:** J.I. Medbø, A. Mamen, H. Oseland & E. D. von Heimburg (2019): The steady state load of five firefighting tasks, International Journal of Occupational Safety and Ergonomics, DOI: 10.1080/10803548.2019.1573013

**To link to this article:** https://doi.org/10.1080/10803548.2019.1573013

Accepted author version posted online: 21 Jan 2019.

**Publisher:** Taylor & Francis & Central Institute for Labour Protection – National Research Institute (CIOP-PIB)

**Journal:** *International Journal of Occupational Safety and Ergonomics*

**DOI:** 10.1080/10803548.2019.1573013



# The steady state load of five fire-fighting tasks

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Word count: ≈3350 words

JOSE: http://www.editorialmanager.com/ijose/default.aspx

# Abstract

**Purpose**. Physiologic demands of five common tasks in firefighting have been examined. **Methods**. Eight male volunteers, being dressed up as smoke divers (+21 kg extra load), carried out the following tasks at constant pace for 5 min: Walking at 1.4 $m \cdot s^{-1}$, walking (all walks at the same speed) while carrying a 10 kg ladder, walking carrying two hose packs of 16 kg together, walking carrying a 32 kg spreader tool, finally climbing up and down a ladder at preset pace. A 5 min break separated each exercise. Heart rate, $O_2$-uptake and ventilation were measured continuously, and blood lactate concentration was recorded after each task. **Results**. The end-exercise heart rate rose from 108 to 180 bpm from first to last task, blood lactate concentration rose from 1 to 7 $mmol \cdot L^{-1}$, $O_2$-uptake rose from 19 to 48 $ml \cdot kg^{-1} \cdot min^{-1}$, and ventilation rose from 38 to 124 $L \cdot min^{-1}$. **Discussion**. Walking was an easy task even when dressed up as a smoke diver. Adding loads increased demands; ladder climbing taxed >90% of the subjects' aerobic power. **Conclusions**. The physiologic demands varied considerably between different tasks.


**Key words**: Firefighting; Ladder climbing; Exercise; Heart rate; $O_2$-uptake; Ventilation; Blood lactate concentration; Rating of perceived exertion.

# 1. Introduction

Firefighting is physically demanding. During simulated firefighting oxygen uptakes of around 40 $ml \cdot kg^{-1} \cdot min^{-1}$ or higher have been found in a number of studies [1, 2, 3, 4, 5, 6, 7, 8, 9]. There are therefore minimum requirements of firefirghters' physical ability. Thus, firefighters' are tested regularly on physical performance tests. The last decades firefighters have increasingly been tested in applied tests that mimic tasks firefighters meet during real firefighting and rescue work [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] as alternatives to standard laboratory tests [6, 7, 11, 13, 14, 15]. In Norway, Fredrikstad fire brigade has recently modified an applied test from Canada [16]. The new Fredrikstad-test puts sufficient physical demands on the participants to allow screening for physical suitability for firefighting [17]. That test consists of twelve tasks that are carried out in sequence at different posts with walk between each task to the next post. The overall physiological demand of that test has recently been established [17]. However, the physiological demand of each task is not known.

The physiological demands of some common tasks have been examined in former studies. Groeller and coworkers [18] found that hose dragging demanded in average an $O_2$ uptake of 2.55 $L \cdot min^{-1}$, while the demands of load carrying were considerably less. Similar results were found by Taylor and coworkers [19] who reported that dragging a fire hose four stairs up was the most demanding task on the $O_2$ delivering system of 15 different tasks examined. Simulated fire extinction with a fire hose was on the other hand among the least demanding tasks. Simulated forcibly entry using a sledgehammer raised the heart rate much without raising the $O_2$ uptake in proportion. This latter observation shows that the heart rate may not be an adequate parameter of the aerobic demand of a task. There is nevertheless limited information of the demands of different firefighting activities. Moreover, no one seems to have related measured demands of fire-fighting activities to a reference activity like walking. Further, although ladder climbing is known to be physically demanding [2, 20], there are incomplete data on the demands on this essential task too. Finally, since most firefighters wear a SCBA with a limited air reserve, we measured the lung ventilation of each task examined.

It takes several minutes of exercise at constant intensity before the $O_2$ uptake and heart rate reach steady state and thus reflect the aerobic demand of the task in question. Consequently, each task must be carried out at constant pace for several minutes, allowing the $O_2$ uptake, heart rate and related parameters to reach a steady state, to provide meaningful data. The physiological demands of three different carrying tasks at a fixed, preset speed, using walking at the same speed with no extra load carried as reference, have been measured. We further provide data on the demands of ladder climbing.

# 2. Methods

## 2.1 Approach to the problem

To study physiological demands during steady state, each participant carried out five different tasks, detailed below, in presumed increasing order of physical demand, for 5 min. The heart rate, $O_2$ uptake and ventilation were registered during the last minute of each task, and further measures of exertion were recorded just after each task.

## 2.2 Subjects

Eight male volunteers served as subjects for the study. They were 35 ± 11 yr old (mean ± *s*), 1.81 ± 0.05 m tall, weighing 84 ± 12 kg, and their maximal $O_2$ uptake was 50.8 ± 2.8 ml · $kg^{-1}$ · $min^{-1}$. They were all participants in a larger approved study [17]. They were further explained that they served as volunteers in the study and could withdraw without giving any reason.

## 2.3 Experiments

The subject dressed up as a smoke diver wearing protecting clothing and bottles with pressurized air, adding an extra mass of 21 kg as detailed further in a parallel paper [17]. In short, the firefighters wore a standard smoke diving ensemble including fireproof jacket and trousers and insulating wool underwear. They used standard protective boots and gloves. The subjects did not wear a fire helmet or an SCBA facemask. However, they wore an SCBA air backpack.

To allow measurement of the $O_2$ uptake and related respiratory parameters (e.g. ventilation and *R*), the subject wore a dedicated Hans Rudolph 7400 series face mask with a Triple V breathing valve (Cortex Biophysik, see below). A portable metabolic cart was placed in the hood of the fireproof jacket worn, and pulled over to the non-dominant shoulder and secured by Velcro bands. Consequently, respiratory parameters were measured continuously and registered at 10 s intervals during each exercise. In addition the subject wore a Polar electro heart rate belt around the chest with a dedicated recorder registering the heart rate at 5 s intervals throughout each exercise.

Each participant carried out the five task detailed below. The four walks were carried out in the main hall, serving as a garage for fire trucks, at Fredrikstad fire station (Norway). From the starting line the subject walked 35 m toward the wall at the far end, turned and walked back, turned around to start a new 70 m cycle. The walking speed was preset to 1.4 m · $s^{-1}$, which means the each 70 m cycle took 50 s. Throughout the exercise the subject received feedback on the walking speed, thus allowing him to adjust the speed to the preset value. Each 70 m walk was repeated six times in 5 min for each of the four walk exercises described below. The chosen walking speed was approximately that found for the average subject when carrying out the different tasks in the Fredrikstad test [17]. Moreover, that speed allowed six full cycles in 5 min.

For the ladder climb a corresponding procedure was carried out. More specifically, each climb of ten rungs up and ten rungs down was preset to take 15 s. That pace equals that of the average participant in a parallel study [17]. Thus, in 5 min each participant (except one) climbed 20 times up and down in 5 min. For one very powerfully built and heavy subject (body mass 112 kg) being moderately fit, it was deemed that this pace would be too demanding for 5 min continuous climbing up and down for him, and that it would clearly involve considerable anaerobic energy release. Therefore, for this latter subject the pace was set to 20 s per cycle up and down. This subject thus climbed 15 times up and down in 5 min.

Each subject carried out the following five tasks and was allowed 5 min rest between two consecutive exercises:

1. 5 min walk at a speed of 1.4 $m \cdot s^{-1}$ (task 1). The subject wore only the firefighter outfit plus bottles with pressurized air plus the metabolic cart measuring his $O_2$ uptake. This additional gear weighed altogether 21 kg.
2. 5 min walk at the speed of 1.4 $m \cdot s^{-1}$ while carrying a 10.1 kg double ladder on the preferred shoulder in addition to the 21 kg outfit described above.
3. 5 min walk at the speed of 1.4 $m \cdot s^{-1}$ while carrying two packs with empty fire hoses weighing 16.2 kg together in addition to the outfit of task 1.
4. 5 min walk at the speed of 1.4 $m \cdot s^{-1}$ while carrying a 32 kg spreader tool in addition to the outfit of task 1.
5. 5 min continuous climb ten rungs up and ten rungs down while wearing the outfit plus metabolic cart (task 1). There was 30 cm between the rungs. Both feet had to be at the top rung before a decline started. Likewise, both feet had to be on the ground before a new climb started. The ladder made and angle of ≈25° to the wall (65° to the level ground), which means that 3 m walk in the ladder equals ≈2.7 m vertical climb [$\cos(25°) = \sin(65°) \approx 0.9$].

Just after completing a task the subject's perceived ratings of exertion was rated on Borg's CR-10 scale [21, 22], and a blood sample was taken from a cleaned finger tip for measuring the blood lactate concentration.

## 2.4 Instruments

Expiratory gases were collected and continuously analysed by a MetaMax II metabolic cart (Cortex Biophysik, Leipzig, Germany). That instrument's performance has been found to be among the better portable metabolic analysers available [23, 24]. The reported $O_2$ uptake has been found to be a few per cent higher than the true value (reference against the Douglas bag technique [24]).

The MetaMax II underwent a full two-point calibration before the first testing each day. More specifically, after a 30 min warm-up period of the instrument, the instrument underwent a standard two-point gas calibration procedure using ambient air in a well-ventilated room, and a gas mix of known content (0.01% $O_2$ and 5.01% $CO_2$ in $N_2$ for the present case), respectively. Calibration of the Triple V volume transducer was done with a calibrated 3 L syringe (Calibration Syringe D, SensorMedics, CareFusion, San Diego, CA, USA), and the unit's barometer was checked against a separate high-precision barometer (PTB 330 digital barometer, Vaisala OY, Vantaa, Finland). In addition, before each testing volume calibration and one-point gas calibration (room air) were carried out.

The heart rate was recorded with an S610i Polar heart rate monitor (Polar Electro OY, Kempele, Finland). The blood lactate concentration was measured by a Lactate Pro LT-1710 analyser (Arkray Inc, Kyoto, Japan). This instrument has been evaluated and found to be accurate for measuring the blood lactate concentration precisely, and further to be suited for field experiments over a wide range of conditions [25, 26]. Rating of perceived exertion was recorded with the Borg CR-10 scale [21, 22]. For comparisons with essential outcomes in this study, the CR-10 scale scores “very easy” as 1 and “very strenuous” as 7.

## 2.5 Data analyses and statistics

Data on $O_2$ uptake, lung ventilation, and heart rate reported as steady state values are mean values during the fifth minute of exercise at constant intensity. The data are summarized as mean ± *SD* of the eight subjects.

# 3. Results

The heart rate during the fifth minute of exercise rose from 108 ± 15 bpm at the end of the first walk to 180 ± 14 bpm at the end of the ladder climb, the latter value being close to the subjects' maximum value of 188 ± 10 bpm (Fig. 1, top panel). The perceived exertion rose from 1.0 ± 0.6 ("very easy") after the first walk to 6.2 ± 1.6 (close to "very strenuous") for the ladder climb (Fig. 1, lower panel). The blood lactate concentrations rose from less than 1 mmol · $L^{-1}$ after the first walk to 7.3 ± 3.2 mmol · $L^{-1}$ at the end of the ladder climb, in fairly close agreement with the numeric value of the reported CR-10 score.

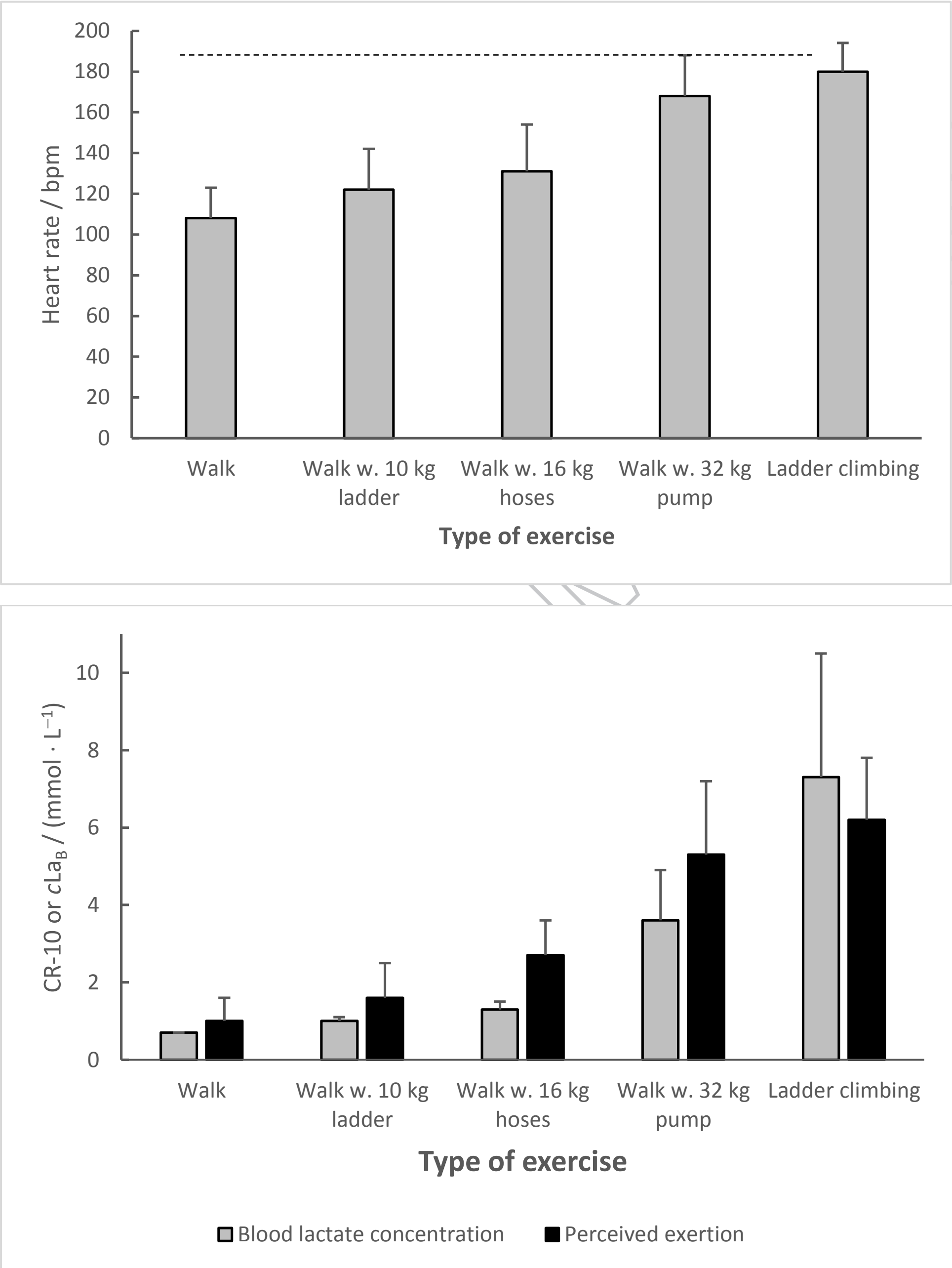


Figure 1. Heart rate (top panel) and blood lactate concentration and perceived exertion ($c\text{La}_B$ & CR-10 score; lower panel) at the end of 5 min continuous exercise of (left to right) walking at 1.4 m · $s^{-1}$, walking while carrying a 10 kg ladder, walking while carrying 16 kg fire hoses, walking while carrying a 32 kg spreader tool, and climbing up and down a ladder at a preset pace. The dashed line for the heart rate marks the maximum

heart rate for the average firefighter. The data are mean ± *SD* of eight firefighters being dressed up as smoke divers wearing protective clothing and a breathing apparatus weighing altogether 21 kg in addition to the tools carried.

The $O_2$ uptake during the last minute of each task rose from 19.2 ± 2.2 ml · kg$^{-1}$ · min$^{-1}$ for level walking to 46.0 ± 4.8 ml · kg$^{-1}$ · min$^{-1}$ for ladder climbing (Fig. 2, grey bars). The latter value was 91% of the subjects' maximal $O_2$ uptake.

For the four walks the $O_2$ uptake was further expressed per kg total mass carried (body mass + protective clothing and bottles + tools carried) to provide a measure of the mechanical efficiency of walking in the different conditions. That value rose slightly from 15.3 ± 1.8 ml · kg$^{-1}$ · min$^{-1}$ for walking while carrying no tool to 18.8 ± 1.1 ml · kg$^{-1}$ · min$^{-1}$ (+23%) when carrying the 32 kg spreader tool (Fig. 2, black bars).

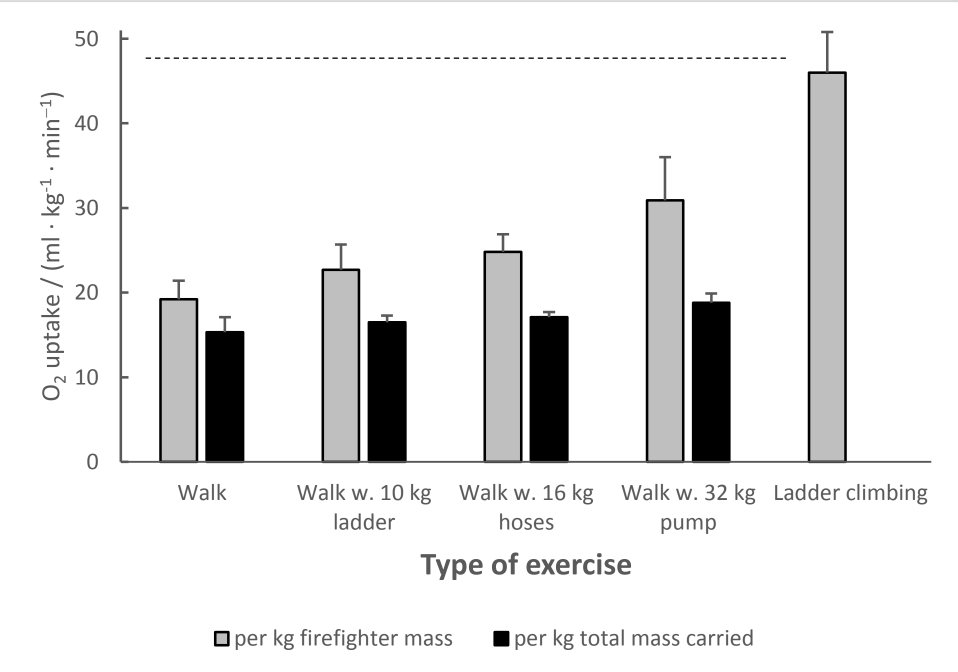


Figure 2. $O_2$ uptake expressed per kg body mass (grey bars) or per kg total mass carried (body mass + protective clothing and bottles + tools carried, black bars) at the end of 5 min continuous exercise of (left to right) walking at 1.4 m · s$^{-1}$, walking while carrying a 10 kg ladder, walking while carrying 16 kg fire hoses, walking while carrying a 32 kg spreader tool, and climbing up and down a ladder at a preset pace. The dashed line marks the maximal $O_2$ uptake for the average firefighter. The data are mean ± *SD* of eight firefighters being dressed up as smoke divers and thus carrying protective clothing and a breathing apparatus weighing altogether 21 kg in addition to the tools carried.

The $O_2$ uptake was further expressed as the $O_2$ cost of movement. For the four walks that means $O_2$ uptake per meter walked per kg "firefighter mass" (body mass + 21 kg protective clothing with bottles). That cost rose from 0.18 ± 0.02 ml $O_2$ · m$^{-1}$ · kg$^{-1}$ for walking with no tools to 0.29 ± 0.05 ml $O_2$ · m$^{-1}$ · kg$^{-1}$ for walking while carrying the 32 kg spreader tool (+61%; Fig. 3).


Figure 3. $O_2$ uptake per meter of level walking, expressed per kg body mass (bm) plus mass of 21 kg of protective clothing (outfit), taken from measurements of the $O_2$ uptake at the last minute of 5 min continuous exercise of (left to right) walking at 1.4 m · $s^{-1}$, walking while carrying a 10 kg ladder, walking while carrying 16 kg fire hoses, and walking while carrying a 32 kg spreader tool. The data are mean ± *SD* of eight firefighters being dressed up as smoke divers and thus carrying protective clothing and a breathing apparatus.

For ladder climbing the $O_2$ cost of climbing one rung up and down was 0.95 ± 0.05 ml $O_2$ · $kg^{-1}$ · $rung^{-1}$. That latter value is not directly comparable to that of level walking, and the values are therefore not included in figure 3. Since the distance between two rungs was 0.30 m, and the sine of the inclination angle was ≈0.9, the $O_2$ uptake corresponds to 0.95 ml $O_2$ · $kg^{-1}$ · $rung^{-1}$ vertical climb = 3.5 ml $O_2$ · $kg^{-1}$ · $m^{-1}$ vertical climb.

The lung ventilation rose from 38 ± 7 L · min$^{-1}$ for level walking to 124 ± 18 L · min$^{-1}$ for ladder climbing (Fig. 4, upper panel). The respiratory exchange ratio (*R*) rose from 0.81 ± 0.03 for level walking to 0.95 ± 0.04 for ladder climbing (Fig. 4, lower panel).

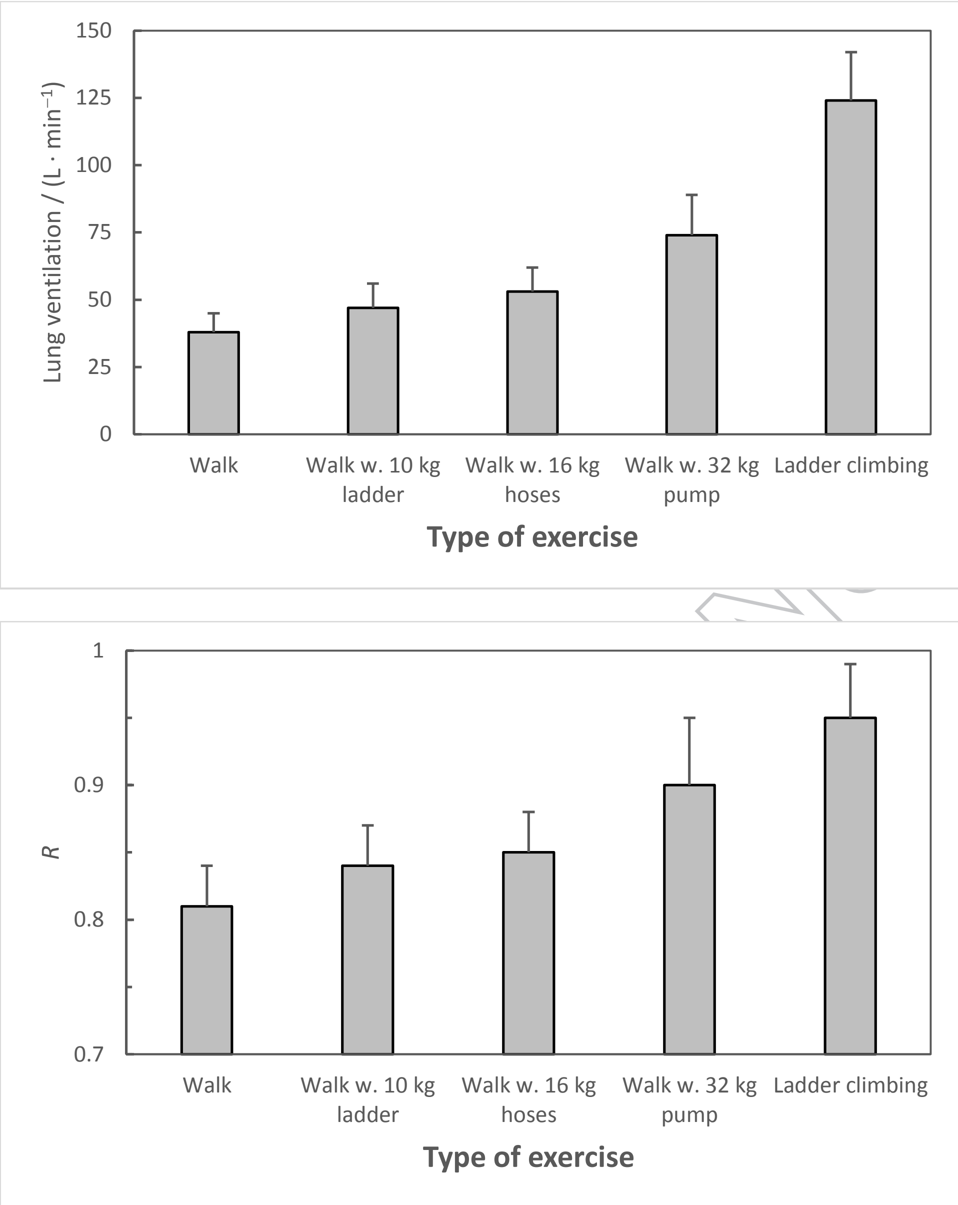


Figure 4. Lung ventilation (top panel) and *R* (lower panel) at the end of 5 min continuous exercise of (left to right) walking at 1.4 m · s$^{-1}$, walking while carrying a 10 kg ladder, walking while carrying 16 kg fire hoses, walking while carrying a 32 kg spreader tool, and climbing up and down a ladder. The data are mean ± *SD* of eight firefighters being dressed up as smoke divers and carrying protective clothing and a breathing apparatus weighing altogether 21 kg in addition to the tools carried. The y-axis of the lower panel starts at 0.7.

## 3.1 Summary statistics

For each parameter examined above (heart rate, blood lactate concentration, CR-10 score, $O_2$ uptake, lung ventilation, and *R*) the values rose statistically significantly with increasing exercise demand.

# 4. Discussion

The main results in this study were first that level walking carrying no extra mass apart from the protective clothing plus bottles with pressurized air, was a task with low physiologic demands. Ladder climbing at the preset pace forced the subjects to exercise near their maximal $O_2$ uptake and heart rate. For the other three tasks, where the subjects were carrying equipment of different masses, the physiologic demands were between these extremes.

The Fredrikstad-test is composed of eight different tasks that are carried out altogether twelve times. Between each task there is 7 to 47 m walk, altogether 289 m for the sum of the eleven walks. Each task lasts less than 1 min and with no rest between tasks. Since it takes several minutes for the $O_2$ uptake and heart rate to reach steady state values, those quantities lag behind each task's demand. Moreover, the responses to the demands of one task are carried over to subsequent tasks. Therefore the demand of each separate task cannot be assessed during continuous measurements of the Fredrikstad-test.

We have here quantified the physiologic demands of four of the tasks, tasks that are carried out altogether seven times during the test, in addition to the walking between tasks. We used level walking with no extra load as a reference for comparisons of walking while carrying extra loads. We have in addition measured the demand of ladder climbing since those measurements were readily carried out. Practical and organizational considerations did not allow corresponding measurements of the four remaining tasks. More specifically, each of them would presumably involve anaerobic energy release when carried out as in the main test.

Our data suggest that the aerobic demand of the five activities examined averaged 19 (walking), 23 (walk while carrying a ladder), 25 (walk while carrying hose packs), 31 (walk while carrying the spreader tool), and 48 ml · $kg^{-1}$ · $min^{-1}$ (ladder climb). The latter value is the average of the seven subjects walking up and down twenty times, excluding data on the one who climbed at a lower pace.

Several former studies have examined physiologic demands of fire-fighting activities. Gledhill and Jamnic found that vertical ascends, particular when carrying heavy equipment, was the most demanding [2]. Our data on the demands of ladder climbing are in line with that. Bilzon and coworkers found that carrying 30 kg drums of liquid foam was the most strenuous task, demanding around 42 ml $O_2$ · $kg^{-1}$ · $min^{-1}$ [5]. Our task of carrying a 32 kg spreader tool, demanding only 31 ml $O_2$ · $kg^{-1}$ · $min^{-1}$, might appear similar to that task. An important difference is that while our subjects carried the spreader tool on a level floor, the subjects of Bilzon et al. carried their drums down a ladder. Thus, it may be more important whether movements are in the vertical or horizontal plane than whether additional masses are moved. Moreover, even descends may be more demanding than level walking.

Rescuing victims has been part of several simulated fire-fighting studies. The demands of such activities are conflicting. The participants in the study of Bugajska and coworkers experienced that task as the most demanding and considerably more strenuous than extending stairways [27]. Recently Taylor and coworkers examined that further [19]. Their results confirm the findings of Bugajska and coworkers that rescue victim is experienced as being "very strenuous". However, the aerobic demand was measured to be around 1.8 L · $min^{-1}$ (20–25 ml · $kg^{-1}$ · $min^{-1}$ for an average male firefighter). There may thus be a mismatch between subjectively experienced and physiologically measured demands, at least for that task. As pointed out above, upper body exercise may raise the heart rate in disproportion to the increase in the $O_2$ uptake. Thus, one specific task may be scored as more or less strenuous depending on what quantity is being measured or rated.

We measured the physiologic demands of five different types of fire-fighting tasks. These values allow us to draft a test based on these tasks and further to estimate the aerobic demand of this hypothetical test. More specifically, in the Fredrikstad-test walking between tasks took 33% of the total time. Consequently, the aerobic demand of that task weighs 33% of the total. In the hypothetical test each of the three next tasks weigh equally, while ladder climbing is given double weight since that task is repeated during the real Fredrikstad-test. The calculated aerobic demand of that hypothetical test is only 29.2 ml · $kg^{-1}$ · $min^{-1}$ for the average subject. Further, the estimated heart rate of this test is 140 bpm, the lung ventilation 69 L · $min^{-1}$, the expected blood lactate concentration 2.8 mmol · $L^{-1}$, and the expected CR-10 score 3.3. All values are far less than those recorded for the real Fredrikstad-test [17].

It could be argued that these data are based on walking at a speed of 1.4 m · $s^{-1}$. It appeared that on the Fredrikstad-test the average subject walked around 10% faster. Correcting for this gives an estimated aerobic demand of around 32 ml · $kg^{-1}$ · $min^{-1}$. That value is still only 70% of the measured $O_2$ uptake during the real test (excluding low values during the first few minutes). It is also lower than our proposed lower limit of 35 ml · $kg^{-1}$ · $min^{-1}$ for strenuous activity during firefighting [11, 17].

These considerations suggest that the Fredrikstad-test is far more demanding physiologically than the hypothetical test composed of the five different tasks examined here. Consequently, the demands of the four kind of tasks not examined here, are presumably higher than for those examined here, perhaps except for the ladder climbing. There may thus be a need for examining the physiologic demand of the four remaining tasks, if possible.

To sum up, real firefighting and rescue work is a mixture of several different tasks. Our results show that the physiological demand varies considerably between tasks. Consequently, tests that include only one or a few tasks may have limited value.

## Conflicts of interest

The authors have no potential conflict of interest in this study.

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