Oxygen Uptake and Heart Rate During Simulated Wildfire Suppression Tasks Performed by Australian Rural Firefighters

Matthew Phillips[1,2], **Warren Payne**[3], **Kevin Netto**[1,4], **Shane Cramer**[5], **David Nichols**[2,5], **Glenn K McConell**[3], **Cara Lord**[1,2] **and Brad Aisbett** [2,6*]

[1]*School of Exercise and Nutrition Sciences, Deakin University, Burwood, Vic, Australia*

[2]*Bushfire Co-Operative Research Centre, East Melbourne, Vic, Australia*

[3]*Institute for Sport, Exercise and Active Living, Victoria University, Footscray, Vic, Australia*

[4]*School of Physiotherapy and Exercise Science, Curtin University, Perth, Australia*

[5]*Country Fire Authority, Burwood East, Vic, Australia*

[6]*Centre for Physical Activity and Nutrition Research, Deakin University, Burwood, Vic, Australia*

[*]**Corresponding author:** Brad Aisbett, Centre for Physical Activity and Nutrition Research, Deakin University, 221 Burwood Hwy, Burwood, Vic, Australia 3125, Tel: +613 9244 6474; Fax: + 61 3 9244 6017; E-mail: brad.aisbett@deakin.edu.au

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based job task analyses [16], identified that there were seven tasks that were both physically demanding and performed by all personnel. Special roles, such as remote area crews where firefighters hike long distances carrying a pack [14] were not included to focus analyses on the core tasks, common to all firefighters. The seven tasks identified comprised advancing a charged (i.e., filled with pressurized liquid) 38-

fire hose. The dry mass of the hose rig was 26.5 kg, 111.1 kg when filled with water. For the hose repositioning task, two firefighters worked together to relocate two lengths of charged 38-mm canvas hose 20 m back from their start position and then 40 m laterally to a new position. The hose weighed 74.5 kg when the two canvas lengths (60 m) were filled with water.

In the blacking out task, two firefighters worked together to 'contain' five major fuel sources (as if they were burnt, burning, or smouldering in a wildfire) in a 50-m by 5-m area. The major fuel sources were identified before all task repetitions in consultation with a local brigade captain, with 30-yr membership with the CFA. For the hose operator task, the two firefighters worked together to drag two lengths of charged 38-mm diameter hose through the marked area and open the hose nozzle and spray water on the fuel source until saturated (lasting approximately five seconds). The rake hoe operator used a rake hoe, which consisted of a 25-cm wide blade (one edge has 'prongs', the other straight) attached to 105- to 130-cm long handle and weighs approximately 2.4 kg [21], to chip or hack away small plants and rake surface litter, clearing all debris around the fuel source before the hose operator applied water.

During the solo handtool task, individual firefighters were instructed to use their rake hoe to chip or hack away small plants and to rake surface litter so as to remove all combustible material from a one-metre wide strip of ground. Each repetition was supervised by a subject-matter expert (a local brigade captain with 30 yr experience with CFA). When required, the subject-matter expert asked participants to re-rake an area of ground to maintain the standard of their work. It was not possible to create a simulation where firefighters worked continuously for the 10-30 minutes considered 'typical' for solo handtool work by Australian rural fire authority crews [15].Multiple repetitions of this duration would have had a drastic negative impact on the state park where the testing was conducted. In an effort to capture the continuous nature of the work, firefighters raked continuously for two minutes before any physiological measures were recorded, followed by 75 strokes. The requisite number of strokes was devised in pilot testing as a trade-off between achieving a continuous work profile and not having a critical adverse effect on the local environment.

For the team fine line building task, a four-person rake hoe team worked to create a one-metre wide fire break. Firefighters used the 'step up' method as described by [22]. Each repetition was supervised by the same subject-matter expert identified previously. As for the solo handtool task, the subject matter expert had the authority to instruct the participants to re-rake an area and it was not possible to have fire crews work continuously for 20-30 minutes. In an effort to capture the continuous nature of the work firefighters raked continuously for two minutes before any physiological measures were recorded. Thereafter, physiological measures were collected on a single firefighter who rotated through each of the four positions in the team, every 25 strokes. The 'team' working with the firefighter being measured changed across successive repetitions, however, the composition of the team is likely to have little impact on the individual, given the nature of the 'step up' approach, where all firefighters worked at their own pace [22].

In the spot fire containment task, firefighters completed 75 rake hoe strokes 'as fast as possible' around a hypothetical spot fire. Firefighters followed a path behind the subject-matter expert, completing 37, one-metre wide strokes along one flank of the 'fire', a stroke on the turn and 37 strokes along the other flank back to their point of origin. Again the simulation was shorter in duration than the five minutes considered 'typical' for spot fire containment [15], but represented a practical compromise between capturing the essence in the task and significant disruption to the environment.

For all handtool tasks, firefighters worked at their normal operational pace. For the solo handtool and team line build tasks, physiological measures were collected after two minutes of steady raking to capture the true cardiovascular response, as cardiovascular measures have been shown to approach a steady state after 90 seconds of continuous work [23]. Physiological responses were collected throughout all other tasks. In team (i.e., team fine line build and

and speed for each task were compared using a one-way analysis of variance (ANOVA), with task as the within-participant factor. Task duration was not compared as differences in task duration would simply reflect simulation design parameters, rather than inherent task differences. Task duration was, however, reported to aid inter-study comparisons with previous literature. Speed was compared to provide context to the VO_2 and HR values elicited during each task. When ANOVA revealed a significant effect for task, simple effects analyses was used to isolate where the differences lay. All results are presented as means ± standard deviations (SD), unless otherwise stated. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS 18.0, IBM, Champaign, Ill) and statistical significance was set at P < 0.05.

There was no difference between the age of the male and female participants (P = 0.992). The age of the sample was 43.2 ± 13.7 yr. The male participants (height; 175.2 ± 7.1 cm, body mass; 84.3 ± 12.5 kg) were 16.8 ± 5.8 cm taller (P = 0.045) and 16.0 ± 14.7 kg heavier (P = 0.001) than the female participants (height; 161.2 ± 6.5 cm, body mass; 70.3 ± 12.8 kg). The mean body mass index for the sample was 27.3 ± 3 $kg \cdot m^2$, with no difference between males and females (P = 0.747). The mean length of firefighting experience for the sample was 11 ± 9 years, with no difference between males and females (P = 0.744).

There were no differences (P = 0.32 to 1.00) in absolute or relative VO_2 between the charged hose advance, hose work during hose work during blacking out or hose relocation tasks (Table 1).

Task	Duration (s)	Speed ($m \cdot s^{-1}$)	Oxygen Uptake ($L \cdot min^{-1}$)	Oxygen Uptake ($mL \cdot kg^{-1} \cdot min^{-1}$)	Mean HR ($beats \cdot min^{-1}$) (%HRmax)	Peak HR ($beats \cdot min^{-1}$) (%HRmax)
Hose work						
Charged Hose Advance	46.2 ± 6.2	1.8 ± 0.2	2.1 ± 0.6	27.0 ± 7.1	141 ± 18 (78 ± 8)	157 ± 17 (87 ± 8)
Hose relocation	95.7 ± 23.3	0.4 ± 0.1	2.0 ± 0.3	23.3 ± 3.7	135 ± 16 (78 ± 8)	152 ± 16 (87 ± 9)
Hose work during blacking out	127.4 ± 30.4	0.5 ± 0.2	1.6 ± 0.3	20.5 ± 3.5	129 ± 14 (74 ± 5)	135 ± 10 (77 ± 6)
Handtool work						
Spot fire containment	100.7 ± 16.5	0.3 ± 0.1	2.3 ± 0.6*#	[illegible]		

line building tasks or between the spot fire containment, handtool work during blacking out, and team line build tasks (Table 1). Mean HR during the solo handtool task was, however, 21 ± 11 beats·min^{-1} (11.7 ± 6.2 %HRmax) and 19 ± 10 beats·min^{-1} (10.9 ± 5.4 %HRmax) higher ($P < 0.01$ for both) than during the handtool work during blacking out and hose relocation tasks, respectively (Table 1). Mean HR for the charged hose advance was 13 ± 10 beats·min^{-1} (7.6 ± 5.6 %HRmax), 22 ± 11 beats·min^{-1} (12.4 ± 6.3 %HRmax), and 12 ± 10 beats·min^{-1} (7.0 ± 6.0 %HRmax) lower ($P \leq 0.05$ for all) than during the spot fire containment, solo handtool, and team line build tasks, respectively (Table 1). Mean HR for the hose work during blacking out task was 21 ± 11 beats·min^{-1} (12.4 ± 6.4 %HRmax), 31 ± 11 beats·min^{-1} (17.2 ± 6.2 %HRmax), and 21 ± 11 beats·min^{-1} (11.8 ± 6.0 %HRmax) lower ($P < 0.01$ for all) than during the spot fire containment, solo handtool, and team line build tasks, respectively (Table 1).

There were no differences ($P \geq 0.20$ for all) in absolute or relative peak HR between the charged hose advance, hose work during blacking out or hose relocation tasks (Table 1). There were also no differences ($P \geq 0.11$ for all) for absolute and relative peak HR between any of the spot fire containment, handtool work during blacking out, solo handtool, and team line build tasks (Table 1). Peak HR the hose work during blacking out task was 33 ± 13 beats·min^{-1} (17.7 ± 7.3 %HRmax) and 30 ± 12 beats·min^{-1} (17.7 ± 7.1 %HRmax) lower ($P < 0.01$) than during the spotfire containment and solo handtool work tasks, respectively (Table 1). Absolute peak HR during the charged hose advance was 15 ± 18 beats·min^{-1} lower ($P = 0.04$) than during the spotfire containment task (Table 1). Though the absolute peak rate during the charged hose advance was 13 ± 13 beats·min^{-1} lower than for the solo handtool work task, the difference did not reach statistical significance ($P = 0.07$). Relative peak HR during the charged hose advance was, however, 8.0 ± 7.6 %HRmax points lower ($P = 0.04$) than during the solo handtool work task (Table 1).

Firefighters' movement speed during the charged hose advance was 1.3 to 1.6 m·s^{-1} higher (all $P < 0.01$) than all other tasks (Table 1). The handtool and hose work during blacking out tasks and the hose relocation tasks were all 0.2 to 0.3 m·s^{-1} faster (all $P < 0.01$) than the spot fire containment, solo handtool, and team line build tasks (Table 1). Firefighters' speed during the spotfire containment task was also 1.0 ± 1.0 m·s^{-1} faster ($P < 0.01$) than during the solo handtool and team line build tasks (Table 1).

The main aim of the current study was to characterize firefighters' VO_2 and HR during physically demanding wildfire suppression tasks. The results show that hose work tasks elicited a VO_2 of 21-27 relative HR intensity for the spot fire containment task in the current study was higher than reported by Brotherhood et al. [5]. The current cohort of participants was, on average, ~19 years older than those tested by Brotherhood et al. [5]. Given the age-related decline in maximum HR [24], it is highly probable that the inter-study age differences account, at least in part, for the inter-study differences in relative HR intensity.

The solo handtool work and team line build tasks were associated with similar, if not only marginally higher, VO_2 and HR responses than the 'normal' (solo) and crew handtool fireline construction tasks simulated by Brotherhood et al. [5]. All tasks were performed in heavy brush and with a similar strike rate (~40-45 strikes per minute), consistent with the similar VO_2 and HR responses. The solo handtool work and team line build tasks in the current study were, however, ~3.5- and ~10.9-times shorter, respectively, than the comparable tasks simulated by Brotherhood et al. [5]. Given that Brotherhood et al. [5] measured VO_2 and HR in the final two minutes, or immediately post-exercise, it would be expected that their VO_2 and HR responses would have been higher, consistent with longer task duration [23]. As the strike rate in the current study were similar to that reported by Brotherhood et al. [5], it is difficult to argue that the solo handtool work and team line build tasks were performed at a higher intensity than the comparable tasks simulated by these previous authors. One possible explanation for the unexpected inter-study similarities could be task economy. Poole and Ross [30] found that experienced sheep shearers sheared more sheep for the same energy expenditure than their less experienced workmates. Though the firefighters' tested by Brotherhood et al. [5] were considerably younger than the current cohort, it is likely that they were more accustomed to rake hoe work than the current cohort. Rake hoe work is the core task for land management fire agencies [31] and only performed sporadically by rural fire crews, such as those tested in the current study [15]. Without direct comparison of age- and fitness-matched firefighters from both agencies, however, this hypothesis cannot be tested.

The physical demands of the handtool work during blacking out task have not, to our knowledge, been previously characterized. Though direct comparisons are not possible, the reported values for the blacking out hose task can be put in context. The mean HR response during the handtool work during blacking out task was 21-31 beats·min^{-1} lower than during the spot fire containment, solo handtool work and team line build tasks (Table 1). No differences in peak HR were observed between the four raking tasks (Table 1). As the handtool work during the blacking out task was performed faster than all other handtool tasks (Table 1), the lower mean HR cannot be attributed to faster movement speeds. With no differences in equipment or task duration, it is possible that firefighters' work patterns account for the observed differences in mean HR. In the spot fire containment, solo handtool and team line build tasks raking were performed continuously. In contrast, the handtool work during mopping task required only intermittent raking efforts as firefighters walked through a 5 m × 50 m area and only used their rake hoe to chip or hack away small plants and rake surface litter, clearing all debris around five designated 'major' fuel sources. It is plausible, therefore, that the intermittent raking efforts increased HR to the similar peak levels as the 'continuous' raking tasks, but as HR presumably fell during the non-raking periods, the mean values were lower than for continuous raking. Interestingly, the mean VO_2 response did not mirror the HR results with no difference in VO_2 between raking tasks (Table 1). One could infer, therefore, that VO_2 did not fall as quickly as HR between raking efforts which in turn did not reduce mean VO_2 below the level observed in continuous raking tasks. Whilst this hypothesis could not be tested using the current data, such a conclusion would contradict work in the excess post-exercise oxygen consumption area where authors have shown that VO_2 recovers to baseline levels more quickly than HR [32,33]. More work examining the frequency and duration of fireground tasks and the impact these variables have on the physiological response across and between task repetitions is required before definitive conclusions can be drawn.

The continuous, dynamic raking based tasks (not including handtool work during blacking out) elicited higher cardiovascular responses than charged hose advance and hose work during blacking out (Table 1). The elevated cardiovascular responses persist despite firefighters moving faster during the hose work than handtool tasks (Table 1). The solo handtool work and team line build tasks were considerably longer than the hose work tasks (and physiological measurements were collected after two minutes, not for the entire task), which could reasonably account for inter-task differences in VO_2 and HR. Differences between the hose work during blacking out, hose relocation and the spotfire containment and handtool during blacking out task could, alternatively, reflect the lower cardiovascular (and in particular VO_2) response to intermittently static (e.g., dragging and holding a hose) than dynamic (raking continuously) work [34]. The known differences in cardiovascular responses between static (or intermittently static) and dynamic tasks [34] could 'under represent' the physical demand of more static tasks if cardiovascular measures are used exclusively. As such, physical demands analyses should also include other measures, including assessment of the force required to execute [25], or the muscle load incurred during [35], each task.

The cardiovascular responses reported in the current study are considered 'moderate' to 'maximum' by the physical activity intensity classifications endorsed by ACSM [12]. ACSM [12] recommend that individuals commencing an exercise program comprising moderate to very hard intensity exercise should use a pre-participation screening tool to ascertain their risk of an adverse cardiac event during exercise. Given the comparable physical demands and established cardiovascular risks associated with both firefighting and exercise related activities, the application of an exercise based pre-participation screening and stratification device could aid in the protection of Australian firefighters from on-duty cardiovascular disease (CVD)-related risks. At present, the CVD risk of recruit and incumbent Australian rural firefighters is not uniformly assessed [36] and evidence of exertion-related cardiac events in Australian rural firefighters is lacking [37] in comparison to North American jurisdictions (e.g., [38]). However, given that Australian rural firefighters are predominantly men aged over 45 [4] stratifying their risk of CVD in the long-term as well as their risk of an adverse cardiac event during vigorous wildfire suppression duties appears prudent.

The cardiovascular responses to physically demanding wildfire suppression tasks are comparable to similar tasks in urban (e.g., [25]) and land management (e.g., [5]) firefighting jurisdictions. In both urban and land management (including North American forestry) firefighters, recruit, seasonal and sometimes incumbent personnel are required to pass physical employment standards [13] before deployment to the fireground. These standards are designed to ensure that personnel have the necessary physically capabilities to perform their duties without undue risk to themselves, their crew and the public [17]. Evidence demonstrating a reduction in risk following physical employment test implementation is scarce. Nonetheless, given the similarities in cardiovascular responses (and by inference, work intensities) between wildfire suppression duties and those performed by other emergency services personnel where physical employment testing is the norm [11,25,39], it appears prudent for Australian rural fire agencies to consider physical selection standards for recruit and incumbent personnel. Though there are many steps required to compile legally defensible physical competency tests and standards [13,17], an integral part of the process is to ensure the testing regime reflects the inherent requirements of the occupation. As such, it would seem sensible for Australian rural fire agencies to devise their own test

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