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

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Abstract

Objective: Australian rural fire crews safeguard the nation against the annual devastation of wildfire. We have previously reported that experienced firefighters identified seven physically demanding tasks for Australian rural fire crews when suppressing wildfires. These firefighters rated the operational importance, typical duration, core fitness components, and likely frequency of the seven tasks. The intensity of these duties remains unknown. The aim of this study was to quantify the oxygen uptake (VO_2), heart rate (HR) and movement speed responses during simulations of these physically demanding wildfire suppression tasks.

Method: Twenty six rural firefighters (20 men, six women) performed up to seven tasks, during which time their HR and movement speed were recorded. The VO_2 for each task was also calculated from the analysis of expired air collected in Douglas bags. Firefighters' HR and movement speed were measured using HR monitors and portable global positioning system units, respectively.

Results: The hose work tasks elicited a VO_2 of 21-27 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and peak HR of 77-87% age-predicted maximal HR (HRmax). Hand tool tasks were accompanied by VO_2 of 28-34 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ and peak HR of 85-95%HRmax. Firefighters' movement speed spanned 0.2 ± 0.1 to $1.8 \pm 0.2 \text{ m}\cdot\text{s}^{-1}$ across the seven tasks. The cardiovascular responses in the hand tool tasks were, in most cases, higher ($P < 0.05$) than during those elicited by the hose work tasks.

Conclusions: The cardiovascular responses elicited during simulations of physically demanding wildfire suppression approximated those reported for similar tasks in urban and forestry fire fighting jurisdictions. The findings may prompt Australian rural fire agencies to consider cardiovascular disease risk screening and physical selection testing to ensure that healthy and fit firefighters are deployed to the fire ground.

Keywords: Firefighters; Job task analyses; Physically demanding occupations

Introduction

Each year, Australia's forest, rural and urban-rural areas are threatened by wildfire [1]. Wildfires can lead to extensive property damage, loss of produce and livestock, and personal injury or even death to residents and firefighters alike [2]. Rural fire authorities and land management authorities are primarily responsible for suppressing wildfires of private and public lands, respectively [3]. Rural fire authority personnel comprise the bulk of Australia's wildfire suppression workforce [4]. In comparison to Australian land management agency fire crews [5-8] and North American fire crews [9-11], little is known about the work performed by Australia's rural fire authorities to safeguard the nation against the annual threat of wildfire. Australian rural fire agencies cannot, therefore, accurately

advise their firefighters on the appropriate level of fitness required to perform their duties safely and effectively, determine the necessity of cardiovascular health screening [12], or devise valid screening tools to assess firefighters' job-specific fitness [13]. Characterising the work performed by Australian rural firefighters is also valuable for fire agencies from North America and continental Europe who can then inform the personnel they send to support Australian rural fire crews about the work they may face when working to curtail the spread of wildfires in Australia.

To date, research quantifying work demands of Australian rural fire agency crews is limited to qualitative job task analyses [14,15]. Dwyer and Brooker [14] reported that 16-20 (precise sample not reported) firefighters nominated hose dragging, rake (i.e., handtool) work, carrying a knapsack, and lifting equipment as the most physically demanding tasks performed during wildfire deployments. More recently, Phillips et al. [15] reported that 31 experienced (21 ± 13 yr firefighting experience) firefighters, participating in a committee-

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-mm diameter hose forward, laterally and back to a vehicle, using a handtool (e.g., a rake hoe) to contain a spot fire, build mineral earth fire breaks individually or in a team, or clear burnt debris during post-fire cleanup work. Although the respondents nominated the operational importance, typical duration, core fitness components, and likely frequency of each task [15], the intensity of these work tasks is yet to be quantified.

A logical first step in quantifying work demands is to evaluate the oxygen consumption (VO_2) and heart rate (HR) responses to each task [17]. These measures are both practical to collect in field settings and describe the cardiovascular fitness demands of each task. The inclusion of time, speed and distance information, as measured using portable global positioning systems (GPS; [18]) is also a valuable addition to contextualise the current findings against previous research. There is a small body of literature reporting VO_2 and HR responses for North American ([19] and Australian land management agency [5] personnel performing firefighting tasks in wild land environments. Brotherhood et al. [5] reported that 34 Australian land management agency firefighters recorded VO_2 of $2.3 \pm 0.4 \text{ L}\cdot\text{min}^{-1}$ ($32 \pm 4 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and HR of $161 \pm 17 \text{ beats}\cdot\text{min}^{-1}$ during the final two minutes of a seven-minute mineral earth fire break building task at 'normal' speed. These values were very similar to the responses recorded during the final 12 minutes of a 23-minute seven-person crew fire break building task [5]. Brotherhood et al. [5] did not simulate the hose work tasks, or any tasks resembling the handtool work during post-fire clean up or handtool spot fire containment cited as common to rural fire authority operations [15]. It is also unclear whether the VO_2 and HR responses of the salaried personnel tested by Brotherhood et al. [5] during solo and team fire break building would accurately reflect those of volunteer rural fire agency personnel performing the same task, given possible differences in fitness between the cohorts [20]. Indeed McFadyen et al. [19] showed that higher fitness levels can lead to increased productivity and VO_2 responses but lower HR. These authors also reported that working with a charged fire hose elicited a VO_2 of 3.2 ± 0.5 and $3.8 \pm 0.6 \text{ L}\cdot\text{min}^{-1}$ for low and high fitness groups, respectively. To the authors' knowledge, the work of McFadyen et al. [19] was only published as an abstract within conference proceedings and not as a full paper so specific detail regarding tasks parameters, measurement procedures and HR responses is not available. The existing literature cannot, therefore, provide any insight into the VO_2 or HR responses for four of the seven physically demanding tasks identified for Australian rural agency crews during wildfire suppression [15] and only limited and/or non-population-or location-specific data on the remaining three tasks. The aim of the current study was, therefore, to quantify the VO_2 and HR responses during physically demanding wildfire suppression tasks, common to all Australian rural fire agency crews.

Methods

Participants

Twenty six rural firefighters (20 men, six women) participated in this study. All participants were active (i.e. routinely attended wildfire

incidents), volunteer members of the Country Fire Authority (CFA), Victoria, Australia. Participants were included in the study if they presented with less than two risk factors for cardiovascular disease as outlined by the American College of Sports Medicine risk stratification process for vigorous exercise [12]. All experimental procedures were approved by the University ethics committee before the study commenced. All participants provided their written, informed consent before testing.

Task simulations

All data collection occurred within Lerderderg State Park, Victoria, Australia. Two specific sites within the park were selected for data collection on the advice of CFA personnel. These sites were routinely used for training due to their similarity to the types of terrain and vegetation encountered during wildfire suppression in south-eastern Australia. These sites also provided immediate access to water points for re-filling fire trucks and sufficient space for multiple repetitions of each task across near-identical terrain. Unless otherwise stated, the terrain was flat and comprised dirt and loose plant litter (i.e., leaves, bark and small branches). All testing was carried out in cool to mild temperatures ($10\text{--}20^\circ\text{C}$).

During all trials, participants wore their own full personal protective clothing and equipment. Firefighters either wore proban-treated two-piece jacket and pant ensemble or overalls (Stewart & Heaton, Australia). All wore leather, fire-resistant gloves (Fire Rescue Safety Australia, Australia), treated leather work boots (Taipan, Australia) and wildfire fighting hard hat (Pacific Helmets, Australia). Firefighters did not wear protective smoke goggles or a respirator filter mask during the tasks as neither item is compulsory on the fireground [21]. Participants were instructed to wear similar clothing under their protective clothing and equipment as they would when on duty at a wildfire emergency. The net weight of the participants' personal protective clothing and equipment was approximately 5 kg.

The seven tasks simulated for the current study were based on the physically demanding tasks identified and characterized by Phillips et al. [15]. These tasks were; advancing a 38-mm diameter firehose 'charged' with water, lateral repositioning of a 38-mm charged fire hose, full repositioning of a 38-mm charged fire hose, rapid handtool work during spot fire containment, solo handtool work, handtool work during team fireline building, and handtool work during blacking out (i.e., post-fire clean up). The hose relocation task served as a composite of the lateral and full hose repositioning tasks identified by Phillips et al. [15], since these tasks are often performed together when operating on the fireground. Hose work during blacking out was not identified by the respondents surveyed by Phillips et al. [15], but is always paired to the handtool work during blacking out task identified in that study as physically demanding. As such, the authors of the current study felt it was an important additional task to include in the measurement battery. In each simulation described below, all firefighters were instructed to complete the task as they would when on duty.

Task simulation parameters

For the charged hose advance task, four firefighters worked together to advance three lengths (approximately 90 m) of charged 38-mm diameter hose forward 80 m. The hose rig used for all testing comprised a branch nozzle (Pro 366 Branch, Protek, Australia), two lengths of 38-mm canvas fire hose and one length of 38-mm of rubber

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 charged hose advance) or paired tasks (i.e., hose relocation and blacking out) physiological responses were measured in only one firefighter per task repetition. However, over the course of the testing sessions, physiological measures were collected from firefighters performing all roles. If a firefighter was measured twice in a single testing session, they rested for 20 min between tasks.

HR and Speed

At the start of each testing session, the nominated participants were fitted with a portable GPS (SPI Elite, GPSPORTS, Australia) and HR monitor (S410, Polar, FI) which were worn during all tasks. The GPS unit fitted between the shoulders in a manufacturer provided harness, whilst the HR was detected using a chest strap. Heart rate and GPS data were recorded at one-second epochs by the portable GPS unit. For each task, mean and peak HR were determined and expressed in both absolute ($\text{beats}\cdot\text{min}^{-1}$) and relative (percentage of age-predicted maximum; HR_{max}) terms. Age-predicted maximum HR was determined using the formula $\text{HR}_{\text{max}} = 208 - 0.7 \times \text{age}$ [24].

Oxygen Uptake

Before each testing session began participants were given a reusable mouthpiece (Hans Rudolph, Kansas City) and nose peg (Hans Rudolph, Kansas City) for the subsequent collection of their expired air. Participants were instructed to retain the mouthpiece and nose clip for the duration of the testing session. Expired air was collected from the mouthpiece via rubber tubing (Hans Rudolph, Kansas City) into a 120-litre air-tight 'Douglas' bag (Shoelle, Australia). The bag and tubing were held by a research assistant throughout each task. The volume of the expired air was measured using a dry gas meter (Harvard Apparatus, Massachusetts). The percentage of oxygen and carbon dioxide in the air captured in each Douglas bag was determined using an online metabolic analyser (True One 2400, Parvomedics, East Sandy, Utah). The metabolic analyser was calibrated using commercially available standard gases (Parvomedics, Utah) prior to all analyses. Expired air volume and composition were analysed within 15 hours of each testing session. Pilot testing revealed no change in bag volume or gas composition over a 24-hour period. Oxygen uptake was expressed in absolute ($\text{L}\cdot\text{min}^{-1}$) and relative ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) terms.

Statistical Analyses

All data was checked for normality using *Shapiro-Wilk test*. Once normality was verified, unpaired t-tests were used to compare height, mass, age and firefighting experience (in years) between male and female participants. There was no effect of gender on VO_2 , HR, or speed ($P \geq 0.20$) and so all data were pooled. It is possible that the non-significant differences for gender could reflect the relatively smaller number of female participants recruited for this study. The VO_2 , HR,

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 \pm 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 $P < 0.05$.

Results

Participants

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 $\text{kg}\cdot\text{m}^{-2}$, 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 ($P = 0.744$).

Mean Oxygen Uptake

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 ($\text{m}\cdot\text{s}^{-1}$)	Oxygen Uptake ($\text{L}\cdot\text{min}^{-1}$)	Oxygen Uptake ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	Mean (beats $\cdot\text{min}^{-1}$) (%HRmax)	HR	Peak HR (beats $\cdot\text{min}^{-1}$) (%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	$2.3 \pm 0.6^{\#}$	$28.6 \pm 6.0^{\#}$	$151 \pm 20^{\#}$ (84 ± 9) $^{\#}$		$170 \pm 17^{\#}$ (95 ± 6) $^{\#}$
Solo handtool work	121.1 ± 12.5	0.2 ± 0.1	$2.6 \pm 0.3^{\#}\dagger$	$33.1 \pm 5.0^{\#}\dagger$	$162 \pm 15^{\#}\dagger$ (91 ± 8) $^{\#}\dagger$		$169 \pm 12^{\#}$ (95 ± 8) $^{\#}\dagger$
Team line build	127.2 ± 26.9	0.2 ± 0.1	$2.5 \pm 0.5^{\#}\dagger$	$33.5 \pm 5.2^{\#}$	$151 \pm 20^{\#}$ (84 ± 9) $^{\#}$		158 ± 20 (88 ± 8)
Handtool work during blacking out	127.4 ± 30.4	0.4 ± 0.1	$2.2 \pm 0.3^{\#}$	$28.4 \pm 5.3^{\#}$	$139 \pm 21^{\#}$ (79 ± 7) $^{\#}$		150 ± 25 (85 ± 9)

Table 1: Duration, Speed, Oxygen Uptake and HR for physically demanding wildfire suppression tasks.

There were also no differences ($P=1.00$) in relative and absolute mean VO_2 between the spot fire containment, handtool work during blacking out, solo handtool, and team fine line building tasks (Table 1). The mean VO_2 for the charged hose advance was 0.4 ± 0.4 $\text{L}\cdot\text{min}^{-1}$ (5.9 ± 6.4 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), 0.6 ± 0.3 $\text{L}\cdot\text{min}^{-1}$ (8.4 ± 5.7 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and 0.5 ± 0.3 $\text{L}\cdot\text{min}^{-1}$ (7.6 ± 5.4 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) lower ($P \leq 0.02$ for all) than for the spot fire containment, handtool work during blacking out, solo handtool, and team fine line building tasks, respectively (Table 1). The mean VO_2 for the hose work during blacking out task was 0.6 ± 0.4 $\text{L}\cdot\text{min}^{-1}$ (8.7 ± 6.9 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), 0.7 ± 0.7 $\text{L}\cdot\text{min}^{-1}$ (9.9 ± 7.6 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$), 0.9 ± 0.6 $\text{L}\cdot\text{min}^{-1}$ (12.4 ± 7.3 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and 0.8 ± 0.6 $\text{L}\cdot\text{min}^{-1}$ (11.6 ± 6.6 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) lower ($P < 0.01$ for all) than for the spot fire containment, handtool work during blacking out, solo handtool, and team line build tasks, respectively (Table 1). The mean

VO_2 during the hose relocation task was 0.7 ± 0.6 $\text{L}\cdot\text{min}^{-1}$ (9.1 ± 7.9 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) lower ($P < 0.01$) than during the solo handtool task (Table 1). The mean VO_2 during the hose reposition task was 0.6 ± 0.6 $\text{L}\cdot\text{min}^{-1}$ lower ($P = 0.05$) than the team line build task, but the difference in relative VO_2 (8.4 ± 8.5 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) did not reach statistical significance ($P = 0.06$).

Mean HR

There were no differences ($P = 1.00$ for all) in absolute or relative mean HR between the charged hose advance, hose work during blacking out or hose reposition tasks (Table 1). There were also no differences ($P = 0.54$ to 1.00) for absolute and relative mean HR between any of the spot fire containment, solo handtool, and team fine

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).

Peak HR

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).

Speed

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).

Discussion

The main aim of the current study was to characterize firefighters' VO₂ and HR during physically demanding wildfire suppression tasks. The results show that hose work tasks elicited a VO₂ of 21 - 27 mL·kg⁻¹·min⁻¹ and peak HR of 77 - 87 %HRmax. Handtool tasks were characterised by VO₂ of 28 - 34 mL·kg⁻¹·min⁻¹ and peak HR of 85 - 95 %HRmax. The VO₂ responses equate to 52 to 84 % of the VO₂ peak recently reported for Australian rural volunteer firefighters [20]. The VO₂ and HR responses were characteristic of 'moderate' to 'maximum' work intensities as classified by ACSM [12].

The VO₂ and HR responses during the suite of hose work tasks (Table 1) were, broadly speaking, consistent with those reported for urban firefighting hose work tasks [25]. Although data describing the

cardiovascular responses to hose work in a forestry firefighting context is available [19], it is only presented in abstract form and the precise tasks performed cannot be determined making comparisons very difficult. When compared to the cardiovascular responses of advancing and repositioning a charged fire hose in an urban environment [25], the mean VO₂ and HR responses for these tasks in the current study are ~ 15 - 35 % lower. These differences cannot be attributed to differences in task duration [23] or terrain [26] as the charged hose advance and reposition tasks simulated in the current study were 1.2 - to 2.5 -times longer and on more challenging terrain (heavy brush vs. concrete) than the equivalent tasks simulated by Gledhill and Jamnik [25]. Further, Gledhill and Jamnik [25] did not report movement speed (or distance of charged hose advance or lateral reposition to calculate speed) so the effect (if any) on inter-study differences in task speed on VO₂ and HR cannot be determined. The lower cardiovascular responses reported in the current study may, instead, reflect the smaller hose diameter and lower weight carried in the current study. Though VO₂ and HR are known to increase with increasing load carriage (e.g., [27]), documented evidence that VO₂ and HR increases when carrying heavier hoses is lacking. Richmond et al. [28] reported no differences in HR during ~ 30 s of simulated search and rescue activities when carrying 45 -mm and 70 -mm hoses. However, these findings are potentially confounded by more firefighters carrying the 70 -mm hose than the 45 -mm hose [28]. It is reasonable to suggest that if the same number of firefighters carries a given hose, their individual HR will increase with heavier hose weights.

The physical demands of the hose work during the blacking out tasks have not, to our knowledge, been previously characterised in the scientific literature. Though direct comparisons are not possible, the reported values for the blacking out hose task can be put in context. The VO₂ and HR responses for this task where participants intermittently sprayed water on pre-identified major fuel sources are marginally lower than static spraying with an 'on-off' pattern by naval firefighters [29]. The slightly higher VO₂ and HR could be a function of duration as the on-off spraying reported by Bilzon et al. [29] was approximately twice as long as the blacking out task simulated in the current study. With double the duration, it is reasonable to expect that VO₂ and HR would be considerably higher in the Bilzon et al. [29] on-off spraying task than the blacking out task used in the current study. It is possible, however, that as the current participants also had to intermittently drag the charged hose, the additional effort elevated their VO₂ and HR response, offsetting some of the expected inter-study differences in VO₂ and HR associated with the different task durations.

The spot fire handtool containment task was associated with ~ 20 - 40 % lower VO₂ and absolute mean HR than the 'fast' handtool fireline construction task simulated by Brotherhood et al. [5]. Both tasks were performed in heavy brush and with a similar striking rate (~ 50 strikes per minute) which doesn't account for the apparent differences. The spot fire handtool containment task was, however, 4.2 -times shorter than the 'fast' fireline construction task [5]. Further, Brotherhood et al [5] measured VO₂ in the final two minutes of the seven-minute task and HR immediately as the task stopped, whilst the current data reflects mean VO₂ and HR responses throughout the task (peak HR in the current study for this task was still lower than that reported by Brotherhood et al. [5]). It is probable, therefore, that the shorter task duration (as designed in consultation with our subject-matter expert) could be responsible, at least in part, for the lower VO₂ and HR responses observed in the current study. Interestingly, the

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 $\text{beats}\cdot\text{min}^{-1}$ 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 \times 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 physical 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 which reflects not only the type and intensity of their occupational duties, but also the frequency and duration of their individual work tasks, as observed during emergency deployments.

Future investigation into the frequency and duration of individual fireground tasks is, most likely, best achieved through direct observations of actual rather than simulated suppression work. The rationale for this recommendation is two-fold. Firstly, monitoring firefighters in real-working conditions allows researchers the opportunity to investigate how other environmental factors, such as heat and smoke affect on physiological responses. It was not possible to simulate these factors in the current study. It is tempting to speculate that hot temperatures or smoke may have increased HR and potentially VO_2 (see [40] for review). However, it is also likely that these environmental factors may have led personnel to pace their efforts, further altering physiological responses [22]. Investigation into these potential confounding variables, and others, including personal characteristics (e.g., gender, BMI, age) through multivariate analyses would, however, necessitate much larger sample sizes than typically used in similar research (e.g., [25,28]). Herein lies the second potential benefit to testing in real working conditions, namely not asking 'time-poor' emergency service workers [41] to make additional time commitments to simulated testing. Indeed, it is possible that these time constraints contributed to the modest sample size ($n=26$) in the current study. Researchers looking to pursue detailed investigations in the moderators influencing firefighters' physiological responses may need to consider remote monitoring of much larger sample sizes (e.g., [42-44]) during real-working conditions. They also, however, need to consider the trade-off between the value attained through testing larger sample against the likelihood that real-working conditions may not allow for detailed analyses of physiological variables, such as VO_2 , from which job-specific fitness assessments are often based [17].

The current study quantified the VO_2 and HR responses during physically demanding, simulated wildfire suppression tasks, common to all Australian rural fire agency crews. Broadly speaking, the cardiovascular responses to physically demanding wildfire suppression tasks are comparable to similar tasks in urban and land management firefighting jurisdictions. Observed differences between hose work and raking tasks could be plausibly attributed to differences in duration and/or task type (static versus dynamic). Across all tasks, the cardiovascular responses would be considered 'moderate' to 'maximum' by the physical activity intensity classifications endorsed by ACSM (2012). These findings may prompt Australian fire agencies to consider pre-participation screening for CVD-related events and design and implementation of a physical competency testing regime to reflect the inherent characteristics of wildfire suppression by Australian rural fire crews.

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