fire

MDPI

Article

Physical Demand Assessment of Volunteer Firefighters During Wildland Firefighting

Tatiana Teixeira [1,*], Pedro Pratas [2], Joana Santos [1,3], Pedro R. Monteiro [4], João Santos Baptista [1], Mário A. P. Vaz [1] and Joana C. Guedes [1]

[1] Associated Laboratory for Energy, Transports and Aeronautics (PROA/LAETA), Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal; jds@ess.ipp.pt (J.S.); jsbap@fe.up.pt (J.S.B.); gmavaz@fe.up.pt (M.A.P.V.); jccg@fe.up.pt (J.C.G.)
[2] Faculty of Engineering, University of Porto, 4200-465 Porto, Portugal; papratas@fe.up.pt
[3] Center for Translational Health and Medical Biotechnology Research (TBIO), School of Health (ESS), Polytechnic Institute of Porto, 4200-072 Porto, Portugal
[4] Center for Rehabilitation Research, Department of Functional Sciences, School of Health, Polytechnic Institute of Porto, 4200-072 Porto, Portugal; pmonteiro@ess.ipp.pt
* Correspondence: tteixeira@inegi.up.pt

Abstract: Wildland firefighting is physically and mentally demanding. The aerobic capacity of firefighters is important due to the demands of the activity and the associated occupational risks. The main objectives of this study were to identify and characterise the physically demanding tasks undertaken by volunteer firefighters during wildland fires (real work conditions). A total of 125 firefighters replied to a survey about sociodemographic, biometric data, and work fitness assessment. A group of 23 was evaluated in a physical stress test using a VO_{2peak} protocol to determine maximum oxygen consumption and ventilatory thresholds. The physical demands and physiological responses were collected during the operations at the firefront (n = 21). The results revealed that wildland firefighting entails physical demands that exceed established reference values, with maximum oxygen uptake exceeding 40%. The cardiovascular strain is particularly notable in tasks performed near the firefront, reflecting fatigue. The physical and cardiac demands associated with forest fire fighting have been demonstrated to contribute to occupational illnesses with prolonged exposure. This study underscores the imperative for interventions to enhance the identification and real-time monitoring of physiological parameters to enhance firefighters' overall health and well-being.

Keywords: physical activity; workloads; aerobic capacity; firefront; health risks

Citation: Teixeira, T.; Pratas, P.; Santos, J.; Monteiro, P.R.; Baptista, J.S.; Vaz, M.A.P.; Guedes, J.C. Physical Demand Assessment of Volunteer Firefighters During Wildland Firefighting. *Fire* **2024**, *7*, 439. https://doi.org/10.3390/fire7120439

Academic Editors: Mingjun Xu, Yubo Bi and Shenshi Huang

Received: 30 September 2024
Revised: 11 November 2024
Accepted: 19 November 2024
Published: 27 November 2024

1. Introduction

Wildland firefighting is distinguished by its high physical and mental demands. The context of a forest fire imposes significant demands on those working in its vicinity. Like other work environments, firefighters are exposed to safety and health risks that could lead to death, accidents, or severe illness, so assessing and analysing occupational exposure is fundamental [1–3]. The European Union reached the highest number of professional firefighters in 2022, with approximately 360,000 [4]. Portugal is one of the few countries where volunteer firefighters are observed, representing about 94% of the total firefighter population in 2019 [4]. However, these individuals may be more susceptible to inherent risks as they engage in other occupational activities outside their volunteer service [5]. The management of wildland fires has presented the highest incidence of fatal accidents among firefighters, with a recorded 170 firefighter fatalities occurring between 2007 and 2016 [6–10]. In September 2023, a total of 59 firefighter deaths were reported in the United States, with volunteer firefighters accounting for 42% of these fatalities [11].

Approximately 45% of deaths among firefighters in the performance of their duties are caused by cardiovascular diseases, which may be related to exposure to smoke, extreme thermal environments, and physically demanding activity [12]. The data provided by the Center for Disease Control and Prevention (CDC) between 1994 and 2023 show a total of 499 deaths of firefighters in wildfires [13].

Physical fitness is essential for physical adaptation to work, as it reduces the risk of exposure through the physiological adaptation of the individual in response to intense exercise. Good physical fitness has already been evidenced to help prevent occupational diseases [14–17]. The physical demands of the job and the health-related limits for performing professional tasks are evaluated using heart rate (HR) and VO_{2peak} [18]. Heart rate variability (HRV) reflects the activity of the autonomic nervous system, which regulates involuntary body functions, including stress response and recovery. High HRV often signifies a robust autonomic nervous system in good health, reflecting a commendable ability to adapt to stressors. Variations in HRV levels may serve as a valuable indicator of escalating fatigue levels within an individual. Monitoring changes in HRV can offer insights into the physiological response to stressors and provide important information regarding overall well-being and adaptive capacity. Therefore, monitoring HRV can give early signs of cardiac issues, allowing for preventive interventions [19–21]. In the context of firefighters, real-time workload analysis has not traditionally incorporated VO_2 as a parameter. Firefighting exposes firefighters to various risks, including asphyxiating chemical agents. This exposure and inadequate personal protective equipment (PPE) make absorbing oxygen for muscle energy production difficult. The combination of these factors, such as exposure to high temperatures and strenuous physical activity, can induce fatigue. The fatigue resulting from these stress factors, among other impacts on biological systems, leads to increased blood acidosis due to a high concentration of lactate, a factor known to contribute to cardiovascular diseases.

Consequently, using VO_2 can help identify fatigue states during firefighting operations. Maximum oxygen consumption (VO_{2peak}) is usually associated with prolonged aerobic activities such as running, cycling, and swimming, which require continuous oxygen supply to maintain aerobic energy production. On the other hand, strength exercises, such as lifting weights, involve short, intense efforts that mainly utilise anaerobic pathways for energy production, making VO_{2peak} less relevant as a performance indicator for these activities. Specific physiological adaptations can occur when performing strength exercises in hot environments, including greater sweat production and a greater thermoregulatory capacity to deal with heat stress. It is important to note that these adaptations are distinct from changes in VO_{2peak}, predominantly concerning aerobic capacity, and are less influenced by anaerobic or thermoregulatory adaptations [22–24].

Several studies have applied different protocols to estimate the aerobic capacity of individuals [25–28]. Evaluating VO_{2peak} values within occupational groups has proven to be a crucial factor in enhancing professional performance. Furthermore, it can be suggested that individuals with lower VO_{2peak} values are more likely to develop chronic illnesses, particularly heart disease [29]. These assessments should be carefully monitored using validated protocols, as recommended by Brian Sharkey (2012) [30].

Stress is an influencing factor in the cardiorespiratory capacity of individuals. Some authors consider physical activity necessary for improving stress levels and cardiorespiratory response, enhancing aerobic capacity [31,32]. Activities of higher intensities increase steady-state oxygen consumption, which can account for the entire energy cost of the exercise. Above this intensity, there will be a sustained contribution from glycolysis, leading to the formation and accumulation of lactate in the blood, which indicates fatigue. The impacts of lactate concentration directly affect various systems of the human body, as seen in the cardiovascular system [33].

Nevertheless, it is crucial to manage muscular effort in these extreme environments by regulating physical and physiological parameters to ensure that individuals do not get into situations critical to their safety and health. In these environments, the demand for

oxygen consumption is higher, leading individuals to enter anaerobic work quickly, as is the case in wildfires, which have a maximum or near-maximum demand [34]. The health consequences most directly linked to emissions from wildland fires include increased mortality and morbidity from cardiorespiratory causes. It is essential to highlight that the released emissions significantly contribute to developing conditions such as asthma and chronic obstructive pulmonary disease (COPD) [35]. This article investigates exposure risks within the work environment, where these risks impact the physical strain of the firefighters in wildfires and their cardiorespiratory response. This study aims to evaluate the physically demanding firefighting tasks performed by volunteer firefighters during wildland fires, considering their laboratory-estimated aerobic capacity.

2. Materials and Methods

2.1. Study Design and Participants

This study was divided into two phases. In the first phase of the study, a sociodemographic questionnaire was applied to characterise a sample of volunteer firefighters and to survey the risk perception of this sample concerning the different tasks of firefighters. Responses to the sociodemographic questionnaire were collected using the SurveyMonkey platform. In addition, volunteer firefighters were recruited to monitor biometric data using a bioimpedance scale (INBody 270, Los Angeles, CA, USA). The study's first phase consisted of a laboratory data trial to assess Portuguese volunteer firefighters' aerobic capacity during an incremental exercise test. The data collection campaign for aerobic capacity took place from 22 May 22 to 31 July 2022. Laboratory assessments were conducted at the Laboratory for Occupational and Environmental Risk Prevention (PROA) in the Faculty of Engineering of the University of Porto, Portugal. The space's average temperature and humidity conditions were maintained, considering weather conditions through natural and controlled ventilation, in a climate chamber (FITOCLIMA 25000 EC20; Aralab, Rio de Mouro, Portugal), with a temperature of 24 ± 0.2°C and a relative humidity of 50 ± 5%. Medical appointments were conducted in person at PROA and at the facilities of the fire departments that agreed to perform the tests. There were no age or gender restrictions for the exercise tests. The clinical history and state of health were collected with the support of a licensed physician, who determined exclusivity criteria and whether the volunteer met the safety criteria for performing physical exertion tests in safe conditions, which included the absence of cardiorespiratory diseases, metabolic disease, or other diseases considered limiting for the performance of the maximum exertion test. Blood pressure and heart rate were measured after a 5-minute rest while seated using a digital sphygmomanometer (Omron, Model M10-IT, Kyoto, Japan). For safety reasons, a physician has supervised all the tests with the medical equipment necessary to carry out the tests in safe conditions.

The second phase involved monitoring the population's response to real-life working conditions. The campaign to collect occupational exposure data before the fire occurred from 15 May to 30 October 2023. Record sheets and completion instructions were provided to the volunteers monitored at the firefront. Monitoring was planned according to the service schedules offered by the fire stations. All equipment was provided to participants at the beginning of each shift and collected at the end. In this phase of the study, no gender or age restrictions were applied to selecting participants; all required was that the participants had been working in forest fire fighting for at least a year.

The protocol was submitted and approved by the ethics committee of the University of Porto (CEUP), with reference number 106/CEUP/2021. The protocol to be applied and the data collection procedure were explained verbally and in writing to the volunteers who provided written consent to participate in the study. Figure 1 shows the study design in schematic form.

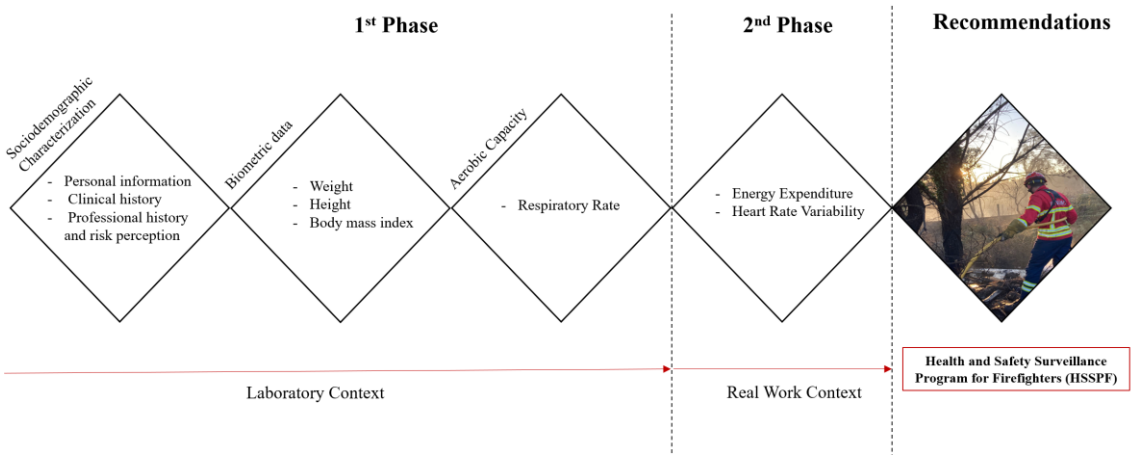

Figure 1. Study Design.

2.2. First Phase: Aerobic Capacity

The incremental physical stress test was performed using a VO_{2peak} protocol on a General Electric treadmill (T2100 treadmill; GE, Boston, MA, U.S.A.). An incremental protocol consisting of seven running phases was implemented, beginning with a light walk tailored to each participant's fitness level by a team of fitness instructors, followed by a progressive increase of 1 $km.h^{-1}$ at each subsequent stage. Each stage lasted 4 minutes, interspersed with a 30-second break to measure capillary lactate levels [36–38]. For the capillary blood collection, the middle finger of each participant's left hand was disinfected with cotton and alcohol, followed by drying with cotton. The first drop of blood was cleaned to prevent contamination, and only the second puncture was used. The same puncture site was utilised for blood sampling in all collection phases. The collected capillary blood was analysed using Lactate Pro 2 test strips, which require only 0.3 µL of blood. The capillary lactate concentration was then determined with the portable analyser (Lactate Pro 2, Arkray Factory, Shiga, Japan). The lactate concentration values were determined at rest, during the 30-second break between stages of the test, and at the end of the test.

Participants could finish the test at any point by requesting to stop or activating the treadmill's emergency button. After completing the test, participants remained at rest until fully recovered, during which their respiratory rate was continuously monitored. Metabolic variables were recorded using a portable telemetric gas analyser (Cosmed K5; Cosmed, Rome, Italy), which transmitted real-time data to a computer via a Bluetooth module. These metabolic variables were monitored across three phases: rest, during exercise, and recovery. The criteria for stopping the stress test were maximum HR, internal temperature data (not to exceed 38.5°C), and respiratory exchange rate (RER) data reaching 1.2 as a secondary endpoint [39]. To ensure accurate measurements, the portable telemetric gas analyser was calibrated one hour before the tests using a gas cylinder with a specified gas mixture (O_2 16%, CO_2 5%, N_2 Balance), following the manufacturer's recommendations.

2.3. Second Phase: Occupational Exposure in Firefront

Teams of wildland firefighting were monitored, consisting of five members: a driver (responsible for transportation and supply), a team leader or Operations Commander (COS) (responsible for leading firefighting operations), two nozzles (responsible for firefighting attack), and one rope (responsible for supporting the attack).

All participants were instructed to fill out a log sheet with information about tasks performed, start and end times, and a brief description of activities during incidents. This information helped identify tasks performed and corresponding periods, facilitating alignment with physiological data.

All participants were observed for periods ranging from 12 to 24 hours, taking into account the work shifts they were assigned. All 24-hour work shifts were included, with monitoring during daytime and nighttime shifts. Equipment was distributed to participants at the beginning of each shift and collected at the end. Participants were instructed to remove the equipment only during personal hygiene situations and rest hours.

2.3.1. Energy Expenditure and Metabolic Rate

The unique model recommended by Swartz et al. (2000) [40] was applied for monitoring activity cycles through accelerometry and monitoring motion data at the waist and wrist. These data enable the calculation of the metabolic rates and energy expenditure through actigraphy (ActiGraph, model GT3XPB, Pensacola, U.S.A.), placed at the waist and on the dominant side of the individual's wrist since this side is typically more involved during heavy tasks. The sensors were placed in strategic locations of the body based on the task's characteristics and the firefighters' personal protective equipment (PPE). The wrist and hip detect different types of movement. The wrist sensor is more sensitive to upper-body movements and finer motor activities, while the hip sensor captures lower-body and whole-body movements more effectively. Combining data from both can give a more comprehensive picture of overall activity levels. Considering the placement of the sensors, the validated equation applied and suggested by Swartz [40] for the combination of wrist and hip has an error variation of 2.6%. The error variation of the metabolic rate is less than 5% at the wrist and 31.7% at the hip [40,41].

2.3.2. Heart Rate Variability

Additionally, each participant used a heart rate monitor (Polar, Models: H9 and H10, Kempele, Finland) positioned externally near the xiphoid process. All equipment was programmed and synchronised to ensure continuous monitoring during work shifts using ActiLife software version V6.13.4.

2.4. Data Processing

Aerobic capacity was assessed using descriptive statistics (mean ± standard deviation) to analyse the VO_{2peak} values obtained during the final stage of the stress test [39]. These values were then compared against the reference standards established by the American Heart Association (AHA) [42]. HRV was analysed based on the anticipated changes according to occupational stress [43]. All HRV results were treated with descriptive statistics and differential analyses to compare results for a 0.05 significance level using the Spearman correlation test. The Kruskal–Wallis test was applied for a significance level of 0.05 to analyse differences between the results obtained during monitoring at rest and monitoring during wildland firefighting. The correlation coefficient was interpreted according to Blair et al. (2008) [44]. According to the authors, values between 0 and 0.25 indicate a "very weak" correlation, while values between 0.25 and 0.40 suggest a "weak" correlation. A "moderate" correlation is observed between 0.40 and 0.60, and values between 0.60 and 0.75 indicate a "moderate to strong" relationship. Correlations between 0.75 and 0.90 are considered "strong", whereas values between 0.90 and 1 represent a "very strong" correlation. The coefficient varies between 1 and −1, indicating positive or negative relationships between the variables.

The collected capillary lactate data were used to identify the aerobic threshold, which is marked as the transition point from aerobic to anaerobic phases (LTP1) and ventilatory threshold (LTP2). LTP1 was determined to be the initial elevation in capillary lactate concentration before its subsequent decline and stabilisation, while LTP2 corresponded to the second sharp increase in capillary lactate concentration [45,46].

Metabolic rates were calculated using the equations proposed by Swartz et al. (2000) [40]. The validation of task times and the identification of moderate to vigorous physical

activity were determined by the equation proposed by Freedson et al. (1998) [47]. The energy expenditure data were converted into VO_{2peak} using the AHA guidelines [42] and considering the equation proposed by Jetté et al. [48].

The raw data obtained from metabolic consumption and HR monitoring underwent processing using a Python programming script, specifically version 3.11.3. The metabolic consumption variables considered were energy expenditure and metabolic rates to evaluate the physical demands of the tasks on a minute-by-minute basis using accelerometry data [49,50]. All monitoring sessions shorter than 30 min or unrelated to direct firefighting tasks were excluded as non-representative. HRV analysis was based on the existing literature and processed using Python code for numerical analysis, matrix calculations, signal processing, and graphical visualisation [51–53]. This allowed for precise, minute-by-minute individual and collective data analysis based on daily records. Cardiovascular workload data were processed with Python HR and HRV analysis tools in time and frequency domains. The algorithm processed data from accelerometers, heart rate monitors, and individual records, generating a .xlsx file with the results. Time and frequency analysis, based on R-R intervals, were performed using the pyHRV toolbox (version 0.3, Plux, Lisbon, Portugal). Stage 1 involved removing outliers (R-R intervals below 300 ms or above 2000 ms) and ectopic heartbeats using the Malik method [20]. Missing heart rate values were interpolated. In Stage 2, time and frequency domain variables were calculated.

3. Results

3.1. Aerobic Capacity

In the first phase of this study, 220 firefighters responded to a survey to collect sociodemographics, and 125 participants collected biometric and work fitness data. This questionnaire revealed that the sample had an average age of 35 ± 11 years, 35% represented the female sample, and wildfires were identified as the most exposure-intensive activity. The biometric assessments resulted in a total sample of 125 participants with an average age of 36 ± 11 years, of which 103 were men, and 22 were women.

A sample of men (n = 23) was considered for the incremental stress test, with average ages of 32 ± 10 years and a body mass index of 25 ± 4 $kg.m^{-2}$, considered a representative sample based on the sociodemographic and biometric data collected. Concerning the stress test values of the 23 participants, it was concluded that they had high VO_{2peak} values according to reference values. These values indicate a commendable respiratory capacity relative to exercise intensity. Nevertheless, an examination of the HR results suggests that when participants engage in prolonged and vigorous exercise, they might experience oxygen debt and increased physiological strain, as shown in Table 1.

Table 1. Aerobic capacity according to the sex (n = 23).

Variable	Result
VO_{2peak}	56 ± 16 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$
HR_{max}	180 ± 25 bpm
LT1	3 ± 1 $mmol{\cdot}L^{-1}$
LT2	6 ± 3 $mmol{\cdot}L^{-1}$

Considering the average age of participants, i.e., 32 ± 10 years, the AHA reference value of oxygen consumption is 42 ± 7 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$. This information allows us to indicate that men have values above the reference values, demonstrating evidence of higher aerobic capacity. However, it is important to consider that the population of Portuguese volunteer firefighters can vary between 18 and 45 years and with individuals potentially older still regarded as fit for duty, even as their aerobic capacity decreases significantly; therefore, with increasing age, firefighters experience a decline in their operational performance. Given the limited sample size, which does not permit robust comparisons

across different age groups, we analysed reference values for aerobic capacity. Figure 2 shows the variation in VO_{2peak} by age group.

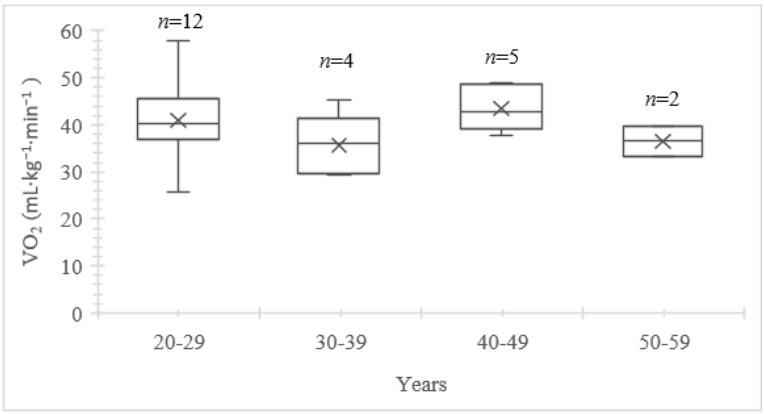

Figure 2. Average values of VO_{2peak} correspond to the last stage of the incremental tests (n = 23).

The concentrations of LTP1 and LTP2 correspond to approximately 40% of VO_{2peak} for LTP1 and around 60% of VO_{2peak} for LTP2. This suggests that at about 60% of VO_{2peak}, capillary lactate values begin to indicate the transition to the anaerobic phase of exercise. The anaerobic phase involves the production of muscular energy without sufficient oxygen, leading to increased lactic acid production and muscular fatigue. This transition is evident in the results, where the ventilatory threshold point reaches around 40% of VO_{2peak}, as depicted in Figure 3.

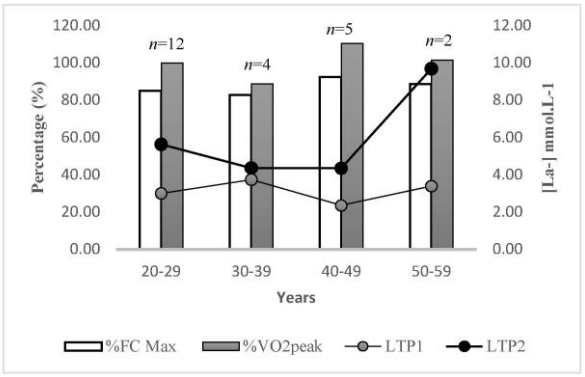

Figure 3. Variation in physiological data during the stress test (n_{total} = 23).

None of the variables exhibit a normal distribution. Upon analysing the correlations among the variables, it was observed that HR and oxygen consumption were the only variables that showed a correlation (ϱ = 0.42; p-value = 0.05). Table 2 shows the p-values from the correlation between the studied variables.

Table 2. Correlation matrix in variables to VO_{2peak} incremental test (n = 23).

		Correlation Matrix				
	Mean ± SD	**Age**	**HR**	**LTP1**	**LTP2**	**VO_{2peak}**
		***p*-Value|ϱ**	***p*-Value|ϱ**	***p*-Value|ϱ**	***p*-Value|ϱ**	***p*-Value|ϱ**
Age (years)	32 ± 10	-----				
HR (bpm)	182 ± 24	0.25|−0.25	-----			
LTP1 (mmol·L^{-1})	3 ± 1	0.93|0.02	0.19|0.28	-----		
LTP2 (mmol·L^{-1})	6 ± 3	0.50|−0.14	0.24|0.26	0.14|0.32	-----	
VO_{2peak} (mL·kg^{-1}·min^{-1})	55 ± 16	0.60|−0.12	0.05|0.42 *	0.24|0.25	0.94|0.02	-----

* p-value statistically significant at a confidence level of 0.05.

3.2. Occupational Exposure in Firefront

3.2.1. Energy Expenditure and Metabolic Rate

Only 21 agreed to undergo real-time monitoring in wildland firefighting, of which 8 were women and 13 were men, with average ages of 34 ± 10 years. A total of 9842 minutes were monitored, with only 5871 minutes used for the present analysis since the remaining minutes represented other activities unrelated to fighting wildfires. In the case of wildfires, it was observed that men were close to the value recommended by the National Institute for Occupational Safety and Health (NIOSH) for energy expenditure during a working day in safe conditions [54], namely 5.2 kcalmin^{-1} for men, while the recommended value is 3.6 kcal.min^{-1} for women. The collected data show that women (n = 8) exceeded the recommended reference values, and men (n = 13) had average values close to the recommended values, as seen in Table 3.

Table 3. Average Expended Energy (n = 21).

	Task	Task Time (minutes)	Energy Expenditure (kcal·min^{-1})
Total	Nozzle	535.00 ± 893.00	4.78 ± 0.56
	Nozzle-Rope	283.00 ± 244.05	4.03 ± 0.69
	COS	205.00	4.92 ± 0.58
	Rope	141.33 ± 52.32	4.28 ± 0.63
Women	Nozzle	213.00	4.40 *
	Nozzle/rope	184.29 ± 95.60	3.97 ± 0.79 *
	Rope	141.33 ± 52.32	4.28± 0.63 *
Men	Nozzle	581.00 ± 945.75	4.91 ± 0.64
	Nozzle/rope	513.33 ± 318.47	4.12 ± 0.46
	COS	205.00	4.74 ± 0.57

* Values above reference values.

A statistically significant relationship was confirmed between the equivalent of VO_{2peak} and energy expenditure (p-value = 0.03 for a significance level of 0.05). This relationship was not evident in the energy expenditure results (4 ± 0.81 kcal·min^{-1}). However, it can be observed in the estimated VO_{2peak} (31 ± 6%), as shown in Table 4.

Table 4. Kruskal–Wallis test for the relationship between the tasks, energy expenditure, and respective VO_{2peak} equivalent (n = 21).

Energy Expenditure			VO_{2peak} Equivalent to Energy Expenditure		
Kruskal–Wallis test	p-value	kcal·min $^{-1}$	Kruskal–Wallis test	p-value	VO_{2peak} equivalent to energy expenditure (%)
3.997	0.136	4 ± 0.81	7.036	0.030 *	31 ± 6

* Significance level of 0.05.

When analysing the data based on tasks, it became clear that tasks performed closer to the firefront, such as those involving the nozzle and rope positions, tend to exhibit higher energy consumption. This is likely due to exposure to high temperatures, which require increased metabolic expenditure. Women show higher energy expenditure values than men in the nozzle/rope positions, reaching maximum values of 5 kcal·min^{-1}.

Furthermore, it was confirmed that the COS task performed exclusively by men in this sample shows values close to the reference value of 5.2 kcal·min^{-1}. This task involves overseeing the entire ground for the team's public safety management and all firefighting operations.

The collected data indicate that the nozzle/rope task is the one that spends the most time in moderate to very vigorous activity. These data, once again, align with the results

obtained earlier, where it was observed that the activity in wildland fires is physically demanding, especially in tasks involving direct attack on the firefront and hose handling (hose pulling), demonstrating that 32% of the task time is spent in moderate activity. However, the data may be biased due to the unknown task switch times, which complicates the analysis on an individual task basis.

It is worth noting that the COS task, despite not being directly associated with practical firefighting work, involves significant movement of the individual across the terrain for effective team and firefighting operations management, demonstrating a moderate activity level for 36% of the task time.

Thus, when evaluating the demands of fighting forest fires through the conducted monitoring and comparing it with the average VO_{2peak} value established by reference values recommended by the AHA, it was reaffirmed that fighting wildfires requires a metabolic consumption equivalent to an oxygen volume close to 40%. Once again, it is evident that the nozzle/rope task and the COS are particularly demanding, as seen in Figure 4.

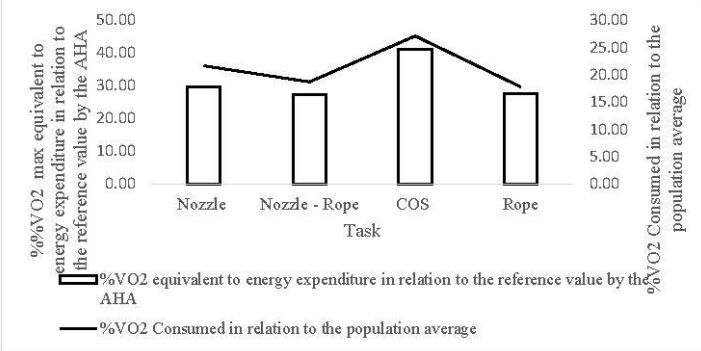

Figure 4. Energy expenditure equivalent to $\%VO_{2peak}$ during forest-fire fighting (n = 21).

The reference value indicated by the AHA presents higher values, suggesting that the sample used for defining reference values is more significant, considering age groups and gender. These reference values make the data more realistic to the aerobic capacity of the individuals evaluated. According to these data, and considering that the nozzle/rope task proves to be the most concerning, it is possible to indicate that these individuals' capacity aerobic maximum (CAM) varies between 23% and 31% of their VO_{2peak}. These data suggest that the two main tasks involving work closer to the firefront are the most demanding regarding respiratory effort. The nozzle/rope task lasts the longest, ranging from 39 to 527 min.

3.2.2. Heart Rate Variability Analysis

When evaluating HRV during wildland firefighting, an increase in low frequency (LF) compared to high frequency (HF) was observed, especially in nozzle/rope tasks. These data affirm the dominance of sympathetic activity and imply that these tasks involve low to moderate-intensity activity. Although the HF values were inconsistent and varied, situations with higher HF values confirmed the prevalence of the parasympathetic system, indicating intense physical activity. Indeed, these higher HF values may be associated with more challenging and prolonged firefighting situations. After applying the non-parametric Kruskal–Wallis test for the distribution of results in the frequency and time domains concerning the assessed tasks, it was possible to verify statistically significant differences between rest and tasks in wildland firefighting, except for the LF/HF ratio and SDNN, as confirmed in Figure 5.

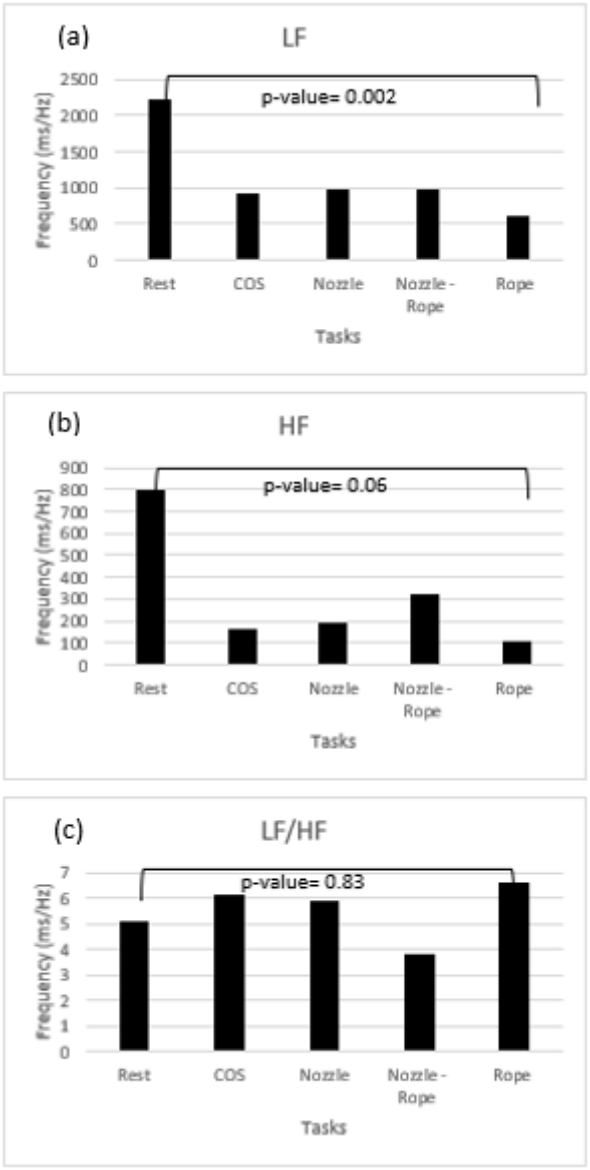

Figure 5. HRV in the frequency domain: (**a**) low frequency (LF); (**b**) high frequency (HF); (**c**) ratio LF/HF.

An examination of HRV in the time domain revealed a consistent linear decrease in the variables of the standard deviation of N-N intervals (SDNN), root mean square of successive R-R interval differences (RMSSD), and percentage of consecutive R-R intervals that differ by more than 50 ms (pNN50), indicating the performance of vigorous physical activities. Notably, the decrease in RMSSD values occurred within the HR range of 120 to 140 bpm, corresponding to 50–60% of VO_{2peak} consumption. The data presented in Table 5 clearly show that the nozzle/rope and COS tasks exhibit a linear decrease in time domain variables, with the highest HR values. Nozzle/rope and COS tasks demand the highest VO_{2peak} consumption. The functions considered to be closer to the front line of the fire were the ones that showed more statistically significant changes in the Kruskal–Wallis test.

Table 5. HRV in the time domain (M—mean; SD—standard deviation).

	SDNN (ms)		RMSSD (ms)		pNN 50 (%)		H.R. (bpm)	
Task	M ± SD		M ± SD		M ± SD		M ± SD	
Rest	108 ± 51		38 ± 24		15 ± 13		89 ± 31	
Nozzle	87 ± 36	*p*-value =	26 ± 11	*p*-value =	6.7 ± 5.5	*p*-value	104 ± 12	*p*-value
Nozzle/rope	83 ± 18	0.17	20 ± 12	0.004	3.6 ± 3.5	< 0.001	107 ± 13.06	<0.001
Rope	102 ± 28		26 ± 9.2		4.1 ± 2.5		100 ± 7.2	
COS	77 ± 3.9		19 ± 4.1		3.5 ± 1.6		108 ± 13.8	

Despite the average values not exceeding 120 bpm, the maximum value observed during work was 148 bpm, associated with a nozzle task executed by a 20-year-old male, representing approximately 78% of its theoretical maximum HR. These data represent a VO_{2peak} equivalent of roughly 53%. These data were collected during a prolonged firefighting incident, with 24-hour combat, reinforcing the strain experienced during extended firefighting periods. However, it is essential to note that peaks and stops during firefighting were not observed, and these data are assumed to be integrated into the task-calculated values.

Nevertheless, as mentioned earlier, considering that extreme environments impose greater demands on firefighters to maintain thermoregulatory balance, indicating a fatigued state between 120 and 140 bpm and representing 50–60% of VO_{2peak}, this may not correspond to the actual work reality. Given that a possible fatigue state was considered at 40% of VO_{2peak} consumed during firefighting, heart rate values above 140 bpm may indicate the firefighter's fatigue state.

The presented results confirmed that older individuals with several years of experience typically hold higher-ranking positions among volunteer firefighters. However, it is essential to note that the population is ageing, with an increasing prevalence of cardiovascular diseases such as hypertension. These combined factors can limit the physiological response of firefighters during firefighting not only due to early entry into a state of exhaustion but also in terms of recovery difficulties and an increased likelihood of death from cardiovascular causes. Given the high demands of wildland firefighting, firefighters' physical fitness is crucial, reflecting their ability to utilise muscle fibres for exercise execution and their aerobic capacity (CAM). However, it is known that exposure to various contaminants present in the fire environment can influence an individual's response to the situation and contribute to the incidence of cardiovascular and respiratory diseases.

4. Discussion

Physical demand involves the effort exerted by the musculoskeletal system to execute a specific task. In contrast, cardiovascular demand concerns the energy the cardiovascular system requires to supply oxygen and nutrients during that task. Evaluating both physical and cardiovascular demands is essential to understanding the physiological impacts of occupational tasks, especially in high-stress environments, to prevent work-related diseases and fatigue [43,51,55–59].

Given the mean age of male participants (32 ± 10 years), the AHA reference value for VO_{2peak} is 42 ± 7 $mL \cdot kg^{-1} \cdot min^{-1}$. The data indicate that male participants exhibited VO_2 values exceeding these reference levels, suggesting a higher-than-average aerobic capacity. This finding supports the classification of the study population as relatively young, which aligns with the elevated VO_{2peak} values observed. These results imply that the assessed volunteer firefighters possess aerobic capacities above typical expectations, reflecting a robust level of physical fitness [60]. Advancing age is associated with a natural decline in aerobic capacity, directly impacting operational performance. Thus, the effects of age-related physiological decline must be considered, as it influences firefighters' functional readiness and endurance during physically demanding tasks [61].

However, 150 min of moderate or 75 min of vigorous activity is recommended [62]. The results indicate prolonged firefighting activities frequently surpass the recommended 150 min of moderate to vigorous exertion, especially for tasks near the firefront. High-intensity activities elevate steady-state oxygen consumption, covering the full energy demand [33].

The physiological response of individuals to physically demanding tasks is influenced by their muscular capacity to utilise oxygen and convert it into muscular energy, thereby delaying the onset of early fatigue, as demonstrated in previous laboratory studies [63,64]. However, effective management of muscular effort is crucial in extreme environments, where oxygen consumption demands are significantly higher, leading individuals to transition to anaerobic metabolism quickly. This is particularly evident in scenarios such as wildfires, which impose maximum or near-maximum physiological demands [34].

The tasks involving wildfire fighting can range from values of 17 $mL \cdot kg^{-1} \cdot min^{-1}$ (or 2.5 $kcal \cdot min^{-1}$) for light tasks to >30 $mL \cdot kg^{-1} \cdot min^{-1}$ (or >10 $kcal \cdot min^{-1}$), depending on the type of terrain in which the firefighting is carried out and the duration of the task, considering that wild firefighting can be of long duration [65]. The primary metabolic rate is observed in sloping terrains that may require the firefighter to consume more oxygen than their capacity [66]. The values reached by Portuguese firefighters are close, representing a cumbersome physical activity that may have severe consequences for the firefighter's health, as it influences the homeostatic balance of different biological systems [67,68]. This study found a strong relationship between the tasks performed at the firefront and the equivalent of $\%VO_{2peak}$, with a p-value of 0.030. Despite finding that the anaerobic phase of exercise occurs at approximately 60% of VO_{2peak}, it is necessary to consider that firefighters need to undergo a process of thermoregulatory adaptation in wildland firefighting. The execution of intense physical work in hot environments can affect oxygen consumption due to the need for the body to undergo a cooling process through an increased sweating rate [69–72]. Thus, it is considered that in wildfire combat environments, the equivalent VO_2 value may be lower, indicating that at 40% of VO_{2peak}, firefighters may already be in overload [46,48,49].

The study of heart rate variability allows for predicting mortality from cardiovascular disease in apparently healthy populations [21,73,74]. Monitoring cardiovascular parameters during the work period has proven to be a fundamental methodology for determining maximum work intensities safely by avoiding excessive accumulated physical fatigue and work-related heart disease [75,76].

Exposure to physical and mental stress, such as the environment of wildfire fighting, is reflected in cardiac adaptations associated with vagal flow [77]. The oscillations in the LF band (p-value = 0.002) indicate slow respiratory cycles, meaning that the influences of the environment on respiratory cycles may explain these alterations [78]. The nozzle/rope tasks present more fluctuating values, and there may be a direct relationship with greater exposure to fire smoke. On the other hand, it is necessary to consider that the cardiac response in extreme environments is also influenced, as evidenced by the significant increase in heart rate [19,51,79]. According to Panumasvivat et al. (2023) [80], firefighters assigned to wildfire-fighting teams had a higher cardiovascular risk than the general population. However, it is necessary to mention that human variability and individual susceptibility are influencing factors in cardiovascular response, knowing that personal factors such as gender, physical fitness, and age are variables influencing autonomous heart control [58]. The cardiac events and their relationship to firefighting can be seen as a combination of vulnerability and cardiovascular overload associated with the task [81].

5. Recommendations

This section proposes a Health and Safety Surveillance Program for Firefighters (HSSPF) based on the results. The primary objective of this program is to develop a foundation for Occupational Health and Safety Services to evaluate the health status of prospective and active firefighters, whether in volunteer or professional roles. The program

does not aim to justify the elimination of candidates or firefighters from their roles; instead, it serves as a strategy for identifying the most suitable tasks for each individual, assigning them to tasks according to their health status. However, individuals who do not meet legal requirements or have debilitating conditions are excluded from this allocation process, representing the exceptions for elimination within the program. Therefore, the different tasks of firefighters should be objectively evaluated through the collection of physiological data, analysing the fatigue induced by these tasks and each candidate's or firefighter's capacity to respond to them. Recognising the existence of seasonal or infrequent tasks, the program allows for the allocation of firefighters to multiple tasks as long as their health status permits.

The proposed program introduces an innovative framework divided into several stages, including a communication platform; a firefighter candidate selection process; a health monitoring process for firefighters; a communication, analysis, and evaluation procedure for work-related accidents; and the establishment of a set of physiological criteria for the selection and monitoring of firefighters, as can be seen in Figure 6.

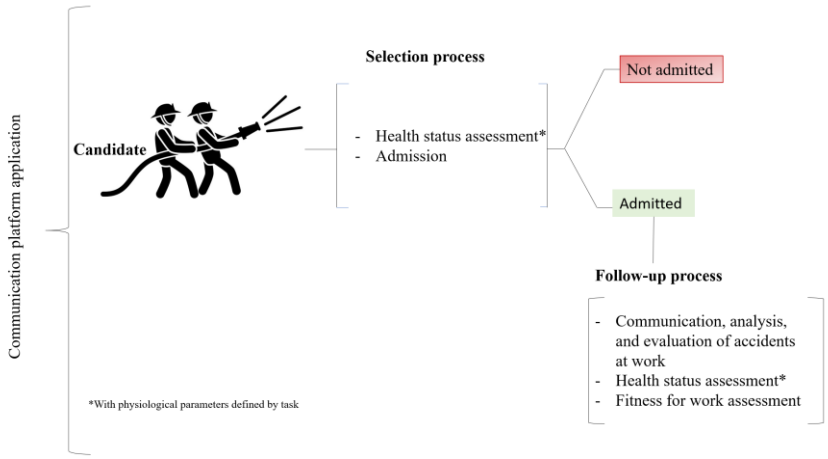

Figure 6. Steps in the HSSPF.

Below is a description of each stage defined for this program proposal:

1. Communication Platform: Effective communication between different entities and individuals involved in the program is essential for its success. Therefore, this program proposes the development of a platform accessible to all involved entities, containing information about candidates and all active firefighters, where all safety and health-related information should be shared. This platform does not necessarily need to be developed from scratch, considering the associated costs, and it is suggested that it be integrated into existing platforms;
2. Firefighter Candidate Selection Procedure: This procedure outlines the main steps for selecting and monitoring the health status of firefighters. Criteria related to physical condition and medical standards have been established to ensure the firefighter's safety in performing various tasks. These criteria should be adjusted according to the needs of Occupational Health and Safety Services. The selection process proposed by the HSSPF is based on analysing candidates' applications and fulfilling pre-existing requirements and criteria defined for each task. The proposed HSSPF selection process is divided into four phases: the application phase, the health assessment phase based on established criteria, the response capacity evaluation phase based on physiological parameters for each task, and the results communication phase;
3. Health Monitoring Procedure for Firefighters: The monitoring process aims to assess the health status of firefighters to ensure their fitness to perform tasks. The occupational physician should prescribe appropriate medical examinations according to the tasks performed by the individual and evaluate the emergence of any symptoms or

diseases. If the firefighter is deemed healthy, they are considered fit to continue their duties. If symptoms or diseases are present, their incapacity, either total or partial, should be assessed, evaluating their fitness to continue the current task or another suitable task based on the program's criteria. The occupational physician must communicate the results to Occupational Health and Safety Services, which should monitor the process and implement improvement strategies where possible. Based on the health assessment results, Occupational Health and Safety Services are responsible for communicating with the relevant authorities and supporting the firefighter's needs during their duties;

4. Procedure for Communication, Analysis, and Evaluation of Work-related Accidents: Communicating work-related accidents and studying their severity is crucial for mitigating risks and reducing their frequency. Given the unpredictable nature of firefighting scenarios, risk elimination is challenging. Therefore, this program aims to implement accident reporting via firefighters or their direct supervisors through an internal platform. A coding system should be adopted for quick, efficient accident and injury reporting to facilitate accessible communication for reporting an accident. This program suggests using the Registration, Investigation, and Analysis of Work Accidents (RIAAT) method, which already uses European coding for work-related accidents [82], making accident reporting by fire brigade commanders, firefighters, or other personnel easier, faster, and more efficient;
5. Physiological Criteria for the Selection and Monitoring of Firefighters: These criteria outline the ideal profile for firefighters to prevent disease development and ensure individual health safety. Considering the physical demands of firefighting, the program recommends comprehensive blood counts, bone marrow tests, blood coagulation tests, lipoprotein panels, blood enzyme tests, and basic metabolic panels. This battery of tests provides the physician with information on the firefighter's or candidate's current health status, particularly regarding blood pressure, glucose levels, blood clotting capacity, heart disease, and kidney function [83]. These evaluation parameters help prevent risk situations such as haemorrhages, early kidney disease caused by heat exposure and dehydration, and cardiovascular diseases developed due to task demands. Important physiological parameters to be evaluated during the individual's fitness examination include sociodemographic characteristics, maximum work capacity and operational fitness, physical fitness, and psychosocial characteristics. For sociodemographic characteristics, an acceptable range for performing tasks safely should be adopted based on task demands and the individual's sex.
6. Regarding maximum work capacity and operational fitness, it is recommended to establish medical limiting parameters for task execution to aid in selecting and monitoring firefighters' health, preventing the worsening or onset of diseases. For physical fitness, it is suggested that the firefighter's profile follows the World Health Organization's guidelines on biometric data. Lastly, psychosocial characteristics consider the psychological impacts of firefighting. Therefore, this program does not recommend selecting individuals with psychiatric disorders or those susceptible to developing such conditions.

6. Conclusions

The firefront presents a significant concern for firefighters' well-being due to high levels of exposure and the difficulties in monitoring and mitigating occupational risks. Our study successfully met its objectives, demonstrating that fighting forest fires, particularly tasks performed near the firefront, greatly impacts firefighters' health.

This research introduces a novel approach to understanding the occupational health challenges firefighters face during forest fire fighting. It confirms that prolonged firefighting places a substantial physical and cardiovascular burden on firefighters, contributing to potential mortality alongside other occupational hazards. HRV (heart rate

variability) analysis validated physiological stress indicators, though further research is needed to understand the multifaceted workload firefighters experience fully.

These findings highlight the urgent need for interventions to improve firefighters' health and safety, particularly through enhanced training and physiological preparedness for the demanding conditions of forest fire fighting. The authors advocate for developing innovative methodologies to assess health risks specific to wildland firefighting, intending to correlate exposure risks to incidents of sudden mortality observed during duty.

Strategic initiatives can be developed by adopting new methodologies and promoting innovation in occupational health and safety practices to improve firefighters' working conditions. We recommend implementing methods that enable a more comprehensive analysis of firefighters' occupational exposure, particularly through the combined assessment of environmental hazards and firefighters' physiological responses. Existing studies indicate that the work environment directly influences firefighters' physiological capacity. Considering the confirmed demands of forest fire fighting, it is advised to adopt measures such as implementing occupational health programs to improve working conditions and mitigate the impacts of prolonged exposure.

Author Contributions: Conceptualization, T.T., J.S., M.A.P.V., and J.C.G.; methodology, T.T. and J.C.G.; formal analysis, T.T., P.P., and J.C.G.; draft writing preparation, T.T. and J.C.G.; drafting and editing revision, T.T., P.P., J.S., P.R.M., M.A.P.V., and J.C.G.; project administration, J.S.B., M.A.P.V., and J.C.G.; funding acquisition, J.S.B., M.A.P.V., and J.C.G. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Foundation of Science and Technology (FCT Portugal) through project grant PCIF/SSO/0063/2018 with DOI: http://doi.org/10.54499/PCIF/SSO/0063/2018, accessed on 11 December 2023. The authors would also like to acknowledge the funding provided by LAETA under the UIDB/50022/2020 project and the Foundation for Science and Technology support through the grant DOI:10.54499/UI/BD/151285/20.

Institutional Review Board Statement: The study was conducted in compliance with the Declaration of Helsinki and received approval from the Ethics Committee of the University of Porto under protocol code 106/CEUP/2021, approved on April 13, 2021.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the participants to publish this paper. This study was submitted to and approved by the ethics committee of the University of Porto (CEUP) under reference number 106/CEUP/2021. The University of Porto Ethics Committee (CEUP) submitted and approved the protocol under reference number 106/CEUP/2021.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors upon request.

Acknowledgments: The authors would also like to acknowledge the support of the Ph.D. Program in Occupational Health and Safety at the University of Porto.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Koopmans, E.; Cornish, K.; Fyfe, T.M.; Bailey, K.; Pelletier, C.A. Health risks and mitigation strategies from occupational exposure to wildland fire: A scoping review. *J. Occup. Med. Toxicol.* **2022**, *17*, 2. https://doi.org/10.1186/s12995-021-00328-w.
2. Teixeira, T.; Dias, I.; Santos, J.; Bustos, D.; Guedes, J. Firefighters Occupational Exposure Assessment: A Systematic Literature Review. In *4th Symposium on Occupational Safety and Health Proceedings Book*; FEUP: Porto, Portugal, 2021; pp. 21–30. https://doi.org/10.24840/978-972-752-279-8_0021-0030.
3. The National Institute for Occupational Safety and Health (NIOSH). Wildland Firefighter Exposure and Health Effects Study. Available online: https://www.cdc.gov/niosh/topics/firefighting/wffhealthstudy.html#print (accessed on 22 November 2023).
4. FPS. Volunteer Firefighters in Europe. Available online: https://www.fireproductsearch.com/volunteer-firefighters-in-europe/ (accessed on 22 November 2023).
5. Pennington, M.L.; Cardenas, M.; Nesbitt, K.; Coe, E.; Kimbrel, N.A.; Zimering, R.T.; Gulliver, S.B. Career versus volunteer firefighters: Differences in perceived availability and barriers to behavioral health care. *Psychol. Serv.* **2022**, *19*, 502–507. https://doi.org/10.1037/ser0000559.

6. Banes, C.J. Firefighters' cardiovascular risk behaviors. Workplace Health Safety. *Work. Health Saf.* **2014**, *62*, 27–34.
7. Durand, G.; Tsismenakis, A.J.; Jahnke, S.A.; Baur, D.M.; Christophi, C.A.; Kales, S.N. Firefighters' physical activity: Relation to fitness and cardiovascular disease risk. *Med. Sci. Sports Exerc.* **2011**, *43*, 1752–1759.
8. The National Institute for Occupational Safety and Health (NIOSH). Exposure Assessment: Program Description. Available online: https://www.cdc.gov/niosh/research-programs/portfolio/exposure-assess.html (accessed on 22 November 2023).
9. Soteriades, E.S.; Smith, D.L.; Tsismenakis, A.J.; Baur, D.M.; Kales, S.N. Cardiovascular disease in US firefighters: A systematic review. *Cardiol. Rev*. **2011**, *19*, 202–215
10. Yoo, H.L.; Franke, W.D. Prevalence of cardiovascular disease risk factors in volunteer firefighters. *J. Occup. Environ. Med*. **2009**, *51*, 958–962.
11. U.S. Fire Administration. Firefighter Fatalities in the United States. Available online: https://apps.usfa.fema.gov/firefighter-fatalities/ (accessed on).
12. Kales, S.N.; Soteriades, E.S.; Christophi, C.A.; Christiani, D.C. Emergency duties and deaths from heart disease among firefighters in the United States. *N. Engl. J. Med.* **2007**, *356*, 1207–1215. https://doi.org/10.1056/NEJMoa060357.
13. CDC. Fire Fighter Fatality Map. Available online: https://wwwn.cdc.gov/Wisards/fffmap/ (accessed on 27 June 2024).
14. Perroni, F.; Guidetti, L.; Cignitti, L.; Baldari, C. Psychophysiological Responses of Firefighters to Emergencies: A Review. *Open Sports Sci. J.* **2014**, *7*, 8–15. https://doi.org/10.2174/1875399X01407010008.
15. Morris, C.E.; Chander, H. The Impact of Firefighter Physical Fitness on Job Performance: A Review of the Factors That Influence Fire Suppression Safety and Success. *Safety* **2018**, *4*, 60. https://doi.org/10.3390/safety4040060.
16. Xu, D.; Song, Y.; Meng, Y.; István, B.; Gu, Y. Relationship between Firefighter Physical Fitness and Special Ability Performance: Predictive Research Based on Machine Learning Algorithms. *Int. J. Environ. Res. Public Health* **2020**, *17*, 7689. https://doi.org/10.3390/ijerph17207689.
17. Chizewski, A.; Box, A.; Kesler, R.; Petruzzello, S.J. Fitness Fights Fires: Exploring the Relationship between Physical Fitness and Firefighter Ability. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11733. https://doi.org/10.3390/ijerph182211733.
18. Fasching, P.; Rinnerhofer, S.; Wultsch, G.; Birnbaumer, P.; Hofmann, P. The First Lactate Threshold Is a Limit for Heavy Occupational Work. *J. Funct. Morphol. Kinesiol.* **2020**, *5*, 66. https://doi.org/10.3390/jfmk5030066.
19. Sollers, J.J.; Sanford, T.A.; Nabors-Oberg, R.; Anderson, C.A.; Thayer, J.F. Examining changes in HRV in response to varying ambient temperature. *IEEE Eng. Med. Biol. Mag.* **2002**, *21*, 30–34. https://doi.org/10.1109/MEMB.2002.1032636.
20. Berntson, G.G.; Bigger, J.T.; Eckberg, D.L.; Grossman, P.; Kaufmann, P.G.; Malik, M.; Nagaraja, H.N.; Porges, S.W.; Saul, J.P.; Stone, P.H.; et al. Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology* **1997**, *34*, 623–648. https://doi.org/10.1111/j.1469-8986.1997.tb02140.x.
21. Kleiger, R.E.; Stein, P.K.; Bigger, J.T. Heart Rate Variability: Measurement and Clinical Utility. *Ann. Noninvasive Electrocardiol.* **2005**, *10*, 88–101. https://doi.org/10.1111/j.1542-474X.2005.10101.x.
22. Barbosa, J.V.; Alvim-Ferraz, M.C.; Martins, F.G.; Sousa, S.I. Occupational exposure of firefighters to hazardous pollutants during prescribed fires in Portugal. *Chemosphere* **2024**, *352*, 141355. https://doi.org/10.1016/j.chemosphere.2024.141355.
23. Gledhill, N.; Jamnik, V.K. Characterization of the physical demands of firefighting. *Can. J. Sport Sci*. **1992**, *17*, 207–213.
24. Hyde, M.; Beighley, A.C. Portugal Wildfire Management in a New Era Assessing Fire Risks, Resources and Reforms. 2018. Available online: https://www.isa.ulisboa.pt/files/cef/pub/articles/2018-04/2018_Portugal_Wildfire_Management_in_a_New_Era_Engish.pdf(accessed on 10 January 2024).
25. Bazuelo-Ruiz, B.; de Rosario, H.; Durá-Gil, J.V. Validation of oxygen consumption prediction equations and new formulas for interval training. *Apunt. Educ. Fis. Deport.* **2020**, *143*, 9–16. https://doi.org/10.5672/apunts.2014-0983.es.(2021/1).143.02.
26. Masuo, Y.; Tamaki, A. A step test to estimate cardiorespiratory fitness from heart rates both during and after exercise: A cross-validation study among adolescent university students. *Jpn. J. Phys. Fit. Sports Med.* **2022**, *71*, 505–514. https://doi.org/10.7600/jspfsm.71.505.
27. Sloan, R.; Visentini-Scarzanella, M.; Sawada, S.; Sui, X.; Myers, J. Estimating Cardiorespiratory Fitness Without Exercise Testing or Physical Activity Status in Healthy Adults: Regression Model Development and Validation. *JMIR Public Health Surveill.* **2022**, *8*, e34717. https://doi.org/10.2196/34717.
28. Matsuo, T.; So, R.; Murai, F. Improved VO2max Estimation by Combining a Multiple Regression Model and Linear Extrapolation Method. *J. Cardiovasc. Dev. Dis.* **2022**, *10*, 9. https://doi.org/10.3390/jcdd10010009.
29. Buttar, K.; Saboo, N.; Kacker, S. A review: Maximal oxygen uptake (VO_2 max) and its estimation methods. *Int. J. Phys. Educ. Sports Health* **2019**, *6*, 24–32.
30. Sharkey, B.J.; Gaskill, S.E. *Fitness & Health*; Human Kinetics: Champaign, IL, USA, 2012. https://doi.org/10.5040/9781718209107.
31. Patel, H.; Alkhawam, H.; Madanieh, R.; Shah, N.; E Kosmas, C.; Vittorio, T.J. Aerobic vs anaerobic exercise training effects on the cardiovascular system. *World J. Cardiol.* **2017**, *9*, 134–138. https://doi.org/10.4330/wjc.v9.i2.134.
32. Cooper, K.H.; Gallman, J.S.; McDonald, J.L. Role of aerobic exercise in reduction of stress. *Dent. Clin. N. Am*. **1986**, *30*, S133–S142.
33. MacIntosh, B.R.; Murias, J.M.; Keir, D.A.; Weir, J.M. What Is Moderate to Vigorous Exercise Intensity? *Front. Physiol.* **2021**, *12*, 1481. https://doi.org/10.3389/fphys.2021.682233.
34. Holmér, I.; Gavhed, D. Classification of metabolic and respiratory demands in fire fighting activity with extreme workloads. *Appl. Ergon.* **2007**, *38*, 45–52. https://doi.org/10.1016/j.apergo.2006.01.004.

35. Youssouf, H.; Liousse, C.; Roblou, L.; Assamoi, E.-M.; Salonen, R.O.; Maesano, C.; Banerjee, S.; Annesi-Maesano, I. Non-accidental health impacts of wildfire smoke. *Int. J. Environ. Res. Public Health* **2014**, *11*, 11772–11804. https://doi.org/10.3390/ijerph111111772.
36. Sousa, A.; Figueiredo, P.; Zamparo, P.; Pyne, D.B.; Vilas-Boas, J.P.; Fernandes, R.J. Exercise Modality Effect on Bioenergetical Performance at V˙O2max Intensity. *Med. Sci. Sports Exerc.* **2015**, *47*, 1705–1713. https://doi.org/10.1249/MSS.0000000000000580.
37. Cardoso, F.; Monteiro, A.S.; Vilas-Boas, J.P.; Pinho, J.C.; Pyne, D.B.; Fernandes, R.J. Effects of Wearing a 50% Lower Jaw Advancement Splint on Biophysical and Perceptual Responses at Low to Severe Running Intensities. *Life* **2022**, *12*, 253. https://doi.org/10.3390/life12020253.
38. Cardoso, F.; Coelho, E.P.; Gay, A.; Vilas-Boas, J.P.; Pinho, J.C.; Pyne, D.B.; Fernandes, R.J. Case Study: A Jaw-Protruding Dental Splint Improves Running Physiology and Kinematics. *Int. J. Sports Physiol. Perform.* **2022**, *17*, 791–795. https://doi.org/10.1123/ijspp.2021-0338.
39. Beltz, N.M.; Gibson, A.L.; Janot, J.M.; Kravitz, L.; Mermier, C.M.; Dalleck, L.C. Graded Exercise Testing Protocols for the Determination of VO_2 max: Historical Perspectives, Progress, and Future Considerations. *J. Sports Med.* **2016**, *2016*, 396839. https://doi.org/10.1155/2016/3968393.
40. Swartz, A.M.; Strath, S.J.; Bassett, D.R., Jr.; O'Brien, W.L.; King, G.A.; Ainsworth, B.E. Estimation of energy expenditure using CSA accelerometers at hip and wrist sites. *Med. Sci. Sports Exerc.* **2000**, *32*, S450–S456. https://doi.org/10.1097/00005768-200009001-00003.
41. Lucena, A.; Guedes, J.; Vaz, M.; Silva, L.; Bustos, D.; Souza, E. Modeling Energy Expenditure Estimation in Occupational Context by Actigraphy: A Multi Regression Mixed-Effects Model. *Int. J. Environ. Res. Public Health* **2021**, *18*, 10419. https://doi.org/10.3390/ijerph181910419.
42. Fletcher, G.F.; Balady, G.J.; Amsterdam, E.A.; Chaitman, B.; Eckel, R.; Fleg, J.; Froelicher, V.F.; Leon, A.S.; Piña, I.L.; Rodney, R.; et al. Exercise Standards for Testing and Training. *Circulation* **2001**, *104*, 1694–1740. https://doi.org/10.1161/hc3901.095960.
43. SJärvelin-Pasanen, S.; Sinikallio, S.; Tarvainen, M.P. Heart rate variability and occupational stress—Systematic review. *Ind. Health* **2018**, *56*, 500–511. https://doi.org/10.2486/indhealth.2017-0190.
44. Blair, R.C.; Taylor, R.A. *SPSS 15.0 Supplement for: Biostatistics for the Health Sciences*, 11th ed.; Pearson Prentice Hall: Saddle River, NJ, USA, 2008.
45. Ghosh, A.K. Anaerobic threshold: Its concept and role in endurance sport. *Malays. J. Med. Sci*. **2004**, *11*, 24–36.
46. Faude, O.; Kindermann, W.; Meyer, T. Lactate Threshold Concepts. *Sports Med.* **2009**, *39*, 469–490. https://doi.org/10.2165/00007256-200939060-00003.
47. Freedson, P.S.; Melanson, E.; Sirard, J. Calibration of the Computer Science and Applications, Inc. accelerometer. *Med. Sci. Sports Exerc.* **1998**, *30*, 777–781. https://doi.org/10.1097/00005768-199805000-00021.
48. Jetté, M.; Sidney, K.; Blümchen, G. Metabolic equivalents (METS) in exercise testing, exercise prescription, and evaluation of functional capacity. *Clin. Cardiol.* **1990**, *13*, 555–565. https://doi.org/10.1002/clc.4960130809.
49. Coyle, E.F. Physical activity as a metabolic stressor. *Am. J. Clin. Nutr.* **2000**, *72*, 512S–520S. https://doi.org/10.1093/ajcn/72.2.512S.
50. Thyfault, J.P.; Bergouignan, A. Exercise and metabolic health: Beyond skeletal muscle. *Diabetologia* **2020**, *63*, 1464–1474. https://doi.org/10.1007/s00125-020-05177-6.
51. Malchaire, J.; Alfano, F.R.D.; Palella, B.I. Evaluation of the metabolic rate based on the recording of the heart rate. *Ind. Health* **2017**, *55*, 219–232. https://doi.org/10.2486/indhealth.2016-0177.
52. Flairty, J.E.; Scheadler, C.M. Perceived and Heart Rate-based Intensities during Self-paced Walking: Magnitudes and Comparison. *Int. J. Exerc. Sci*. **2020**, *13*, 677–688.
53. Anônimo. Heart Rate Variability (HRV) Science for Sport. Available online: https://www.scienceforsport.com/heart-rate-variability-hrv/(accessed on 11 July 2018).
54. The National Institute for Occupational Safety and Health (NIOSH). Work Practices Guide for Manual Lifting. 1981. Available online: https://www.cdc.gov/niosh/docs/81-122/pdfs/81-122.pdf (accessed on 11 January 2024).
55. Nystoriak, M.A.; Bhatnagar, A. Cardiovascular Effects and Benefits of Exercise. *Front. Cardiovasc. Med.* **2018**, *5*, 135. https://doi.org/10.3389/fcvm.2018.00135.
56. Garde, A.; Laursen, B.; Jørgensen, A.; Jensen, B. Effects of mental and physical demands on heart rate variability during computer work. *Eur. J. Appl. Physiol.* **2002**, *87*, 456–461. https://doi.org/10.1007/s00421-002-0656-7.
57. Flickinger, K.; DeMaio, R.; Prescott, P.; Weissman, A.; Salcido, D.D.; Coppler, P.J.; Ratay, C.R.; Nagle, E.; Rittenberger, J.; Goss, F.; et al. Abstract 131: Perceived Exertion and Physical Demand of Performing 10-minutes of Compression-only CPR. *Circulation* **2022**, *146* (Suppl. 1), A131. https://doi.org/10.1161/circ.146.suppl_1.131.
58. Dong, J.-G. The role of heart rate variability in sports physiology. *Exp. Ther. Med.* **2016**, *11*, 1531–1536. https://doi.org/10.3892/etm.2016.3104.
59. Franklin, B.A.; Thompson, P.D.; Al-Zaiti, S.S.; Albert, C.M.; Hivert, M.-F.; Levine, B.D.; Lobelo, F.; Madan, K.; Sharrief, A.Z.; Eijsvogels, T.M.; et al. Exercise-Related Acute Cardiovascular Events and Potential Deleterious Adaptations Following Long-Term Exercise Training: Placing the Risks Into Perspective–An Update: A Scientific Statement From the American Heart Association. *Circulation* **2020**, *141*, E705–E736. https://doi.org/10.1161/CIR.0000000000000749.
60. Raghuveer, G.; Hartz, J.; Lubans, D.R.; Takken, T.; Wiltz, J.L.; Mietus-Snyder, M.; Perak, A.M.; Baker-Smith, C.; Pietris, N.; Edwards, N.M. Cardiorespiratory Fitness in Youth: An Important Marker of Health: A Scientific Statement From the American Heart Association. *Circulation* **2020**, *142*, E101–E118. https://doi.org/10.1161/CIR.0000000000000866.

61. National Joint Council for Local Authority Fire and Rescue Services. *Firefighter Fitness: Best Practice Guide*; Kingston upon Thames, United Kingdom National Joint Council for Local Authority Fire and Rescue Services: London, UK, 2016.
62. WHO. *Physical Activity*; WHO: Geneva, Switzerland, 2024.
63. Hargreaves, M.; Spriet, L.L. Skeletal muscle energy metabolism during exercise. *Nat. Metab.* **2020**, *2*, 817–828. https://doi.org/10.1038/s42255-020-0251-4.
64. Ferguson, R.A.; Ball, D.; Krustrup, P.; Aagaard, P.; Kjær, M.; Sargeant, A.J.; Hellsten, Y.; Bangsbo, J. Muscle oxygen uptake and energy turnover during dynamic exercise at different contraction frequencies in humans. *J. Physiol.* **2001**, *536*, 261–271. https://doi.org/10.1111/j.1469-7793.2001.00261.x.
65. Alvar, B.A.; Sell, K.; Deuster, P.A. *NSCA's Essentials of Tactical Strength and Conditioning*; Human Kinetics: Champaign, IL, USA, 2022.
66. McAnaney, C.; Ganti, A. In Response to Metabolic Demand of Hiking in Wildland Firefighting by Sol et al. *Wilderness Environ. Med.* **2019**, *30*, 217–217. https://doi.org/10.1016/j.wem.2018.12.003.
67. Kiesewetter, A.; Schmiemann, P. Understanding Homeostatic Regulation: The Role of Relationships and Conditions in Feedback Loop Reasoning. *CBE Life Sci. Educ.* **2022**, *21*, ar56. https://doi.org/10.1187/cbe.21-04-0092.
68. Turrigiano, G. Homeostatic signaling: The positive side of negative feedback. *Curr. Opin. Neurobiol.* **2007**, *17*, 318–324. https://doi.org/10.1016/j.conb.2007.04.004.
69. Ely, B.R.; Cheuvront, S.N.; Kenefick, R.W.; Sawka, M.N. Aerobic Performance Is Degraded, Despite Modest Hyperthermia, in Hot Environments. *Med. Sci. Sports Exerc.* **2010**, *42*, 135–141. https://doi.org/10.1249/MSS.0b013e3181adb9fb.
70. Kaiser, B.W.; Kruse, K.K.; Gibson, B.M.; Santisteban, K.J.; Larson, E.A.; Wilkins, B.W.; Jones, A.M.; Halliwill, J.R.; Minson, C.T. The impact of elevated body core temperature on critical power as determined by a 3-min all-out test. *J. Appl. Physiol.* **2021**, *131*, 1543–1551. https://doi.org/10.1152/japplphysiol.00253.2021.
71. Sawka, M.N.; Wenger, C.B.; Young, A.J.; Pandolf, K.B. *Physiological Responses to Exercise in the Heat*; Institute of Medicine (US) Committee on Military Nutrition Research: Washington, DC, USA, 1993.
72. Rowell, L.B.; Murray, J.A.; Brengelmann, G.L.; Kraning, K.K. Human Cardiovascular Adjustments to Rapid Changes in Skin Temperature during Exercise. *Circ. Res.* **1969**, *24*, 711–724. https://doi.org/10.1161/01.RES.24.5.711.
73. Galinier, M.; Pathak, A.; Fourcade, J.; Androdias, C.; Curnier, D.; Varnous, S.; Boveda, S.; Massabuau, P.; Fauvel, M.; Senard, J.; et al. Depressed low frequency power of heart rate variability as an independent predictor of sudden death in chronic heart failure. *Eur. Hear. J.* **2000**, *21*, 475–482. https://doi.org/10.1053/euhj.1999.1875.
74. Dekker, J.M.; Crow, R.S.; Folsom, A.R.; Hannan, P.J.; Liao, D.; Swenne, C.A.; Schouten, E.G. Low Heart Rate Variability in a 2-Minute Rhythm Strip Predicts Risk of Coronary Heart Disease and Mortality From Several Causes. *Circulation* **2000**, *102*, 1239–1244. https://doi.org/10.1161/01.CIR.102.11.1239.
75. Michael, S.; Graham, K.S.; Davis, G.M. Cardiac Autonomic Responses during Exercise and Post-exercise Recovery Using Heart Rate Variability and Systolic Time Intervals—A Review. *Front. Physiol.* **2017**, *8*, 301. https://doi.org/10.3389/fphys.2017.00301.
76. Yamamoto, Y.; Hughson, R.L.; Nakamura, Y. Autonomic Nervous System Responses to Exercise in Relation to Ventilatory Threshold. *Chest* **1992**, *101*, 206S–210S. https://doi.org/10.1378/chest.101.5_Supplement.206S.
77. RPrell, R.; Opatz, O.; Merati, G.; Gesche, B.; Gunga, H.-C.; Maggioni, M.A. Heart Rate Variability, Risk-Taking Behavior and Resilience in Firefighters During a Simulated Extinguish-Fire Task. *Front. Physiol.* **2020**, *11*, 482. https://doi.org/10.3389/fphys.2020.00482.
78. A Tiller, W.; McCraty, R.; Atkinson, M. Cardiac coherence: A new, noninvasive measure of autonomic nervous system order. *Altern. Ther. Health Med*. **1996**, *2*, 52–65.
79. Dias, M.; Silva, L.; Folgado, D.; Nunes, M.L.; Cepeda, C.; Cheetham, M.; Gamboa, H. Cardiovascular load assessment in the workplace: A systematic review. *Int. J. Ind. Ergon.* **2023**, *96*, 103476. https://doi.org/10.1016/j.ergon.2023.103476.
80. Panumasvivat, J.; Sirikul, W.; Surawattanasakul, V.; Wangsan, K.; Assavanopakun, P. The Urgent Need for Cardiopulmonary Fitness Evaluation among Wildland Firefighters in Thailand. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3527. https://doi.org/10.3390/ijerph20043527.
81. Kales, S.N.; Smith, D.L. Firefighting and the Heart. *Circulation* **2017**, *135*, 1296–1299. https://doi.org/10.1161/CIRCULATIONAHA.117.027018.
82. Coker, R.H.; Murphy, C.J.; Johannsen, M.; Galvin, G.; Ruby, B.C. Wildland Firefighting. *J. Occup. Environ. Med.* **2019**, *61*, e91–e94. https://doi.org/10.1097/JOM.0000000000001535
83. Jacinto, C.; Santos, F.; Fialho, T.; Guedes Soares, C.; Silva, S. Reliability of Coding of a set of ESAW variables within the Portuguese official system for accidents at work. 2010 Available online: https://www.researchgate.net/publication/305222496_Reliability_of_Coding_of_a_set_of_ESAW_variables_within_the_Portuguese_official_system_for_accidents_at_work (accessed on 10 November 2024).