



Training Implications for Firefighters through objective Measurement of the Physiological Demands of Firefighter Job Tasks

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Abstract

The purpose of this study was to describe the direct measurement of physiological demands of firefighter job tasks within a modified Candidate Physical Abilities Test (CPAT) broken out by specific task. Twenty male firefighters from a large municipal fire department in the southwest United States participated in the study. To directly measure cardiorespiratory demands of firefighting job tasks, the study incorporated the measurement of individual firefighter physiological demands on four different physiological variables (VO₂, Heart Rate-HR, Respiratory Exchange Ratio-RER, Energy Expenditure per Minute-EEM). These four variables were measured during participant completion of a modified physical protocol for firefighters (CPAT); 8 tasks repeated for 15 minutes in duration at baseline, 6 weeks post-baseline, and 14 weeks post-baseline, using the Cosmed K4b2 portable metabolic system. Tukey's HSD comparison test was performed to compare the differences between responses of each task ($p \leq 0.05$). Results demonstrated significant differences between some tasks. VO₂ requirement to complete the tasks increased from baseline to 14 weeks post-baseline while RER decreased. Knowledge of physiological work required of specific and accumulated firefighter job tasks could inform type of training, timing and fitness ability needed to safely perform job tasks and directly target fitness maintenance for the job.

Keywords: Firefighter job tasks; Tactical strength; Conditioning; Functional training

Abbreviations: CPAT: Candidate Physical Ability Test; RER: Respiratory Exchange Ratio; HR: Heart Rate; EEM: Energy Expenditure per Minute Tukey's; HSD: Honestly Significant Difference; BMI: Body Mass Index; CVD: Cardiovascular Disease

Introduction

It is well known that firefighting is physically demanding occupation often requiring high intensity work in a continuous or intermittent manner. Additionally, other aspects of the job such as long shift work, reported sleep deprivation and the necessity to rapidly respond to emergency calls place firefighters at even greater health risk [1]. It is important to acknowledge and evaluate the various demands of career firefighters to inform exercise training design to directly target the observed health risks of persons in this profession. Previous studies examining large cohorts of career firefighters report specific health risks that are associated with the job, such as the documented decrease in cardiorespiratory fitness, increase in body mass index (BMI), and higher incidence of occupational injury among firefighters as they age [2-6]. Korre et al. [7] further supported the link between cardiovascular disease (CVD) risk and BMI, specifically the correlation between increased BMI and left ventricular mass increase in this population of which

both are indications of CVD risk. These studies support the need for exercise training that addresses cardiovascular endurance for heart health and body weight reduction in this population.

Regarding type of exercise training and propensity for injury, Lentz et al. [8], conducted a systematic review examining the relationship between physical fitness and occupational injury in emergency responders and found a consistent trend between lower levels of aerobic fitness and increase in injury risk. They concluded that future research should focus on interventions that address both aerobic endurance and components of fitness such as muscular strength, balance, and agility to determine the optimal level of fitness conducive to effective job performance and injury prevention. While aerobic endurance and muscular strength are important health-related components of fitness needed for successful job performance in first responders, skill related

components of fitness (balance, agility, speed, power, coordination and reaction time) are also important requirements for safe job performance in this population.

Recent work conducted by Gerstner et al. [9,10] discussed the age-related changes in muscle quality required for peak torque in career firefighters. The ability of firefighters to produce maximal strength at both slow and fast velocities is necessary for successful, injury free completion of job required tasks. These authors reported a decrease in peak torque and an increase in intramuscular fat infiltration both of which are associated with metabolic and cardiovascular risk factors. They conclude by suggesting the implementation of tactical strength and conditioning exercise training to target performance requiring strength at fast velocities. Persons interested in becoming a career firefighter are oftentimes required to demonstrate their physical capability to perform firefighter job tasks prior to getting hired for the job. Men and women interested in this job are usually young adults in peak physical condition prepared to be tested on their fitness and specific aptitude for the required job tasks. Many fire departments have adopted the Candidate Physical Ability Test (CPAT) to determine candidate physical readiness for the profession.

The CPAT was developed in 1997 by the Fire Service Joint Labor-Management Task Force Technical Committee to measure critical skills of firefighting job tasks. This committee conducted a job analysis and administered job task surveys to more than 1000 fire fighters across ten departments, to ascertain the necessary skills needed to perform firefighter job tasks. The aim was to develop an authentic and valid evaluation tool to ensure that all fire fighter candidates had the physical ability to complete critical tasks effectively and safely. Currently, the CPAT is approved by the International Association of Fire Chiefs and the International Association of Fire Fighters as an appropriate pre-employment physical test to determine physical capabilities of firefighter candidates [11]. The CPAT is comprised of a series of eight firefighting tasks completed for time with an established a pass/fail time of 10 minutes and 20 seconds. However, when on a fire or emergency scene, firefighters are often required to work for longer periods of time and pace themselves rather than work at their maximum level for 10 minutes. We are just beginning to investigate the cumulative physiological effect or metabolic demand of firefighter job tasks when performed for a prolonged period rather than for a shorter time at maximal intensity [1].

It has been reported that firefighters often face health challenges that can be related to the job such as increased incidence of cardiovascular events over time while the job task demand remains high [2-6]. Moreover, we know that as a part of the natural aging process, there is an age-related decline in cardiorespiratory fitness [12]. There is also literature supporting a decrease in regular physical activity among firefighters as they age [2,13,14]. The purpose of this study was to further describe the direct measurement of physiological demands of firefighter job tasks within a modified CPAT course broken out by specific task. Knowledge of physiological work required of specific and accumulated firefighter job tasks could inform type of training,

timing and fitness ability needed to safely perform job tasks and directly target fitness maintenance for the job.

Materials and Methods

Experimental approach to the problem

The National Fire Protection Association recommends a minimum cardiorespiratory fitness capacity of 12 metabolic equivalents (METS), which is approximately $42 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ VO₂ for firefighters to adequately and safely perform firefighter job tasks [15]. It is important to note that the $42 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ VO₂ is a peak value not a value that firefighters normally maintain for a prolonged period of time.

Previously, our team examined physiological requirements of completing a modified CPAT course in a continuous manner [1]. For that study, the modified CPAT was not used as a full effort test for completion time. The test was used to mimic a typical series of job specific tasks. The firefighters in that particular municipal fire department were required to complete a yearly VO₂ max test as a part of their job. We took their reported value above $42 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ VO₂ as "fit for the job" and were really asking the question, "What is the VO₂ required to do the 8 job related tasks in a steady state manner over 15 minutes time and could the VO₂ required of the typical work move in a favorable direction (e.g. would heart rate be lower on the total or specific task over time)?" The current methodology expands scientific knowledge by further describing the physiological demand (HR, VO₂ and RER) by breaking out each individual CPAT task as compared to the number/length of other CPAT tasks. This is one of very few studies to use an actual direct measure of the firefighter job tasks rather than MET calculations, field or treadmill testing to determine the work of the job [2,6,16].

Participants

Twenty firefighters from a large municipal fire department in the southwest United States participated in the study. Participants ranged in age from 33 to 57 years old ($M=44.10$, $SD=6.43$) and averaged 16 years on the job ($M=16.6$, $SD=6.62$). Both male and female firefighters with 8 or more years on the job were recruited ($N=22$) although only males chose to participate in the study. Two participants dropped out for personal reasons after the first round of testing. No additional exclusion or inclusion criteria were included although after inquiry of the department under study, it was noted that no participants had been on light duty in the past year prior to participating in the study. A signed letter of support from the fire chief of the fire department under study was obtained. The study was approved by the Institutional Review Board at the sponsoring University. All participants signed the approved informed consent prior to taking part in the study.

Procedures

To directly measure cardiorespiratory demands of firefighting job tasks, the study incorporated the direct measurement of individual firefighter physiological demand on four different physiological variables (VO₂, Heart Rate-HR, Respiratory Exchange Ratio-RER, Energy Expenditure per Minute-EEM). These four variables were measured during participant completion of a

modified version of a standardized physical protocol for firefighters (CPAT- Table 1); 8 tasks repeated for 15 minutes in duration at baseline, 6 weeks post-baseline, and 14 weeks post-baseline, using the Cosmed K4b2 portable metabolic system. Participants were instructed to work at an even pace over the 15-minute time frame in order to elicit a steady state aerobic response to typical firefighter job tasks. After completion of task 8, they re-started task 1 and continued completing tasks until they finished 15 minutes of total work. However, few firefighters completed more than 8 tasks during the 15-minute time frame. Therefore, to adequately perform statistical analyses, VO₂, HR, RER, and EEM values were averaged across the first set of 8 tasks for each participant at each time point. The Cosmed K4b2 portable metabolic system was calibrated per

system protocols (turbine, room air and reference gas) prior to use on the first participant each day of testing. The specific course used during the study was modified to accommodate what was available at the site training center yet closely mimic the official CPAT course (see Table 1 for modifications to CPAT). This course was held outdoors, and ambient temperature was monitored during each testing session ranging between 63- and 82-degrees Fahrenheit. Participants wore their full turnout gear which included turnout pants, coat, boots, and helmet although did not wear their self-contained breathing apparatus. Weight (lbs.) was measured with and without prior to performing the physical tasks at each testing time point (Table 1).

Table 1: CPAT Course Task Descriptions and Modifications. [1].

CPAT Task	Official Course	Modified Course
Task 1: Stair Climb	20 second warm-up at 50 steps per minute precedes 3 minutes of stair climbing at 60 steps per minute. Candidates carry an additional 25 lbs. in event.	Participants walked up and down a stairwell for 3 minutes at a pace of 60 steps per minute. Participants carried 25 lb. hose bundle over right shoulder.
Task 2: Hose Drag	With 8 feet (8') of hose slung over shoulder, run 75 feet (75') around drum, make a 90° turn, and run an additional 25 feet (25'). Candidates then crouch down on one knee and pull 50 feet (50') of hose.	Replicated event exactly.
Task 3: Equipment Carry	Carry circular saw and chain saw 75' to cone and 75' back to starting position.	Replicated event using two 25 lb. weight plates to simulate both saws.
Task 4: Ladder Raise and Extension	Raise a 24foot (24') extension ladder from the ground to wall, then extend a 24' pre-positioned extension ladder secured to wall.	Replicated event exactly.
Task 5: Forcible Entry	Strike a fixed measuring device using a 10 lb. sledgehammer until the buzzer sounds.	Participants struck a car quarter panel 10 times from waist height using a 10 lb. sledgehammer.
Task 6: Search	Crawl through darkened 3 foot (3') high, 4 foot (4') wide, and 64 foot (64') long confined space. Candidates make two 90° turns and circumvent interior obstacles.	Replicated event through darkened burn room while performing a left wall search.
Task 7: Rescue	Drag 165 lb. mannequin 35 feet (35'), around drum, and 35' back to starting position.	Replicated event with 170 lb. hose dummy dragged over asphalt.
Task 8: Ceiling Breach and Pull	Candidates use a 6-foot (6') pike pole to press a 60 lb. hinged door up 3 times. Candidates then use pike pole to pull an 80 lb. hinged door down 5 times. This sequence is repeated 4 times.	Participants raised a 45 lb. Olympic barbell, simulating the pike pole, three times overhead. Participants then grasped the rope of the fixed 24' extension ladder as high up as they could and pulled down 5 times. This sequence was repeated 4 times.

*Candidates wear 50 lb. weighted vests and walk 85 feet (85') between events in actual CPAT course. Participants in study wore Cosmed K4b2 unit (2.7 lbs.), FF gear without air bottle (weight in gear was measured), and also walked 85' between events.

Statistical Analysis

Table 2: Demographic Characteristics and Descriptive at Baseline.

Characteristic	Total Sample (N=20) M (SD)
Demographic Characteristics	
Age (yrs, at Baseline)	44.10 (6.43)
Weight (lb)	205.03 (24.36)
Height (in)	71.10 (2.57)
Weight in gear (lb)	228.91 (25.58)
Years on the Job	16.6 (6.62)
BMI (kg/m ²)	28.63 (3.59)
Dependent Variables at Baseline	
VO ₂ (mL/kg/min)	25.20 (3.34)
Heart Rate (beats/min)	157.17 (10.78)

Respiratory Exchange Ratio	1.18 (0.07)
Energy Expenditure per Minute (EEM) (kcal/min)	13.75 (1.55)
Dependent Variables at Midpoint	
VO ₂ (mL/kg/min)	25.87 (3.68)
Heart Rate (beats/min)	159.54 (10.78)
Respiratory Exchange Ratio	1.17 (0.07)
Energy Expenditure per Minute (EEM) (kcal/min)	13.85 (1.45)
Dependent Variables Final	
VO ₂ (mL/kg/min)	27.48 (3.64)
Heart Rate (beats/min)	156.46 (9.99)
Respiratory Exchange Ratio	1.13 (0.04)
Energy Expenditure per Minute (EEM) (kcal/min)	14.49 (1.61)

Means and standard deviations for all continuous descriptive data were calculated. Additionally, frequencies and percentages were determined for categorical descriptive data (Table 2). To determine differences in responses between tasks, a 2-level model with a random intercept, unstructured error structure, maximum likelihood estimation, and between-within method for denominator degrees of freedom was estimated using SAS Proc Mixed. Least squares mean with Tukey's HSD comparison test evaluated differences between specific tasks for all outcome variables (i.e.,

(VO₂, RER, HR, and EER), while adjusting for multiple comparisons. Table 3 provides these differences of least squares means adjusted for multiple comparisons, and identifies significant differences at the p=.05, .01, and .001 levels. Group mean values were determined for each of the eight tasks at each time point. Figure 1 provides graphical representations of the eight tasks performed versus each group mean outcome variable (i.e., VO₂, RER, HR, and EER) for each of the three time points (i.e., baseline, midpoint, and final).

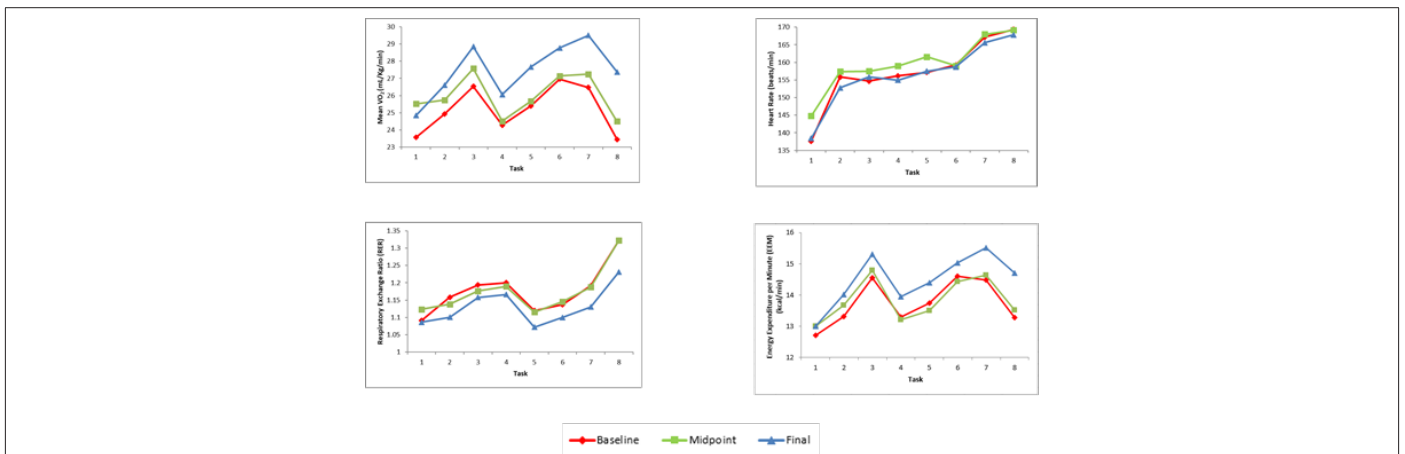


Figure 1: Mean values for outcome variables (VO₂, RER, HR, and EEM) at each time point (baseline, midpoint, final) by task (1-8).

Results

Table 3: Differences of Least Squares Means with Tukey's HSD Adjustment.

CPAT Tasks Compared	VO ₂	RER	HR	EEM
1,2	-1.453***	-0.033	-15.170***	-0.760**
1,3	-3.328***	-0.077***	-15.763***	-1.970***
1,4	-0.694	-0.086***	-16.494***	-0.580*
1,5	-1.940***	-0.003	-18.495***	-0.968***
1,6	-3.315***	-0.028	-18.817***	-1.780***
1,7	-3.410***	-0.071***	-26.745***	-1.967***
1,8	-0.773	-0.193***	-28.606***	-0.923***
2,3	-1.875***	-0.043**	-0.593	-1.210***
2,4	0.76	-0.053***	-1.325	0.181

2,5	-0.487	0.03	-3.326	-0.208
2,6	-1.862***	0.005	-3.647	-1.020***
2,7	-1.956***	-0.037	-11.575***	-1.207***
2,8	0.681	-0.160***	-13.436***	-0.163
3,4	2.634***	-0.009	-0.732	1.390***
3,5	1.388***	0.074***	-2.733	1.002***
3,6	0.013	0.049**	-3.054	0.189
3,7	-0.081	0.006	-10.982***	0.002
3,8	2.556***	-0.117***	-12.843***	1.047***
4,5	-1.246**	0.083***	-2.001	-0.389
4,6	-2.621***	0.058***	-2.323	-1.201***
4,7	-2.715***	0.015	-10.250***	-1.388***
4,8	-0.079	-0.107***	-12.111***	-0.343
5,6	-1.375***	-0.025	-0.322	-0.812***
5,7	-1.469***	-0.067***	-8.249***	-1.000***
5,8	1.167**	-0.190***	-10.111***	0.046
6,7	-0.094	-0.043*	-7.928***	-0.187
6,8	2.543***	-0.165***	-9.789***	0.858***
7,8	2.637***	-0.123***	-1.861	1.045***

Demographic and variable descriptive data are included in Table 2. All 20 participants with complete data were male, with a mean age of 44.1 (± 6.43) years at baseline. Significant differences among VO₂, RER, HR, and EEM for comparison among tasks are indicated in Table 2. Among all the comparisons, tasks 2 and 5 are most similar to each other in terms of the outcome variables. Tasks 1 and 3, tasks 1 and 7, tasks 3 and 8, tasks 5 and 7, and tasks 6 and 8 were significantly different from each other for all the outcome variables. Figure 1 shows the mean VO₂, RER, HR, and EEM for each task during the baseline (red), midpoint (green), and final (blue) testing times (Figure 1 & Table 3)

Discussion

Physiological Measures

The traditional method of evaluating firefighter's fitness for service is commonly a standardized cardiorespiratory fitness evaluation via a graded exercise test (e.g., VO₂ max or Sub-max test such as the Bruce Treadmill Protocol). While this remains a valuable instrument for evaluating both cardiorespiratory fitness and cardiac risk, it does not adequately represent the job-specific physiological demands of firefighting. The CPAT and the modified version we created, on the other hand, appears to represent the net physiological demand as a combination of aerobic and anaerobic challenges, similar to those experienced within a fire-fighting scenario.

This investigation demonstrates the varied physiological demands of the different tasks that compose the CPAT. Because this is a continuous test, the heart rate values steadily increased throughout the test, despite some peaks and valleys in VO₂ values, which were much more acutely responsive to task changes. This alone is an interesting finding, as HR and VO₂ are often considered to be linearly related and is the concept used to predict VO₂ max

from submaximal tests [16]. Because VO₂ assessment via expired gas analysis is most commonly used during graded exercise testing, and not variable intensity exercise tasks, this linear relationship may not hold true in all circumstances. The traditional CPAT is a continuous and modulating intensity test, and is an entirely different task, in that it allows some degree of recovery during easier tasks, such as with tasks 4 and 8, during which VO₂ dropped while HR did not. Additionally, while this group of firefighters did not demonstrate particularly high VO₂ max values, their training specificity related to their job tasks, near or at lactate threshold, may have resulted in high sustained RER values.

Comparing between the VO₂ and RER measurements, there are some unusual features present. First, the average VO₂ measurement has a distinct peak during task 3, whereas the peak in RER is spread out across tasks 3 and 4. Second, moving from task 4 to 5 results in an increase in average VO₂ and a contrasting decrease in RER. Finally, moving from task 7 to 8 results in a decrease in VO₂ with a contrasting and drastic increase in RER. This final difference may be skewing the RER measurement when averaged over all tasks. Further investigation of this phenomenon, which was consistent across all 3 time periods, needs to be performed for more information. It would be possible to make similar comparisons with HR as well; however, HR increases consistently with each task. This means that there is likely an exhaustion factor that is confounded with the progression through each task that makes any type of comparison difficult. A new set of data would need to be collected in a way to eliminate this confounding between exhaustion and task in order to make comparisons with HR.

The most notable spikes in VO₂ occurred during tasks 3 and 7, in which a heavy weight was carried or dragged. Unlike a standard graded exercise test, which is largely a measurement relative VO₂

max, the introduction of additional weight is a relevant job-specific task that relies upon not only relative VO₂ max, but also anaerobic and muscular strength components. This may help explain the apparent lag in the RER responses to the firefighter tasks. RER spikes occur in the tasks immediately following the most strenuous tasks (tasks 4 and 8), despite those tasks having much lower VO₂ values. This is likely an effect of delayed CO₂ production associated with bicarbonate buffering of hydrogen ions in response to an anaerobic workload. While RER values were higher than expected considering this was not a maximal test, the incorporation of anaerobic and lifting tasks may be responsible for this observation. Again, these observations demonstrate how different the CPAT is to a graded exercise test in terms of physiological strain. As was described in a previous paper [1], the participants were tested at three time points. At the final time point, VO₂ values increased at each task, while RER trended lower, but the relationship between each task remained stable. The increase in VO₂ over time for each task reflects an increased work output, as the total number of tasks completed within the 15-minute job task performance increased from an average of 10.72 to 12, meaning the tasks were completed more quickly.

Practical Applications

Based on these data, it is recommended that firefighter exercise program design include intervals of work that incorporate continuous cardiorespiratory work with intermittent bouts of high intensity work. High intensity interval training (HIIT) would suit firefighters in this regard, as it employs intermittent bouts of vigorous activity followed by lower intensity periods of recovery [17]. Several studies have demonstrated the effectiveness of HIIT in eliciting cardiorespiratory adaptations when compared to more traditional steady-state endurance training (moderate-intensity continuous training; MICT), citing significantly reduced time commitment and training volume to achieve similar improvements to cardiorespiratory fitness (CRF), as well as increased participant enjoyment [17-19]. Specifically, improvements to CRF resulting from HIIT are attributable to body-wide adaptations that include increased lactate threshold and increased mitochondrial biogenesis and respiration in active skeletal muscle, as well as increased VO₂max, left ventricular mass, stroke volume, and contractility [19-20]. Further adaptations include increased resting glycogen content, adaptations to peripheral vascular structure and function, and improved exercise performance [17].

Traditional HIIT protocols usually employ large, continuous movements associated with cardiorespiratory exercise, such as cycling, running, stair climbing, or multiple muscle group, body weight resisted exercise. HIIT is especially unique, as it can elicit improvements to muscular strength alongside simultaneous improvements to CRF and presents a potent training stimulus for firefighters that can directly parallel the nature of job-specific tasks. This is clearly exemplified in the CPAT course itself, which in its very nature constitutes HIIT (Table 1). The course consists of eight vigorous job tasks requiring the use of multiple muscle groups to move heavy loads (e.g. tasks 2, 4, and 8), often over long distances (e.g. tasks 1, 3, and 7), separated by intervals of rest (i.e. walking a distance of 85 feet between each station).

Including a similar style of HIIT into firefighter physical conditioning programs could induce adaptations to CRF that could potentially improve job task performance when on a fire or emergency scene. Transitioning firefighter cardiorespiratory exercise from more traditionally practiced MICT to HIIT would result in significant reductions to time commitment and training volume needed to improve markers of CRF. Additionally, incorporating a HIIT style of functional movement training could potentially serve to reduce exercise-related injuries within this population, of which constitute up to a third of injury reports in some municipalities [21]. Functional movement training should address mobilization of the stabilizing muscles along with training supporting muscle groups that facilitate dynamic firefighter job tasks. Lastly, when thinking about the timing of when job demands of firefighters are performed (e.g. under high stress situations and/or middle of the night) and the potential for injury, it is prudent to consider training programs that target pre-habilitation such as functional movement training [22].

Conclusions

With respect to fitness, designing effective exercise prescriptions to impact firefighter health and longevity is the aim of every municipal, volunteer or wildland fire department. Knowing the actual physical requirement helps us to create exercise programs specific to the demands of the job. Specifically, these data indicate an increase in VO₂ over time when performing firefighter job tasks with a lower RER as a result of repeated exposure to performing interval-type job tasks in a continuous or aerobic manner (Figure 1). Therefore, employing dynamic, job-specific exercises through HIIT protocols could stimulate functional training adaptations to muscular strength and aerobic capacity, mimicking the vigorous demands of firefighter job tasks to promote pre-habilitation against on- and off-duty injuries.

Author Contributions

Authorship is limited to those who have contributed substantially to the work reported. Conceptualization, Dierdra Bycura; Data curation, Dierdra Bycura and Anthony Santos; Formal analysis, Dierdra Bycura and Christopher Ropak, Investigation, Dierdra Bycura and Anthony Santos; Methodology, Dierdra Bycura; Writing – original draft, Dierdra Bycura, Christopher Ropak and Anthony Santos.

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Conflicts of Interest

The authors declare no conflict of interest.

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