PHYSIOLOGICAL DEMANDS AND VENTILATORY REQUIREMENTS DURING SIMULATED LARGE STRUCTURE FIREFIGHTING TASKS

By

F. Michael Williams-Bell

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Science

in

Kinesiology

Waterloo, Ontario, Canada, 2007

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

Michael Williams-Bell

I understand that my thesis may be made electronically available to the public.

Michael Williams-Bell

ABSTRACT

The ability to measure the physiological demands and air requirements during simulated firefighting tasks while wearing full personal protective ensemble (PPE) and positive pressure self-contained breathing apparatus (SCBA) has been a difficult process based on undeveloped technology. The capability of integrating a portable Cosmed $K4b^2$ breath by breath gas collection system with a standard SCBA has permitted a novel approach to investigate metabolic demands and ventilatory requirements while breathing through the same system that would be used in an actual fire scene. The purpose of this study was to determine the physiological demands and air requirements during three large structure firefighting scenarios: (1) maximal high rise stair climb, (2) 5^{th} floor high rise scenario, and (3) subway system scenario. The hypotheses were that (a) the 5^{th} floor high rise scenario would be the most physically demanding and that (b) the years of service as a firefighter would result in decreased total air consumption during the three scenarios. Thirty-three male and three female healthy firefighters performed each of the three tasks at an equivalent pace similar to what would be expected at a fire scene. Scenario (1) consisted of stair climbing until consuming 55% of a typical SCBA air cylinder and then descending to a safe exit. Scenario (2) comprised a 5 floor stair climb, hose drag and room search, forcible entry, victim rescue drag, and 5 floor descent. Scenario (3) involved a stair descent, tunnel walk, portable ladder walk, ladder setup, victim rescue drag, tunnel walk, and stair ascent. Average maximum floors climbed for scenario (1) and mean completion times for scenarios (2) and (3) were 20 ± 2.5 floors, 5 min 3 s ± 57 s, and 12 min 5 s ± 1 min 10 s, respectively. Mean VO_2 during each of the scenarios were 3168 ± 878 ml/min, 2947 ± 461 ml/min, 2217 ± 371 ml/min, corresponding to a relative VO_2 of 35.5 ± 9.1 ml/kg/min, 33.1 ± 4.6 ml/kg/min, and 25.2 ± 4.6 ml/kg/min. In relation to the peak treadmill

oxygen uptake, the three scenarios revealed that firefighters were working at 70 ± 10%, 65 ± 10%, and 49 ± 8% of VO_{2peak}, respectively. Average heart rate values for the three scenarios were 170 ± 13 bpm, 160 ± 14 bpm, and 139 ± 17 bpm, corresponding to 88 ± 4%, 88 ± 6%, and 76 ± 7% of HR_{peak}, respectively. These results indicate that the most physiologically demanding scenario was the maximal stair climb, followed by the 5th floor high rise and subway system scenarios. Respiratory exchange ratio was consistently greater than 1.0 during the maximal stair climb and 5th floor high rise scenarios indicating that a considerable amount of energy was derived from anaerobic metabolism. With regards to the air requirements for each of the scenarios, total air consumption revealed averaged values of 74.9 ± 6%, 48.0 ± 7.0%, and 59.9 ±5.6%, of the air in a typical 30-min cylinder, respectively. These data also revealed that increasing age of the firefighter as well as increasing years of experience as a firefighter result in significant correlations with greater air consumption to complete the given task ($p < 0.05$). Contrary to the hypotheses, the maximal stair climb scenario appeared to be the most physically demanding while increased years of service as a firefighter resulted in greater air consumption. Furthermore, it appears that firefighters who are able to produce more power per kg of body mass have greater performance times and more efficient air consumption. These data are instrumental in quantifying the physiological demands and air requirements during simulated firefighting tasks while breathing on a positive pressure SCBA.

ACKNOWLEDGEMENTS

To Rich, thank you for the opportunity to take on such an involved study and having the trust in me to oversee it right to the end. I appreciate your patience with me as at times it seemed that two years was not nearly enough time to complete everything that we wanted. I have learned so much from this research and your guidance throughout the past two years that have allowed me mature as a student and a person.

To all the students and research assistants that participated in this study, I thank you for your hard work and dedication during the long days in Toronto and your abilities to efficiently collect data and allow for the whole process to run as smooth as possible. I could have never completed any aspect of this research without all your help.

Eric Lamontagne and Rodrigo Villar, you two were instrumental in keeping me directed on the task at hand and provided much needed assistance and advice along the way. The success of this study would not have been possible without your hard work and dedication, as well as putting up with me on a daily basis.

Drew Harvey, thank you for introducing me to the Cosmed and more importantly teaching me all the quirks and idiosyncrasies that this wonderful machine had to offer. You gave me a great understanding of fire research which allowed me to take on the challenge of this study. Dave Northey, your patience during the long hours in front of the mechanical calibrator and your willingness to give me advice and explain the finer aspects of reliable research and metabolic calibration were extremely valuable and I cannot thank you enough for everything that you have done. It was a pleasure working with you over the past two years.

Andrew Robertson, Justin Chung, Chris Vigna, and Kevin Foley, I definitely would not have been able to get through the past two years without going insane if it was not for our weekly outings to a variety of fine establishments in Waterloo or numerous road trips to the Rogers Centre in the summer. You all have been great friends and I look forward to continuing our friendships as we move on in life.

Last but definitely not least, thank you to my family for sticking by me the past seven years. I would not have been able to accomplish the things I have without your love and support, and of course the many homemade meals.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1-RM – One repetition maximum muscular strength test

BF% - Body fat percent

BMI – Body mass index (kg/m^2)

HR – Heart rate (bpm)

HR_{peak} – Peak treadmill heart rate (bpm)

MSA – Mine Safety Appliance

NFIRS – National Fire Incident Reporting System

PPE – Personal protective ensemble

RER – Respiratory exchange ratio

SCBA – Self-contained breathing apparatus

TFS – Toronto Fire Service

USFA – United States Fire Administration

V_E – Minute ventilation (l/min)

VCO_2 – Carbon dioxide output (ml/min)

VO_2 – Oxygen uptake (ml/min), (ml/kg/min)

VO_{2peak} – Peak treadmill oxygen uptake (ml/min), (ml/kg/min)

1.0 INTRODUCTION

1.1 Rationale

The physical nature and cardiovascular strain during firefighting has been well documented leading to many recommendations for minimum requirements of aerobic power (Barnard & Duncan, 1975; Gledhill & Jamnik, 1992; Lemon & Hermiston, 1977b). However, the safety of the firefighter and his/her ultimate lifeline is determined by the volume of air remaining in the air cylinder. In North America, more than 100 firefighters lose their lives each year while on duty, with approximately 84% of structure related fatalities occurring from asphyxia and smoke inhalation (Hodous, Pizatella, Braddee, & Castillo, 2004). Inside a burning structure, the firefighters' only line of defense between themselves and the extreme environmental conditions is wearing the personal protective ensemble (PPE), consisting of bunker pants, jacket, flash hood, gloves, boots, and helmet, as well as a self-contained breathing apparatus (SCBA). The ability to perform efficiently during fire suppression relies on the amount of air contained within the SCBA cylinder. Most fire departments operate on '30 minute' air cylinders with a maximum pressure of 4,500 psi containing approximately 1240 l of air; however, with an absolute quantity of air contained within each cylinder, a firefighter's physiological characteristics will determine the maximum amount of time he/she will be able to work while breathing through a single SCBA tank.

The primary challenge revolves around the fact that the SCBA was developed for single dwelling use. Structural fires occurring in high rises, large department stores, or in a subway system pose a significant challenge to firefighters. The origin of the fire may be a sizeable distance from the entrance to the fire scene and could result in the firefighters consuming a large proportion of their SCBA cylinder before reaching the fire. The small amount of air that remains would not be sufficient to perform critical firefighting tasks while maintaining adequate air supply to allow for safe evacuation from the fire scene. The ability to manage air supply with respect to controlling the amount of time in the hazardous area is known as “air management” (National Fire Protection Association, 2006).

Currently, the modern SCBA is equipped with a digital heads up display (HUD) that allows the firefighter to monitor the amount of time remaining on their SCBA cylinder based on the current rate of air consumption. The main problem with this technology is that fire suppression tasks are not steady-state with work intensities changing very quickly and, thus, drastically altering the rate of air consumption. The second safety device installed in every SCBA is the low-air alarm, which is programmed to sound an audible alarm when there is 25% of air remaining in the cylinder. With the standard ‘30 minute’ air cylinder, the 25% low-air alarm theoretically comprises 7.5 minutes of breathable air supply remaining (Bernzweig, 2004). As every firefighter is different in terms of body size, muscular strength, and aerobic conditioning, this reported 7.5 minutes of remaining air supply when the low-air alarm sounds might be a significant overestimate of the actual time remaining for an individual. The biggest problem exists with the implementation of the National Institute of Occupational Safety and Health (NIOSH) mandate to establish an upper limit of 25% for the audible low-air alarm in 1960 (Bernzweig, 2004). Prior to this time, the strategy in fire suppression was to limit offensive firefighting, where as today vigorous offensive firefighting is common place (Bernzweig, 2004). The proposed formula for optimal and efficient air management is (Bernzweig, 2004):

SCBA Air Volume =

Work Period + Exit Time + Margin of Error for Self-Rescue

Based on this formula and with the current low-air alarm standard of 25%, firefighters would be required to utilize the other 75% of their air supply during the ‘work period’ and ‘exit time’.

Scientific research has not been performed to determine the physiological demands and air requirements during simulated high rise, large department store, and subway system structural fires. As a firefighter dives deeper into a fire suppression task and further away from breathable atmospheric air, the ability to manage the remaining air supply becomes increasingly important. With structural fires accounting for 31% of all fires (Fabio, Ta, Strotmeyer, Li, & Schmidt, 2002) and 16% of all fire related deaths (Hodous et al., 2004), a further understanding of air management in large structures is critical.

Previous research has not been able to capture breath by breath measurements while individuals wear full PPE and SCBA during fire suppression simulation scenarios. In order to monitor the air requirements and physiological demands, the Cosmed K4b^2 breath by breath gas collection system has been integrated into the Mine Safety Appliances (MSA) firefighter mask worn by the Toronto Fire Services.

1.2 Objectives

(1) Determine the maximum vertical distance firefighters can climb in a high rise structure while consuming 55% of air from a typical ‘30 minute’ air cylinder allowing for a safe exit.

(2) Determine the air requirements while performing critical firefighting tasks on a single floor in a high rise structure.

(3) Determine the air requirements of performing critical firefighting tasks in a subway system.

1.3 Hypotheses

(1) The 5th floor high rise scenario would be the most physically demanding of the three scenarios based on the variety of simulated firefighting tasks involved comprising upper and lower body work.

(2) Years of service as a firefighter would produce more efficient techniques to complete simulated firefighting tasks and result in decreased total air consumption during the three scenarios.

2.0 REVIEW OF SCIENTIFIC LITERATURE

2.1 Line of duty injuries and casualties in firefighting

Firefighting requires wearing personal protective equipment and a self contained breathing apparatus, adding additional physiological strain in order to complete already demanding physical tasks. Excluding the tragic events at the World Trade Center on September 11th, 2001, data from the United States Fire Administration (USFA) reveals between the years of 1977 and 2005, an average of 113 firefighters were killed per year while on-duty (United States Fire Administration, 2006). Between 1998 and 2001, of the 410 total firefighter fatalities, 42% of deaths occurred due to myocardial infarctions (Hodous et al., 2004). Structural fires account for approximately 31% of all fire situations (Fabio et al., 2002) and comprise 16% of all deaths (Hodous et al., 2004). According to reports prepared for the USFA, between 1979 and 2002, 75% of fatalities in structural fires occurred at non-residential structures (Brassell & Evands, 2003). However, in the period from 1994 to 2002, this percentage decreased to 49% (Brassell et al., 2003).

Death due to smoke inhalation/asphyxia accounts for approximately 17% of all firefighter fatalities and 84% of structure related fatalities (Hodous et al., 2004). Injuries are also a large area of concern when it comes to firefighter safety and workers compensation costs. In one year alone (1999), over 45,000 firefighters were injured at a fire scene, with 85% of these injuries occurring while fighting structural fires (United States Fire Administration, 2002). Research analyzing various injuries at structural fires between 1993 and 1997 suggests that the most common type of injury involves contact or exposure to the fire, which includes smoke inhalation, accounting for 31% of all injuries (Fabio et al., 2002). The average per-claim worker's compensation cost for a firefighter sustaining an on-duty injury has been reported around $5,000, with smoke inhalation/asphyxiation costing approximately $1,080 (Walton, Conrad, Furner, & Samo, 2003). Firefighters are required to work under extreme physical conditions for sustained periods of time while relying on a finite amount of air within the air cylinder of the SCBA. With fires being unpredictable and unruly, risk of injury or fatality from smoke inhalation/asphyxia will always be of grave concern.

The type of structure appears to be an important indicator of the associated risk to firefighters at a fire scene. A thorough analysis of the National Fire Incident Reporting System Database (NFIRS), setup by the USFA, revealed an increased odds for injury in structures with a higher total number of stories (3 stories or more) (Fabio et al., 2002). Additionally, increased odds for injury were found when the origin of the fire was either below ground level or 10 to 49 feet above ground. The authors concluded that the increased response required at high rise fires compared to residential dwelling fires, primarily due to the transportation of equipment, places additional physical and mental stresses on firefighters that may have an effect on decision making processes.

2.2 Physiological Demands of Firefighting

The ability to quantify the physiological demands of critical firefighting tasks has evolved tremendously over the past four decades. Evaluating these demands requires the capability to measure the primary indicators of physical demand: heart rate (HR) and oxygen consumption (VO_2). Furthermore, other physiological characteristics have been determined to be predominantly required for firefighting tasks including increased levels of muscular strength and endurance, aerobic and anaerobic power, as well as motor abilities, such as: agility, manual dexterity, balance, and flexibility (Gledhill et al., 1992).

Initially, measuring HR responses during live firefighting to predict oxygen consumption or using the Douglas bag method during fire simulation scenarios were the safest and most practical indicators of the physical demands placed upon firefighters. Studies have shown that within the first minute following a fire alarm, firefighters can increase their heart rate between 47 bpm to 61 bpm from a resting level (Barnard et al., 1975; Kuorinka & Korhonen, 1981). Furthermore, Barnard et al. (1975) indicated that in response to two subsequent fires, one firefighter had a heart rate recorded above 160 bpm for 90 mins, including a 15 min period with an extremely high heart rate of 188 bpm. The authors concluded that in almost all fire scenarios, the firefighters heart rates were elevated between 175 bpm and 195 bpm within the first 3 to 5 minutes of the fire.

Lemon and Hermiston (1977b) conducted one of the original studies examining the energy cost of simulated critical firefighting tasks through expired gas analysis. Incumbent firefighters completed the four most strenuous firefighting tasks (aerial ladder climb, victim rescue, hose drag, ladder raise), as determined by firefighters and administration personnel, while wearing a Douglas bag in order to determine the physiological requirements of these tasks. Despite performing these tasks in a controlled environment that eliminates external stresses such as heat and emotional stress, the data still indicated that the firefighters were working between 60% and 80% of their treadmill VO_{2peak}, with an average oxygen uptake of approximately 2.2 L/min for the four tasks. In addition, average heart rate during the four tasks corresponded to the firefighters working at 72% of peak heart rate. The authors concluded that those firefighters with a VO_{2peak} greater than 40 ml/kg/min might be able to supply a greater percentage of their total oxygen cost aerobically. Although this research was fundamental in establishing the ground work in regards to evaluating the physical demands of firefighting, the authors highlight the potential limitations of utilizing the Douglas bag method in collecting expired gases during a non steady-state work environment.

Following the work by Lemon and Hermiston (1977b), Kilbom (1980) attempted to further quantify the physiological demands of firefighting. He reported that firefighting requires an oxygen uptake of 1.9 l/min, with a suggested VO_{2peak} of 2.8 – 3.0 l/min. The author concluded that due to the apparent age-induced decline in maximal aerobic power, pre-employment examinations should call for firefighter recruits to have a minimum VO_{2peak} of 3.6 l/min.

Davis, Dotson, and Santa Maria (1982) reported that firefighters should have a fitness level of 14 METS (49 ml/kg/min) in order to meet their occupation's job requirements, while the minimum level should be 12 METS (42 ml/kg/min). Average heart rate during 5 simulated firefighting tasks (ladder extension, standpipe hose carry, hose pull, rescue, forcible entry) was 169 bpm (92% of HR_{peak}), while the peak heart rate attained was 179 bpm (97% of HR_{peak}). Differences in heart rate data from this study and that obtained by Lemon et al. (1977b) might be due to variations in protocol. It appears that Lemon et al. (1977b) had subjects participate in the four tasks separately, where as Davis et al. (1982) had individuals participate in a sequential five event circuit. In relating the simulated tasks with physical performance measures in the Davis et al. (1982) study, the variables which were determined to be major predictors of physical work capacity based on their canonical loading values were: maximal treadmill heart rate (L = 0.70), maximal treadmill grade (L = 0.47), submaximal oxygen pulse (L = 0.57), push-ups (L = 0.64), sit-ups (L = 0.62), chin-ups (L = 0.61), standing long jump (L = 0.41), age (L = 0.61), and perfect body fat (L = -0.44).

Sothmann et al. (1990) studied 20 incumbent firefighters while monitoring heart rate, oxygen consumption, and inspired ventilation during simulated firefighting tasks and found the subject group had an average VO_{2peak} of 39.9 ml/kg/min. This group of firefighters worked at 76% of VO_{2peak} (30.3 ml/kg/min) during the simulated tasks with an inspired ventilation of 46.7 L/min, and reached a mean heart rate of 173 bpm. The authors concluded that based on the current data, firefighters require a minimum VO_{2peak} of 33.5 ml/kg/min in order to attain performance requirements. In addition to these findings, the authors studied an additional 32 firefighters in order to validate the proposed minimum VO_{2peak} value, and found that those individuals with a VO_{2peak} between 33.5 – 51.0 ml/kg/min had a much greater probability of completing the simulated firefighting protocol under the allotted completion time compared to those firefighters with a VO_{2peak} between 26.0 – 33.49 ml/kg/min.

Due to the obvious safety concerns and technical limitations in studying actual fire emergencies, researchers have used heart rate measurements to predict oxygen consumption during fire suppression. In order to achieve this extrapolation, Saupe, Sothmann, and Jasenof (1991) developed a regression equation to predict oxygen uptake by measuring heart rate in the field and determining VO_{2peak} from a maximal treadmill test to volitional fatigue:

$$\text{Corrected } VO_2 = -11.37 + 1.09\ (\text{Treadmill } VO_2 \text{ ml/kg/min})$$

Sothmann, Saupe, Jasenof, and Blaney (1992) utilized this equation in order to examine the heart rate and predicted oxygen uptake responses of 10 firefighters during actual emergencies. During the live fire emergencies, the firefighters were working at an average heart rate of 157 bpm (88% of HR_{peak}), which corresponded to a mean VO_2 of 25.6 ml/kg/min (63% of VO_{2peak}). This data further emphasized the previous recommendations for a minimum

VO_{2peak} ranging from 33.5 to 42.0 ml/kg/min, which the authors concluded appears to be appropriate in relation to studying actual emergencies.

With many recommendations for a minimum VO_{2peak} for firefighter applicants reported, Gledhill et al. (1992) conducted a task analysis to detail the specific tasks conducted by incumbent firefighters. The aim was to evaluate the physical abilities related to these tasks, determine those tasks identified as physically demanding, and determine the physiological requirements to complete these tasks. Based on this analysis the most demanding tasks (10% of the tasks evaluated) required a mean VO_2 of 41.5 ml/kg/min, whereas 90% of the other tasks evaluated required a mean VO_2 of 23 ml/kg/min. The authors determined that working at an oxygen uptake of 41.5 ml/kg/min was approximately 85% of the subjects average VO_{2peak}, which has been suggested that activity of this intensity be limited to 10 minutes (Astrand & Rodahl, 1986). Therefore, based on the extensive task analysis and physiological measurements, they recommended that recruit firefighters have a minimum VO_{2peak} of 45 ml/kg/min.

A recent investigation by Holmér and Gavhed (2007) quantified the ventilatory demands of a 22 min, 11 task simulated fire scenario while wearing full PPE, SCBA, and a portable gas collection system. However, the full face mask of the SCBA was replaced by a low resistance half-mask that was not connected to the air cylinder of the SCBA. The portable gas collection system utilized measured and reported expired ventilation, oxygen, and carbon dioxide values every 10 seconds. The data indicated that firefighters exhibited an average oxygen consumption of 2.75 l/min (33.9 ml/kg/min) with an expired ventilation value of 82 l/min (BTPS) and mean heart rate of 168 bpm. The most demanding activity (2 – 3 min duration) within the scenario was the “tower” exercise in which the firefighters had to ascend three flights of stairs and then descend four flights of stairs to an underground floor. This specific task required an average oxygen uptake of 3.55 l/min (43.8 ml/kg/min) with a mean expired ventilation of 102 l/min (BTPS) and average heart rate of 179 bpm. The authors indicated that for similar type of work there is high degree of individual differences in energy requirements, and that the individual must make the final determination in balancing the physical work load with their own physical work capacity (Holmer & Gavhed, 2007).

These previous studies have been very beneficial in determining average oxygen consumption during simulated firefighting tasks, but there are limitations when applying these minimum requirements to the general recruit population. The majority of the studies suggesting a minimum VO_{2peak} value analyzed average maximal oxygen consumption from relatively small sample sizes of all male subjects. As well, controlling the work rate of critical firefighting tasks does not come without major difficulty. The individual's self determined working pace may result in various work rates and energy expenditures during simulated firefighting tasks. In the 21st century, there are considerably more female recruits being hired than a decade ago, and further research may prove that gender differences occur physiologically in order to complete the same task.

Despite the considerable focus on increased heart rate and oxygen consumption during actual and simulated firefighting scenarios, work performance during these tasks requires a large amount of anaerobic energy expenditure (Davis & Dotson, 1987). Using VO_2 as a measure of energy cost requires the assumption that the majority of energy is being supplied through aerobic sources (Lemon et al., 1977b). However, in most firefighting tasks, anaerobic metabolism is a major contributor possibly accounting for more than 50% of the energy required (Lemon et al., 1977b). Of the four firefighting tasks (aerial ladder climb, victim rescue, hose drag, ladder raise) examined by Lemon et al. (1977b), average respiratory exchange ratio values (RER) ranged from 0.97 to 1.07, possibly indicating a high anaerobic component. Furthermore, Gledhill et al. (1992) collected blood samples five minutes following completion of a series of firefighting tasks and revealed that peak lactate concentrations were in the range of 6 to 13 mmol/L.

Although there have been numerous simulation scenarios conducted by various researchers over the past three decades, it appears that the most physically demanding of all the activities is the victim search and rescue (Holmer et al., 2007; Romet & Frim, 1987). Participation in this activity alone has been reported to result in elevated heart rates averaging approximately 153 bpm.

2.3 Implications and responses to wearing Personal Protective Equipment

The physically demanding nature of the firefighting occupation is further enhanced due to the personal protective ensemble (PPE) that must be worn to protect against the extremely high external temperatures. Studies have reported that ambient temperatures during firefighting can range from 38°C to 93.3°C (Faff & Tutak, 1989; Smith, Petruzzello, Kramer, & Misner, 1996) and may even exceed 200°C (Baker, Grice, Roby, & Matthews, 2000). Teitlebaum and Goldman (1972) described that when wearing multiple clothing layers compared to wearing the equivalent weight on a belt required an increased energy cost while walking on a treadmill. PPE worn by firefighters is not only effective in preventing heat from the external environment penetrating the clothing, but also creates a microenvironment within the PPE prohibiting the heat generated by the firefighter from escaping (Cheung, McLellan, & Tenaglia, 2000; Faff et al., 1989; Holmer, Kuklane, & Gao, 2006; White & Hodous, 1988). In an unclothed exercise situation, thermal energy regulation between the human and ambient environment is accomplished directly across the skin (Cheung et al., 2000). With the addition of protective clothing, the microenvironment formed directly above the surface of the skin establishes the new environmental layer between the body and the environment (Cheung et al., 2000).

In order to determine the physiological response of wearing PPE during exercise, Baker et al. (2000) walked subjects at a moderate workload of 7 km/h on a treadmill and found that the addition of wearing PPE in a thermoneutral ambient environment resulted in an increased heart rate response of 25 bpm when compared to the same intensity while wearing a regular sports ensemble (171 bpm vs. 146 bpm, respectively). A significant increase in VO_2 at this exercise intensity was observed while wearing the PPE resulting in a workload of approximately 74% of VO_{2peak} compared to 66% in the sports ensemble (39.9 ml/kg/min vs.36.1 ml/kg/min, respectively). These data indicate that performing routine exercise in PPE adds an increased workload on the firefighter in terms of higher oxygen consumption and heart rate.

An important factor in firefighter safety is the rise in core temperature from heat stress during firefighting tasks, especially throughout the recovery period. Even during rest periods or passive cooling recovery (sitting in front of a fan), core and tympanic temperature continues to increase in the range of 0.25°C to 0.9°C following consecutive bouts of exercise (Carter, Banister, & Morrison, 1999; Faff et al., 1989; Ftaiti, Duflot, Nicol, & Grelot, 2001; Holmer et al., 2006; Selkirk & McLellan, 2004). Smith et al. (1996) reported that firefighters performing two 8 min tasks (advancing hose, chopping a wood block) while in a live fire scenario resulted in near maximal heart rates at the end of the 16 min protocol (182.3 bpm) with a mean tympanic temperature of 40.1°C and blood lactate level of 3.8 mmol/L.

Holmér et al. (2006) found that when walking at a lower intensity (5 km/h) on a treadmill wearing full PPE including the weight of an SCBA, metabolic energy production was increased by 37% compared to working at the same intensity in under garments. The authors concluded that the most important factor resulting in heat stress is metabolic heat production produced by physical work, and not slight variations in the heat transfer properties of the PPE. This is in line with previous work by O'Connell, Thomas, Cady, and Karwasky (1986), who reported a 35% increase in oxygen consumption with the addition of PPE, SCBA, and equipment while walking for 5 minutes on a stepmill ergometer at 60 steps/min.

2.4 Implications of using a Self-Contained Breathing Apparatus

Respiratory protective devices are commonly used when there is an inability to prevent exposure from contaminated atmospheres. Respiratory protective devices are usually classified as (i) filtering (air-purifying) devices, (ii) air line (supplied-air) apparatus, and (iii) self-contained breathing apparatus (SCBA) (Louhevaara, 1984). The use of an SCBA is limited to tasks that require near maximal or maximal effort, as is the case in the firefighting service (Louhevaara, 1984). SCBA's are classified as "demand" or "pressure-demand" respirators with their ability to reduce the inspired resistance and create an additional protection factor to external toxins by maintaining the positive pressure within the face mask (Raven, Bradley, Rohm-Young, McCLure, & Skaggs, 1982).

Many previous studies over the past three decades have examined the use of an SCBA during incremental maximal exercise and steady-state submaximal exercise using a treadmill or bicycle ergometer. In all studies, the added weight of the SCBA resulted in increased heart rates during each submaximal exercise intensity ranging from 6 bpm to 20 bpm (Louhevaara, Smolander, Korhonen, & Tuomi, 1986; Louhevaara, Smolander, Tuomi, Korhonen, & Jaakkola, 1985; Louhevaara, Tuomi, Korhonen, & Jaakkola, 1984; Wilson et al., 1989). These investigations analyzed early SCBA models and found that during light and moderate submaximal exercise, expired ventilation was decreased when compared to control trials without wearing an SCBA, whereas oxygen consumption was increased during the same work intensity (Louhevaara et al., 1986; Louhevaara et al., 1985; Louhevaara et al., 1984; Wilson et al., 1989). During heavy exercise, expired minute ventilation was increased by 8.1 l/min – 10.1 l/min, along with an increase in oxygen consumption of 0.54 l/min – 0.8 l/min (Louhevaara et al., 1986; Louhevaara et al., 1985; Louhevaara et al., 1984). Throughout all exercise intensities, tidal volume was decreased while wearing the SCBA when compared to the control trial (Louhevaara et al., 1985).The authors indicated that the additional increase in ventilation while wearing the SCBA during heavy exercise was due to shorter inspiratory and expiratory times with a subsequent increase in breathing frequency (Louhevaara et al., 1985). They suggested that the observed changes in breathing pattern might be due to the prevention of free and efficient thoracic motion caused by the shoulder harness of the heavy SCBA (Louhevaara et al., 1985).

However, Wilson et al. (1989) found at heavy and maximal exercise, expired ventilation was not significantly changed, whereas oxygen uptake continued to produce a significant increase when compared to the no SCBA control condition. Contrary to the work by Louhevaara et al. (1985), Wilson et al. (1989) reported that breathing frequency while wearing an SCBA was decreased when compared to no SCBA. Furthermore, this finding was offset by a significantly greater tidal volume in the SCBA condition, thereby maintaining expired ventilation levels at maximal exercise. The authors concluded that the significantly greater peak expired pressure in the SCBA condition, accompanied by a significantly decreased peak expired flow, suggests an increased work of breathing while wearing an SCBA during exercise. The differences in the data seen by Louhevaara et al. (1985) and Wilson et al. (1989) might be due to the different exercise protocols utilized by both groups. Louhevaara et al. (1985) applied a steady-state exercise protocol of five minute stages with subjects exercising at 25%, 40%, and 57% of their individual maximal oxygen consumption, where as Wilson et al. (1989) implemented a treadmill ramp protocol increasing grade 0.5% every 12 seconds until the subject reached volitional fatigue. These differences in methodology might explain the variation in the results from a steady-state exercise protocol and a ramped maximal exercise test.

Raven, Davis, Shafter, and Linnebur (1977) and Manning and Griggs (1983) have shown that work performance time decreases by approximately 20% while wearing an SCBA. In addition, Wilson et al. (1989) found that subjects wearing an SCBA took approximately one minute longer to reach the same absolute work rate when compared to not wearing an SCBA. Based on the results of Louhevaara et al. (1986), the authors determined that in order to operate efficiently while wearing an SCBA in situations lasting 20 – 30 min, an individual must have a VO_{2peak} of at least 3.5 l/min. To further this conclusion, they suggested that regular short pauses of approximately 30 seconds are necessary between work phases because wearing an SCBA has a small impact on gas exchange and breathing pattern during recovery. Despite the apparent negative effects of respirator wear on performance time, it appears that individuals with a high aerobic power (> 50 ml/kg/min) are able to supersede the effect of the SCBA on performance time (Eves, Jones, & Petersen, 2005; Louhevaara et al., 1986; Wilson et al., 1989).

Although research examining the specific use of the SCBA is vital, for the firefighting industry research including the wearing of both SCBA and PPE is important. Davis and Santa Maria (1975) found that when firefighters wore their PPE (helmet, coat, boots) and SCBA while walking on a treadmill, their physiological measurements of heart rate and oxygen consumption were increased by 33% compared to an equivalent work rate wearing only exercise clothing.

Twenty years later, Louhevaara, Ilmarinen, Greifahn, Kunemund, and Makinen (1995) found that performing a graded maximal exercise test while wearing the SCBA and PPE resulted in a 25% decrease in work performance time when compared to not wearing either piece of equipment. This decrease in maximal power output was attributed to the extra mass of the SCBA and PPE. At maximal exercise, expired ventilation, absolute oxygen consumption, heart rate, and the respiratory exchange ratio showed no significant differences. Based on individual characteristics of the participants, the authors concluded that subjects with a high anaerobic capacity are more efficient in terms of work performance while wearing heavy PPE and SCBA. However, even though the SCBA and PPE were used, the full standard issued face mask was not worn by any of the individuals and might be the cause for no statistical differences in gas exchange variables.

Since the initial research examining the physiological responses while wearing the SCBA, many modifications have been made by manufacturers to increase the protection and safety of wearing the device. Recently, Dreger, Jones, and Petersen (2006) examined the use of a current SCBA model and PPE on maximal oxygen uptake. The results indicated that maximal oxygen consumption was reduced by approximately 17%. This reduction in VO_{2peak}

was significantly related to a decrease in peak ventilation, which was attributed to a reduced tidal volume, while breathing frequency was unchanged at peak exercise.

In addition to these findings, Eves et al. (2005) investigated the effects of wearing the SCBA, as well as each of the individual components of the system, without wearing full PPE (wearing only the PPE jacket). After completing four maximal graded exercise tests, the results showed that wearing only the SCBA pack and harness system while breathing through a low-resistance two-way valve reduced maximal oxygen uptake by approximately 5%, where as wearing the entire SCBA system or just the SCBA regulator both reduced VO_{2peak} by approximately 15%. These results differed from the work done by Louhevaara et al. (1985) in that at submaximal levels, Eves et al. (2005) found that ventilation was unchanged. This difference may be the result of a more advanced, remodeled SCBA from the previous model used in research two decades earlier. The authors suggested that wearing the SCBA reduces maximal oxygen uptake by limiting expired ventilation, but this response was secondary to the reduction caused by the increased expiratory breathing resistance of the SCBA regulator. They further concluded that during incremental exercise, expiratory flow rate and ventilation appear to be sufficient while wearing the SCBA below a minute ventilation of 110 l/min. Therefore, the SCBA used in this study does not appear to have a significant effect on normal firefighting operations, based on the assumption that a ventilation of 90 l/min is sufficient for most firefighting tasks (Eves et al., 2005).

3.0 METHODS

3.1 Subjects

35 male and 3 female fire fighters between the ages of 30 and 53 were recruited from the Toronto Fire Service as volunteers to take part in this study. Informed written consent was obtained prior to commencing any phase of the project.

3.2 Physiological Measurements

In order to obtain a physiological profile of each of the firefighters, all participants had their peak aerobic power (VO_{2peak}) evaluated using an incremental treadmill exercise to exhaustion on a Quinton treadmill (Quinton, Bothwell, WA), followed by an evaluation of muscular strength and endurance (Donovan & McConnell, 1999). The maximal exercise protocol consisted of a four minute warm-up at 3 miles/hour, followed by increases of 1 mile/hour every two minutes until a speed of 6 miles/hour is reached, and then increasing the grade by 2% every two minutes until volitional fatigue.

Breath by breath gas exchange measurements and heart rate were evaluated during the incremental treadmill tests using the Cosmed $K4b^2$ portable system (Cosmed, Rome, Italy). The $K4b^2$ is a telemetric gas collection system that consists of a portable unit (170 x 55 x 100 mm, 475 g), fixed onto a chest harness worn by the subject and connected to a battery pack (170 x 48 x 90 mm, 330 g) that is fixed to the harness and strapped onto the individual's back. A heart rate telemetry receiver is connected to the portable unit and receives data transmitted by a Polar heart rate monitor (Polar Electro Canada, Lachine, QC) strapped around the chest of the subject. Gas volumes and flows are measured using a flowmeter with a bi-directional digital turbine and opto-electric reader capable of measuring volumes in the range of 0 – 300 l/min. The opto-electric reader is comprised of three diodes that are capable of detecting the turn of the turbine. The O_2 analyzer is a gas filter correlation thermostated analyzer capable of measuring gas concentrations in the range of 7 – 24% with an accuracy of 0.02%. The CO_2 analyzer is a non-dispersive infrared thermostated analyzer capable of measuring gas concentrations ranging from 0 – 8% with an accuracy of 0.01%. Expired gases are transferred to the gas analyzers through a semi-permeable Nafion capillary tube that removes humidity in the expired air. The soft, flexible facemask (Hans Rudolph, Kansas City, MO) covers the individual's mouth and nose and is fastened to a bonnet on the subject's head. For these tests, the $K4b^2$ was harnessed on the participants with data being transmitted through a telemetry system to a personal computer in order to visualize the data in real-time. Following the test, complete data sets were downloaded directly from the portable $K4b^2$ unit to the personal computer. Prior to each test, the flowmeter was calibrated using a 3.0 litre syringe, while the O_2 and CO_2 analyzers were calibrated using a two point calibration of room air and a certified medical gas tank (~ 16.00% O_2 and 5.00% CO_2).

Muscular strength measures were obtained using a predictive one-repetition maximum (1-RM) formula, as previously described (Kraemer & Fry, 2006):

$$\text{Predicted 1-RM} = \text{Load Lifted} / (1 - 0.025 * \text{reps})$$

Prior to each of the predicted 1-RM strength tests, participants completed a five repetition warm-up using an approximately 40% load of their 1-RM (Kraemer et al., 2006). Following a one minute rest period (Armstrong, Brubaker, Whaley, & Otto, 2006; Kraemer et al., 2006), a load was determined that would fatigue the participant under ten repetitions. Following the predictive 1-RM test, a three to five minute rest period was implemented before proceeding to the next predictive 1-RM test. The muscular strength tests that were utilized (in order of testing protocol) were maximal handgrip using a hand dynamometer (Takei Co. Ltd., Tokyo, Japan), the flat bench press using a 20 kg Olympic bar, seated 45° incline leg press, military shoulder press using a 20 kg Olympic bar, and standing bicep curls using a 7 kg bent curl bar. As muscular strength and endurance play an important role in the physical demands of fire suppression, using more dynamic free-weight exercises represents a more “job-specific” testing model than the standard fitness test (push-ups, sit-ups, pull-ups, body weight, standing long jump) (Rhea, Alvar, & Gray, 2004).

Muscular endurance was evaluated for upper and lower body using the flat bench press and seated 45° incline leg press. To determine upper body endurance, a flat bench press utilizing an absolute load of 30 kg was lifted to a cadence of 60 beats/min, which corresponds to 30 repetitions/min. The absolute load of 30 kg was selected in order to guard against any inability of the subjects in lifting a heavier weight. For lower body endurance, a seated 45° incline leg press was utilized with participants lifting an absolute load of 123 kg at a cadence of 50 repetitions/min. For both muscular endurance tests, participants were required to lift the load until no further repetitions could completed or there was an inability to maintain cadence.

3.3 Cosmed K4b^2 and SCBA Integration

In order to collect breath by breath gas exchange variables while subjects were wearing the full SCBA system, the Cosmed K4b^2 was carefully integrated into the SCBA without altering any of the positive pressure properties. Modifications to the SCBA face mask were made by creating an elbow to connect to the expiration port of the mask, allowing for a three inch tube to be connected to the elbow and protruding to the right of the mask. The flowmeter of the K4b^2 system was connected to the distal end of the three inch tube. Sampling expired gases was accomplished by installing a rubber tube through the voice box into the nose cup of the SCBA mask, with the distal end exposed external to the mask. The Nafion sampling tube from the K4b^2 system was mounted into the rubber hose allowing for expired gas concentrations to be determined.

Figure 1: Front view of the modifications made to the MSA SCBA facemask to integrate the Cosmed K4b^{2}system.

Figure 2: Side view of the modifications made to the MSA SCBA facemask to integrate the Cosmed K4b^{2}system.

3.4 High Rise Protocol

The two high rise scenarios were conducted on the same day approximately two hours apart, with the order of the tasks being randomized for each subject. The maximal stair climb scenario was implemented to determine the total number of flights that each subject is able to climb and safely exit before their SCBA low air alarm sounds at 25% of air remaining. Each fire fighter wore full PPE (bunker pants, jacket, flash hood, gloves, and helmet) that weighed approximately 9.2 kg, and the integrated SCBA and Cosmed $k4b^2$ system. Prior to the test, subjects stood for two minutes with full SCBA and PPE worn while breathing room air in order to collect resting data. Following the test, one minute of recovery data was collected. Firefighters were requested to ascend flights of stairs in a stairwell, while carrying an additional 18 kg high rise pack (comprised of two rolled up sections of 38 mm hose), until depleting ~55% of the air in their cylinder, at which time they were instructed to remove the high rise pack, turn around and descend in order to achieve a safe exit (Figure 3). Performance time was recorded for each flight during the maximal stair climb scenario and it was determined that a firefighter had completed a given flight when both feet were on the landing of the next flight. The height of each flight was measured and in accordance with the performance time results, velocity and work rate were calculated for each flight of the entire scenario. Velocity was calculated from the formula:

$$\text{height of the flight (m) / time to complete flight (sec)}$$

In order to calculate work rate, kinetic and potential energy was calculated for each flight climbed using the formulas:

$$Kinetic\ Energy = 1/2mv^2,$$

where m = body mass + PPE+SCBA

v = velocity

$$Potential\ Energy = mgh,$$

where m = body mass + PPE + SCBA

g = gravitational constant 9.81 m/s^2

h = height of flight

Total work was calculated by adding the kinetic and potential energies, then dividing by the time it took to complete the given flight of stairs was used to calculate work rate in Watts:

(Kinetic Energy + Potential Energy) / Time to complete flight

Determination of the turn around pressure is described in the Discussion section 5.1.

The next task was utilized to determine the physiological characteristics and ventilatory demands while performing a combination of critical fire fighting tasks. Prior to the testing protocol, subjects stood for two minutes while wearing full SCBA and PPE and breathing room air in order to collect resting data. Following the test, one minute of recovery data was collected. Each fire fighter wore full PPE and integrated SCBA and Cosmed $k4b^2$ system for the entire duration of this task. Firefighters were requested to ascend five flights of stairs while carrying an additional 18 kg high rise pack (comprised of two rolled up sections of 38 mm hose) (Figure 3). When arriving at the fifth floor, the firefighter dropped the high rise pack and crawled on hands and knees down the hall advancing a 38mm hose a distance of 18.3 m (Figure 4). At various intervals during the hose advance, each firefighter completed three separate room searches simulating a scan for a victim (Figure 5). After completing the room searches and hose advance, the firefighter carried out a forcible entry simulation of breaching a door (force plate resistance set at 700 – 800 psi) (Figure 6) and then rescued a 75 kg mannequin a distance of 22.9 m back to the stairwell (Figure 7) and descended five flights of stairs.

For both of the high rise scenarios, firefighters were requested to perform the tasks at an equivalent rate that would be required at an actual fire scene.

Figure 3: Maximal stair climb and first task of the 5th floor high rise scenario while wearing full PPE and SCBA and carrying the 18 kg high rise pack.

Figure 4: Hose pull task during the 5th floor high rise scenario.

Figure 5: Room search task during the 5th floor high rise scenario.

Figure 6: Forcible entry task during the 5th floor high rise scenario.

Figure 7: Victim rescue drag task during the 5th floor high rise scenario.

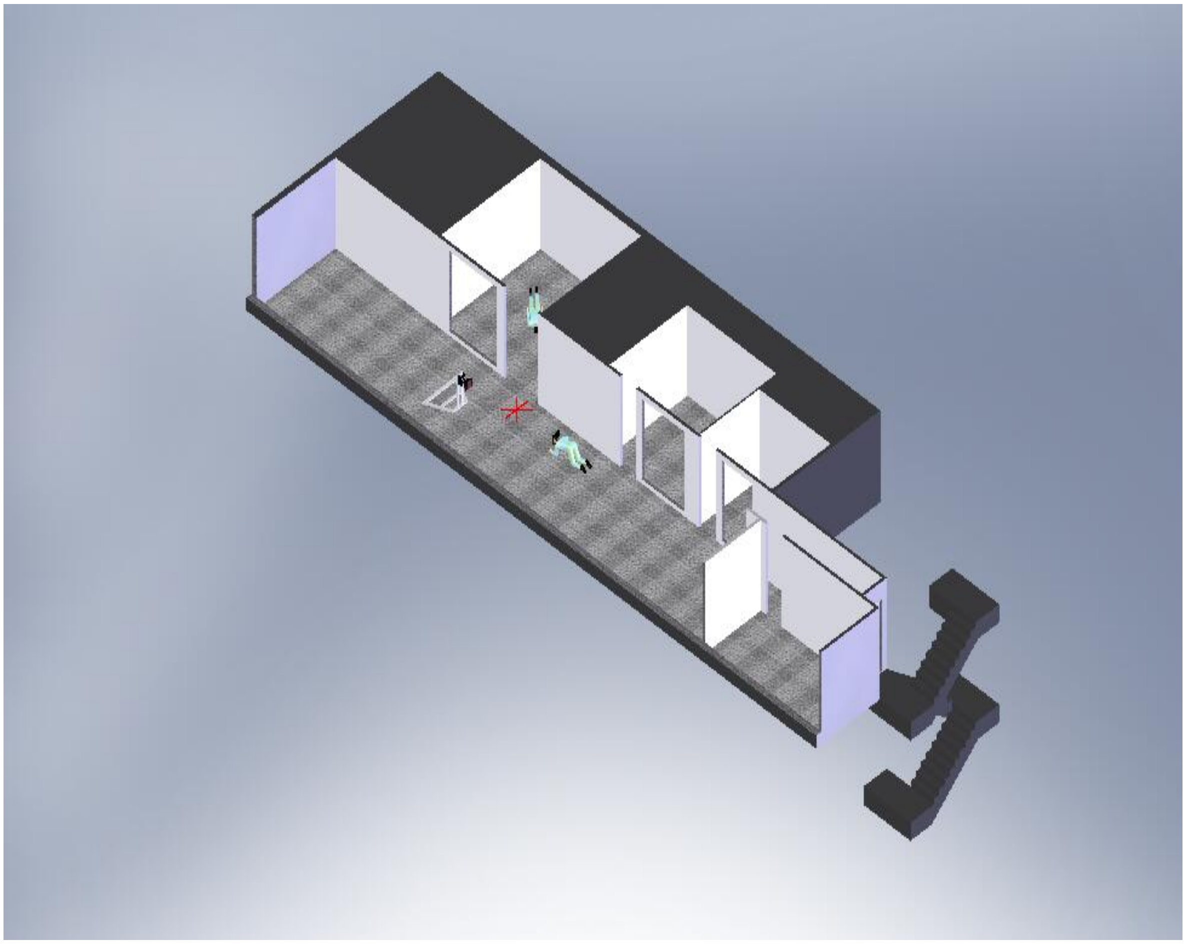

Figure 8: Schematic of the 5th floor high rise scenario. Each firefighter entered the floor by the stairwell, searched one room on the left and two rooms on the right with a concurrent 38 mm hose drag. The firefighter on his/her hands and knees is completing the final portion of the hose drag ending at the red mark. The mannequin for the victim rescue drag is found in the 3rd room on the right.

3.5 Subway System Scenario

This scenario comprised critical firefighting tasks that simulate the typical requirements for an individual firefighter at a subway system fire scene. Each firefighter wore full PPE and integrated SCBA and Cosmed $k4b^2$ system. Prior to the test, subjects stood for two minutes while wearing full SCBA and PPE and breathing room air in order to collect resting data. Following the test, one minute of recovery data was collected while continuing to breathe through the SCBA regulator. Two firefighters (firefighter A and firefighter B), working together as a team, picked up a 22 kg high rise pack (comprised of two 38 mm hose bundles, hose nozzle, and tool) and descend 22 stairs in order to reach a subway platform, walk a distance of approximately 30.5 m to the entrance of the subway tunnel, walk 152.4 m to specialized ladder, pick up the specialized ladder hanging track side, walk an additional 100.6 m toward a subway car, remove their high rise packs and attach the ladder in order to mount the subway car, perform a 54.9 m search through two subway cars, the firefighter A rescued a 75 kg mannequin a distance of 27.4 m back through the first subway car while firefighter B acted as a guide to avoid potential obstacles, following completion of rescuing the mannequin from the first subway car firefighter B rescued the 75 kg mannequin 27.4 m through the second subway car while firefighter A acted as his/her guide, after completing the rescue drag the firefighters descended the subway car and walked a distance of approximately 283.5 m back to the base of the stairwell, and ascended 22 stairs in order to exit the fire scene. Firefighters were requested to perform the tasks at an equivalent rate that would be required at an actual fire scene.

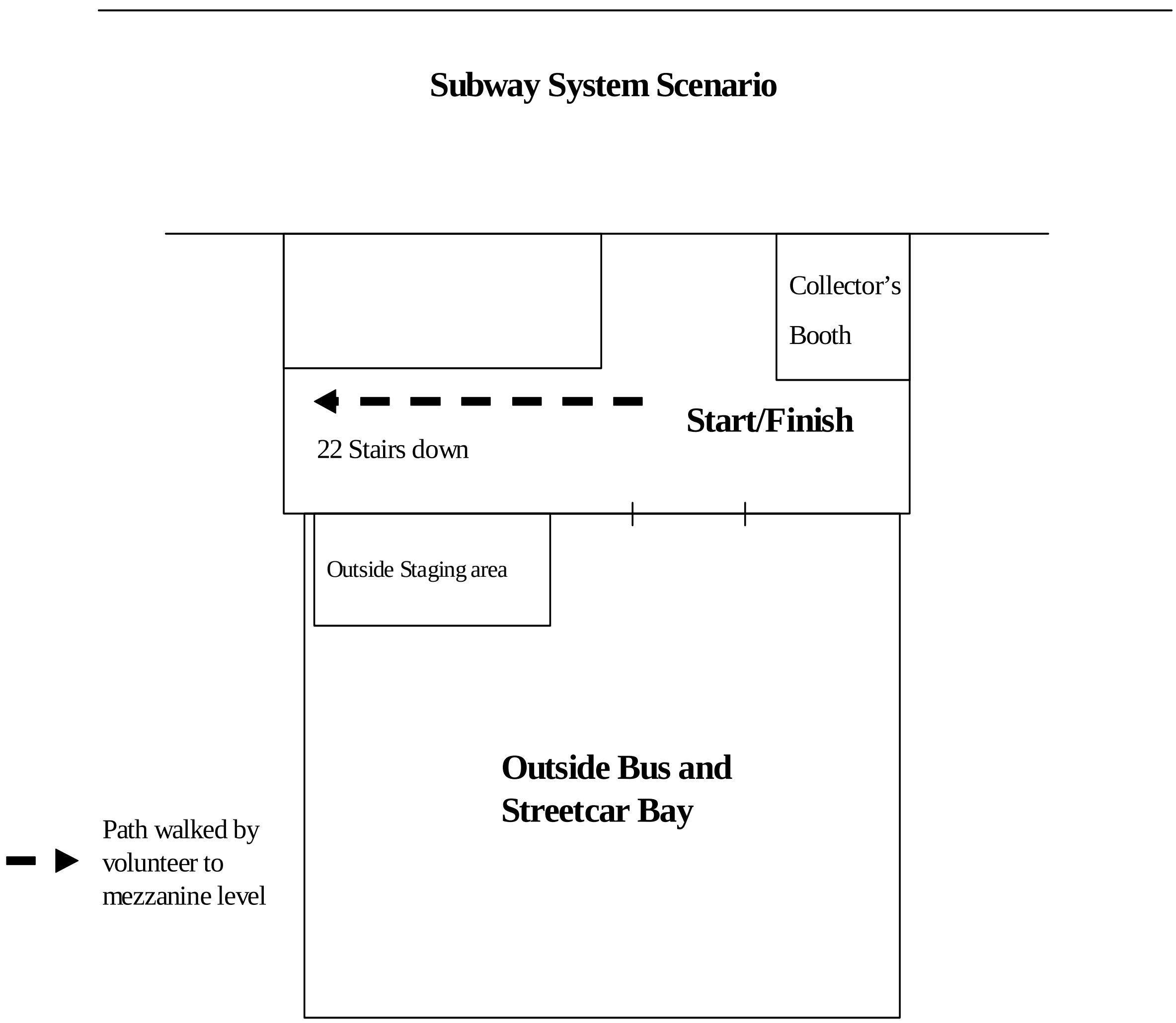

Figure 9: Schematic of the stair climb task and start/finish position for the subway system scenario.

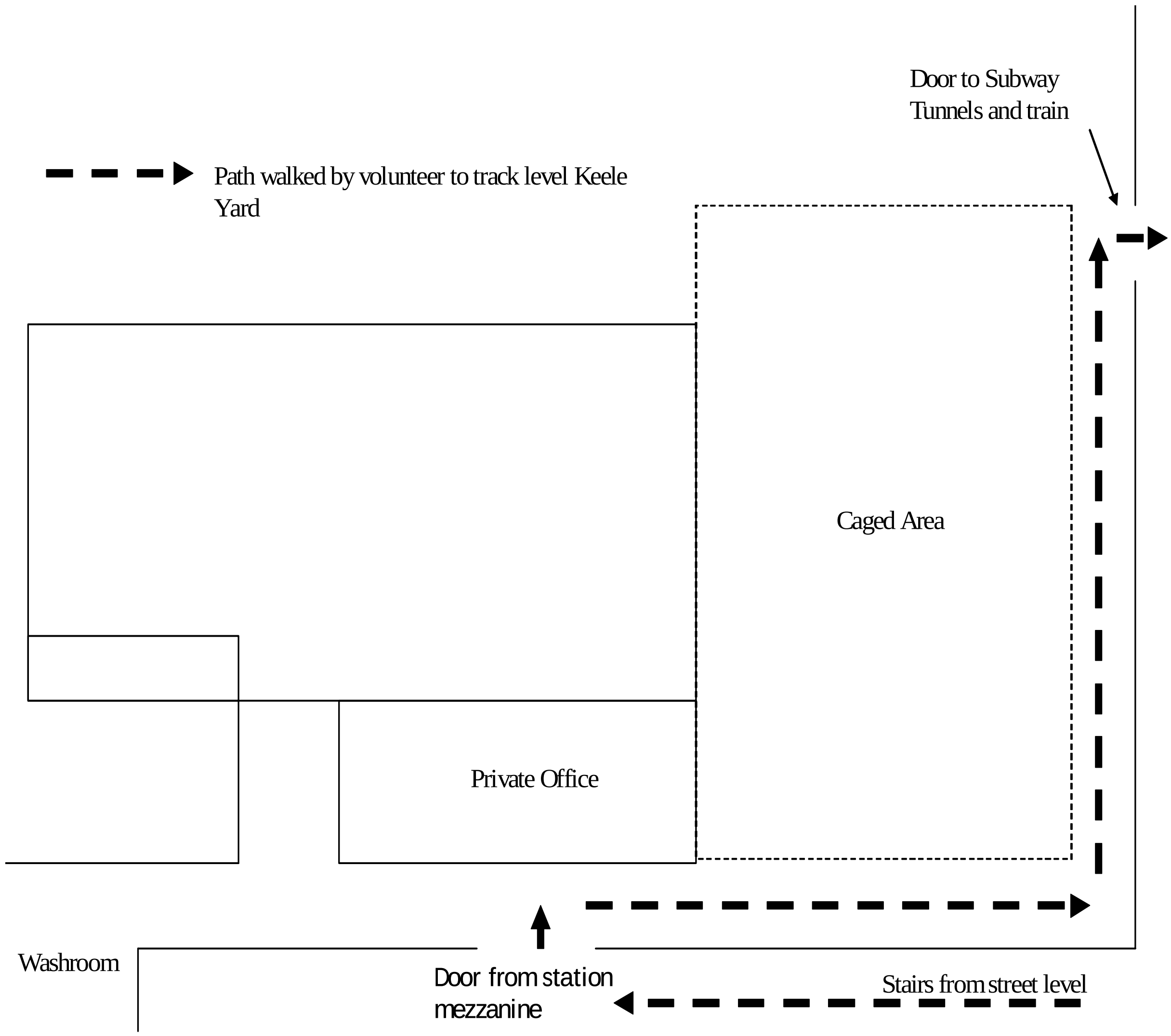

Figure 10: Schematic of the walk from the bottom of the stair climb to the track level for the subway system scenario.

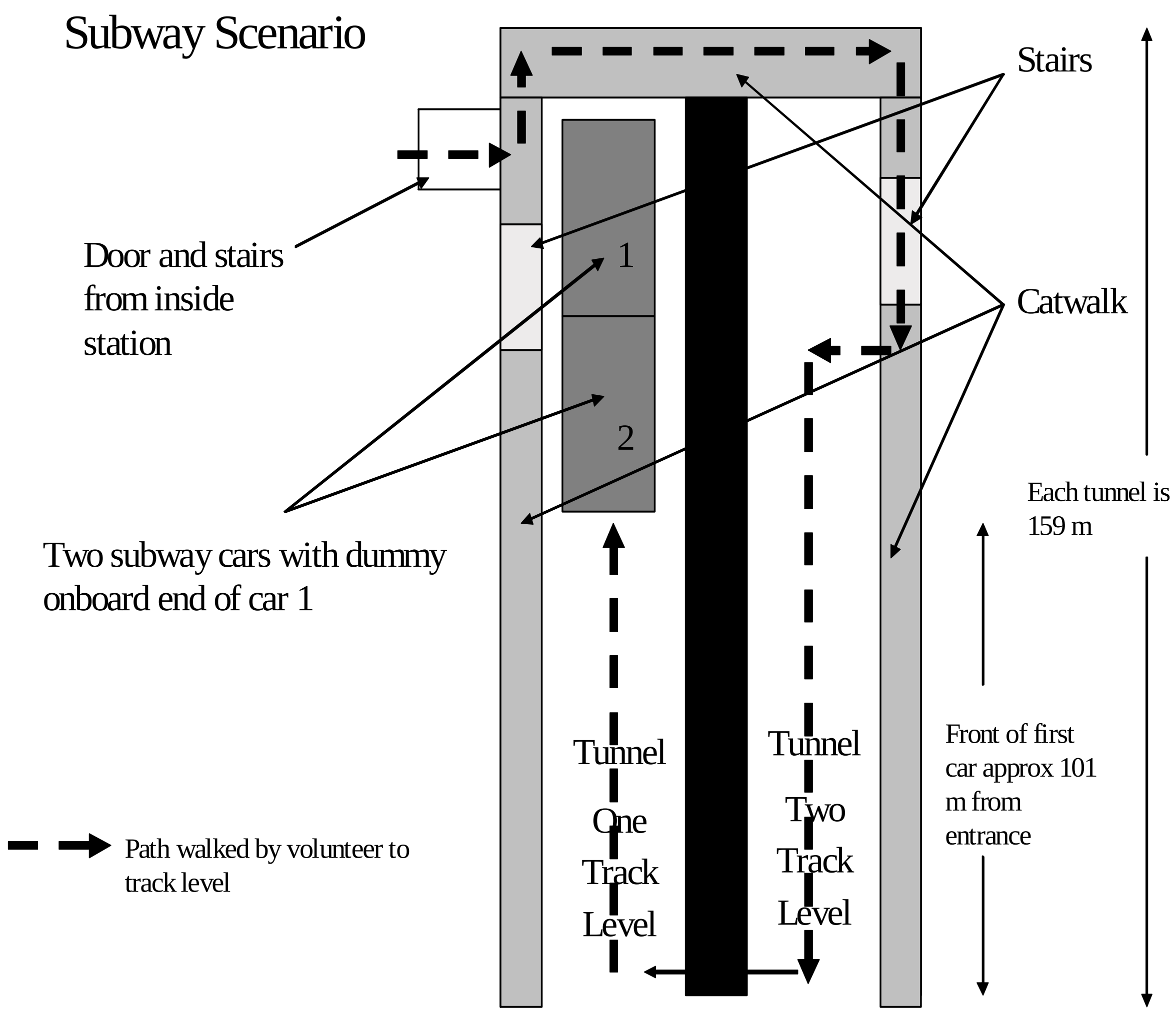

Figure 11: Schematic of the track level and pathway walked by each firefighter for the subway system scenario.

Figure 12: The ladder carry task for the subway system scenario. The length of the tunnel is indicative of the tunnel walk completed prior to picking up the ladder.

Figure 13: The ladder setup task for the subway system scenario.

Figure 14: The victim rescue drag for the subway system scenario. Firefighter A is dragging the victim while Firefighter B acts as a guide to help avoid any potential obstacles.

Figure 15: Final stair ascent at the completion of the subway system scenario.

3.6 Mechanical Calibration

In order to determine the validity of the modifications made to the SCBA facemask when integrating it into the Cosmed K4b^2 breath by breath gas collection system, a mechanical calibrator developed by the University of Waterloo and Vacumed (CA) was used. The mechanical calibrator is comprised of two 3 litre syringes, one containing inspired gases while the other contains a certified medical gas (~ 16% O_2 and 5% CO_2) that will act as the expired gas. A schematic of the mechanical calibrator can be found in Figure 16. The mechanical calibrator works using a motorized piston that is capable of drawing air into the system and pushing air out of the system. The system can be adjusted to allow for different tidal volumes, as well as manipulated to set various flow rates. During inspiration, air is inspired through the device under test (DUT) into the inspiration syringe; at the same time, air is drawn in from the known medical gas contained in the Douglas bag and flows into the expiration syringe. Once inspiration has been completed, the commencement of expiration results in the air contained in the inspiration syringe being pushed out through a separate tube and into room air while the known medical gas contained in the expiration syringe is passed through the DUT. One-way valves are placed in both the expiration and inspiration tubes in order to prevent any contamination of gases within the system. Furthermore, a three-way valve is placed at the front of the calibrator to deter inspired gases from flowing into the expiration syringe, and vice versa.

A variety of flow rates were chosen at a tidal volume of 3.0 L to verify that the modifications made to the SCBA facemask still obtained valid results. Due to complications with back pressures and one-way valve failures when the full SCBA facemask was attached to the mechanical calibrator, only the 3 inch elbow and connected turbine were attached to the calibration system. Three elbows were constructed to be utilized during the simulation testing; therefore, all three elbows were tested using the mechanical calibrator to determine their validity. Thirty second data sets were collected at flow rates of 15, 22.5, 30, 37.5, 45, 52.5, 60, 67.5, 75, 82.5, and 90 l/min. These flow rates were chosen based on the range that would be observed during simulated firefighting tasks. Data sets were then averaged over 30 seconds to obtain one set of values for each variable. Data collected from the integrated SCBA Cosmed $K4b^2$ system were compared against predicted values determined from the mechanical calibrator. Predicted values were calculated based on the tidal volume, flow rate, and ambient environment (temperature, barometric pressure, and humidity). For expired gases, it was assumed that the temperature of the known medical gas was equivalent to that of room air and the humidity was dry at 0%.

VO_2 values were also determined by calibrating the flow turbine at 15, 22.5, and 30 l/min and collecting 30 second data sets at each flow rate using the same procedure described above. Data from the mechanical calibration procedure can be found in Appendix A.

It should be noted that these calibration techniques were only preliminary to determine the usability of the integrated SCBA Cosmed $K4b^2$ system. Further calibrations to establish the reliability and validity of the system will be forthcoming following completion of this thesis.

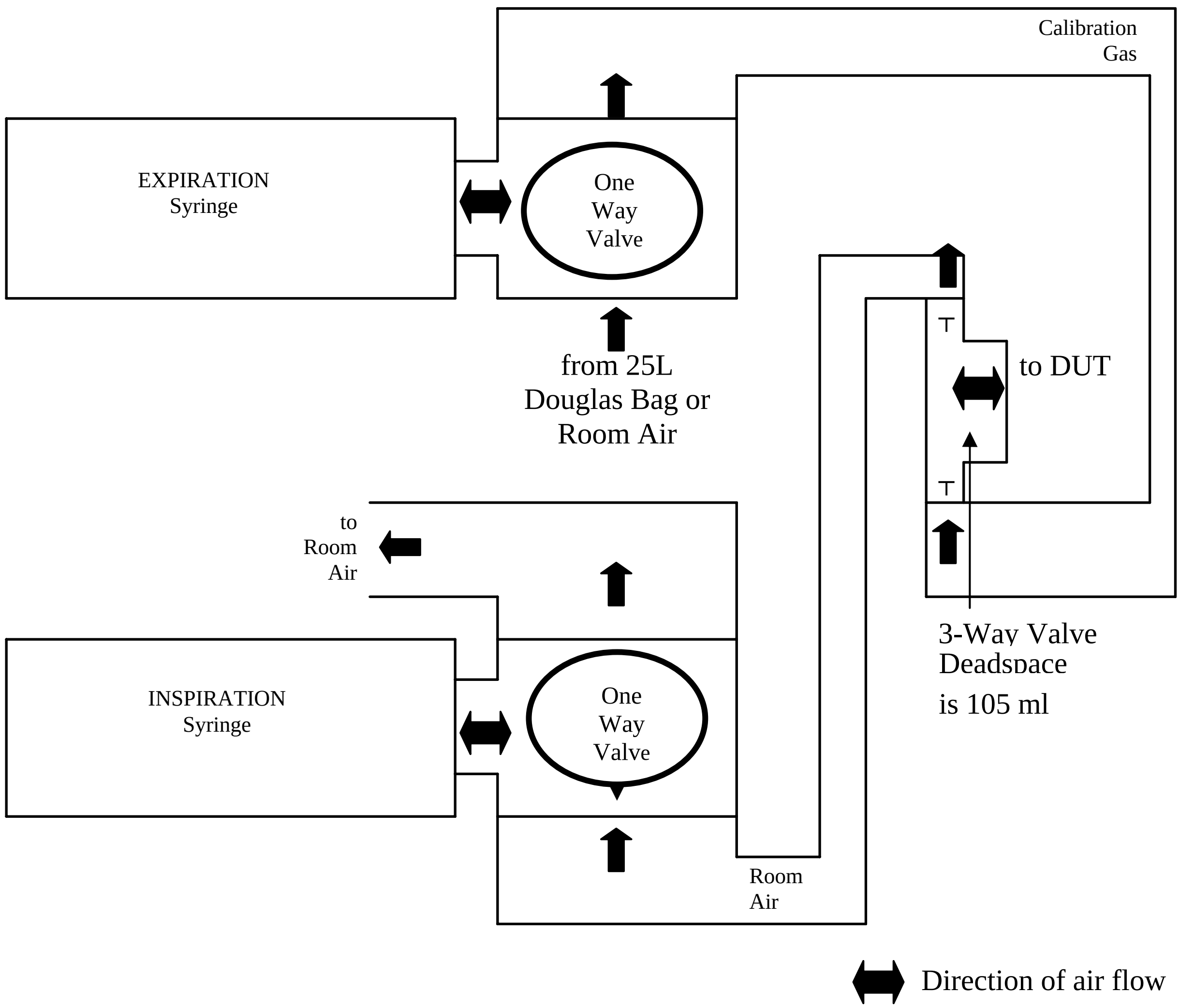

Figure 16: Schematic of the mechanical calibrator. Arrows represent the air flow through the system and subsequently out to the device under test (DUT).

3.7 Statistical Analysis

Physiological measures that were collected during each of the firefighting scenarios include minute ventilation (V_E), oxygen consumption (VO_2), carbon dioxide production (VCO_2), respiratory exchange ratio (RER), and heart rate (HR). All data were smoothed over 5 breaths. VO_2 and heart rate values were expressed relative to their maximal values as determined by the maximal incremental treadmill test. Average values were calculated for each of the individual components of the scenario, as well as for the entire scenario as a whole. For the 5th floor high rise scenario, the hose drag and room search data were averaged from the beginning of the second hose drag to the completion of the final hose drag.

During each of the protocols, performance times were recorded for every component of the scenario. As well, SCBA tank pressures were recorded using MSA Accountability Software (Mine Safety Appliance, Pittsburgh, PA) to determine total air consumption throughout each scenario.

Average values for the entire scenario, as well as for individual components were calculated and linear regressions were run between the physical fitness testing measures and physiological variables from the scenario. Furthermore, the total amount of air consumption was determined and simple regressions were run between the physical fitness testing measures and gas exchange variables collected throughout each of the scenarios. Significance level for all statistical analyses was set at $p < 0.05$.

Average values for V_E (l/min), VO_2 (ml/kg/min), and HR (bpm) were tested for differences between the three scenarios using an One-way repeated measures ANOVA, followed by a Bonferonni post-hoc test, in order to determine which scenario was the most physically demanding.

4.0 RESULTS

4.1 Firefighter Characteristics

38 participants were recruited to take part in this study; however, two withdrew from this study and are not included in the analysis. The remaining 36 firefighters were comprised of 33 males and 3 females. The mean anthropometric characteristics are summarized in Table 1. Due to the small number of female subjects in this study, data were analyzed using a combined group including both male and female subjects. The average anthropometric characteristics for the combined group for age was 40.7 ± 6.5 years (range 30 to 53 years), 12.3 ± 8.5 years of service as a firefighter (range 0.5 to 30 years), height of 178.3 ± 6.4 cm (range 164 to 196.5 cm), body mass of 87.5 ± 12.2 kg (range 60.2 to 111.2 kg), BMI of 27.5 ± 3.4 kg/m^2 (range 20.8 to 34.6 kg/m^2), and body fat% of 18.8 ± 3.7% (range 8.7 to 26.5%).

Table 1: Anthropometric values for males, females, and combined groups.

	Males (n = 33)	**Females (n = 3)**	**Combined (n = 36)**
Age (years)	41.5 ± 6.5	31.7 ± 1.5	40.7 ± 6.5
Height (cm)	179.2 ± 5.9	168.7 ± 4.2	178.3 ± 6.4
Body Mass (kg)	89.0 ± 11.4	71.3 ± 9.8	87.5± 12.2
Body Mass Index (kg/m^2)	27.7 ± 3.4	25.0 ± 2.4	27.5 ± 3.4
Body Fat %	18.8 ± 3.7	18.7 ± 2.6	18.8 ± 3.7

Values are mean ± S.D.

4.2 Physical Fitness Tests

One female subject was unable to complete the physical fitness tests due to scheduling restrictions, thus, only two females are included in this portion of the analysis. Furthermore, one male subject's VO_{2peak} data could not be obtained due to injury at the time of the physical fitness testing; therefore 32 males were used in this analysis. Due to technical difficulties with the polar band heart rate system, 28 participants' peak heart rates were recorded during the incremental treadmill test.

Absolute (ml/min) and relative (ml/kg/min) VO_{2peak}, VCO_2, RER, and HR values for male and female firefighters are presented in Table 2, while muscular strength and endurance measures are summarized in Table 3. The treadmill VO_{2peak} value was 4470 ± 696 ml/min, corresponding to 51.4 ± 6.5 ml/kg/min. Muscular strength tests revealed an average maximal handgrip strength of 57 ± 7 kg, bench press of 96 ± 27 kg, shoulder press of 67 ± 15 kg, biceps curls of 51 ± 8 kg, combined total upper body strength of 213 ± 46 kg, and leg press strength of 352 ± 70 kg. Average muscular endurance repetitions to fatigue values were 42.4 ± 14.0 for upper body endurance and 52.8 ± 34.9 for lower body endurance.

Table 2: Treadmill VO_{2peak}, VCO_2, RER, and HR values

	Males (n = 32)	**Females (n = 2)**	**Combined (n = 34)**
VO_{2peak}(ml/min)	4535 ± 644	3425 ± 901	4470 ± 696
VO_{2peak} (ml/kg/min)	51.6 ± 6.8	48.9 ± 3.5	51.4 ± 6.5
VCO_2 (ml/min)	4489 ± 592	3913 ± 85	4455 ± 590
RER	0.99 ± 0.08	1.18 ± 0.29	1.01 ± 0.10
HR_{peak} (bpm)	183 ± 9	186 ± 9	184 ± 9

Values are mean ± S.D.

Table 3: Average Muscular Strength and Endurance Values

	Males (n = 32)	**Females (n = 2)**	**Combined (n = 34)**
		Muscular Strength (kg)	
Handgrip	58 ± 6	39 ± 2	57 ± 7
Bench Press	96 ± 27	84 ± 37	96 ± 27
Shoulder Press	68 ± 15	67 ± 15	67 ± 15
Biceps Curls	51 ± 7	39 ± 10	51 ± 8
Leg Press	355 ± 70	311 ± 75	352 ± 70
Total Upper Body	215 ± 45	174 ± 108	213 ± 46 kg
		Muscular Endurance (reps)	
Upper Body	42.6 ± 14.2	38.5 ± 10.6	42.4 ± 14.0
Lower Body	48.9 ± 30.1	114.0 ± 65.1	52.8 ± 34.9

Values are mean ± S.D.

4.3 High Rise Maximal Stair Climb Scenario

For this scenario, 3 data sets could not be analyzed due to equipment errors during collection, resulting in 33 firefighters being incorporated into this portion of the analysis. Maximal stair climb following a predetermined air consumption based on a given cylinder pressure resulted in an average of 20 ± 2.5 floors climbed (range 14.5 to 23 floors), with the average duration of the ascent portion of the climb lasting 6 min 31 s ± 1 min 5 s. Including the descent segment of the task, the mean total completion time for the entire task was 10 min 23 s ± 1 min 26s. The age of the firefighter correlated significantly with maximal number of stairs climbed ($r = -0.30$, $p < 0.05$) (Figure 17). Firefighter's body mass ($r = -0.46$, $p < 0.05$) (Figure 18), body mass index ($r = -0.42$, $p < 0.05$), and body fat percentage ($r = -0.44$, $p < 0.05$) showed individual correlations with the maximum number of stairs climbed. Relative VO_{2peak} revealed a significant correlation with the maximum number of stairs climbed ($r = 0.52$, $p < 0.05$) (Figure 19). Upper body strength measures of bench press ($r = -0.39$, $p < 0.05$), shoulder press ($r = -0.37$, $p < 0.05$), and total upper body strength ($r = -0.38$, $p < 0.05$) (Figure 20) also revealed significant relationships with the maximum number of stairs climbed.

A complete summary for V_E, VO_2, VCO_2, RER, and HR during each flight of the ascent portion of the stair climb can be found in Appendix B. Mean V_E during the ascent portion of the stair climb scenario was 86.3 ± 16.7 l/min (range 57 to 114 l/min) (Figures 21 and 22), while the average during the final flight climbed was 100 ± 14.7 l/min (range 70.9 to 128.3 l/min). Mean absolute VO_2 during the stair climb was 3168 ± 878 ml/min (range 2015 to 4249 ml/min) (Figures 23 and 24), with a relative VO_2 of 35.5 ± 9.1 ml/kg/min (range 23.8 to 42.6 ml/kg/min) (Figures 25 and 26) corresponding to 70 ± 10% (range 53 to 85%) of VO_{2peak} (Figures 27 and 28). Average absolute VO_2 during the final flight completed of the ascent portion of the scenario was 3460 ± 633 ml/min (range 2138 to 4594 ml/min), with a relative VO_2 of 38.6 ± 6.4 ml/kg/min (range 20.78 to 48.26 ml/kg/min) corresponding to 76 ± 10% of VO_{2peak}. Mean VCO_2 for the stair climb was 3373 ± 1110 ml/min (range 2118 to 4267 ml/min) (Figure 24), while during the last flight climbed the average was 3698 ± 740 ml/min (range 2308 to 5001 ml/min). Average relative VO_2 during the stair climb ascent showed a significant correlation with the maximum number of floors climbed ($r = 0.53$, $p < 0.05$) (Figure 29). Furthermore, relative VO_2 during the last flight completed correlated significantly with the maximum number of floors climbed ($r = 0.59$, $p < 0.05$) (Figure 30). Mean respiratory exchange ratio (RER) during the ascent portion of the stair climb was 1.05 ± 0.15 (range 0.86 to 1.29) (Figure 31), whereas during the final flight climbed the average RER value was 1.07 ± 0.09 (range 0.89 to 1.31), indicating a considerable anaerobic component during the task. Average heart rate for the entire stair climb ascent was 162 ± 11 bpm (range 138 to 185 bpm) (Figures 32 and 33) corresponding to 88 ± 4% of $HR_{peak,}$ and for the final flight climbed was 170 ± 13 bpm (range 144 to 200 bpm) corresponding to 93 ± 3% of HR_{peak}. Average velocity during the stair climb was 0.19 ± 0.05 m/s (Figure 34), while during the final floor climbed the mean velocity was 0.15 ± 0.05 m/s. Mean velocity during the final floor climbed showed a significant correlation with the maximum number of stairs climbed ($r = 0.47$, $p < 0.05$) (Figure 35), as well as the total amount of time to climb the first 14 floors ($r = -0.45$, $p < 0.05$) (Figure 36), Average power during the ascent portion of the stair climb scenario was 237.7 ± 72.9 W, while the mean power during the final floor climbed was 238.8 ± 38.1 W.

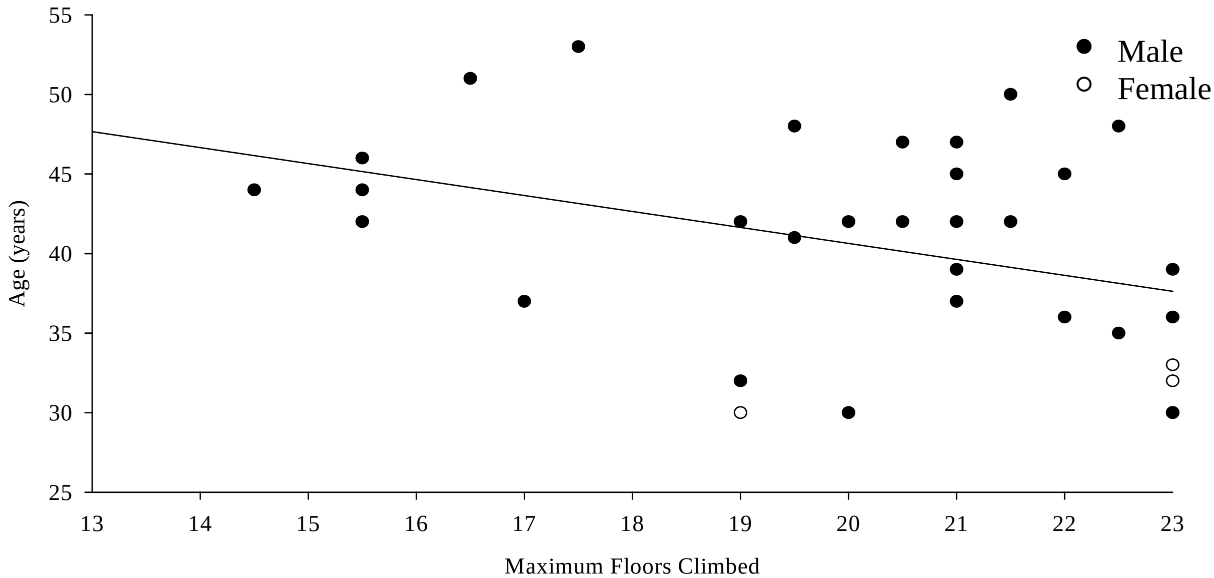

Figure 17: Relationship between age of the firefighters and the maximum number of floors climbed ($r = -0.30$, $p < 0.05$).

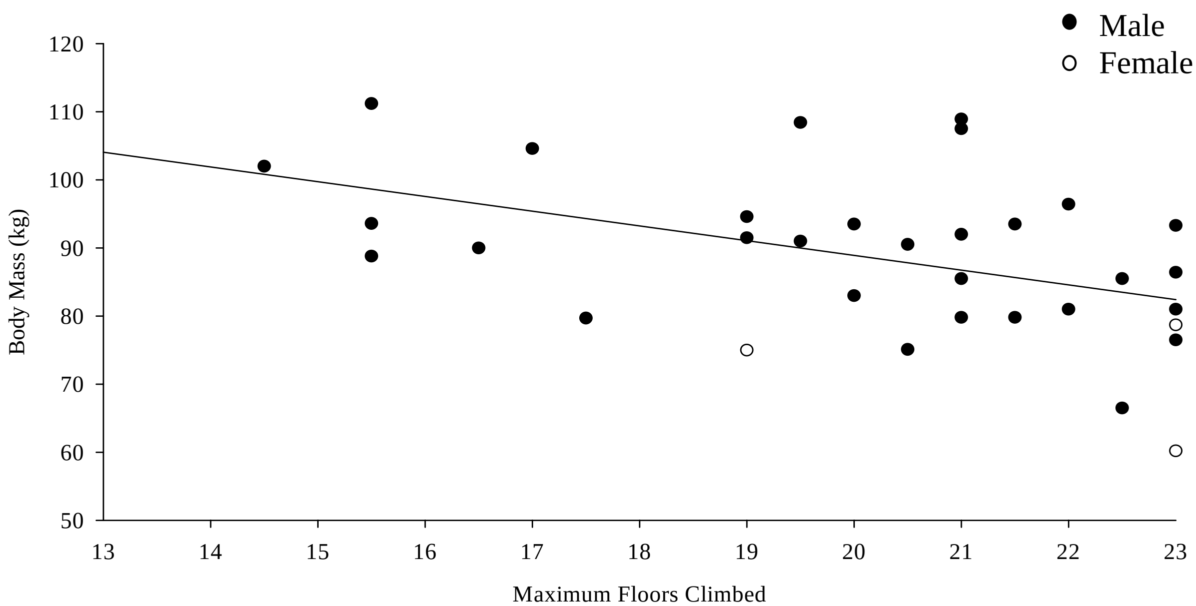

Figure 18: Relationship between body mass of the firefighters and the maximum number of floors climbed ($r = -0.46$, $p < 0.05$).

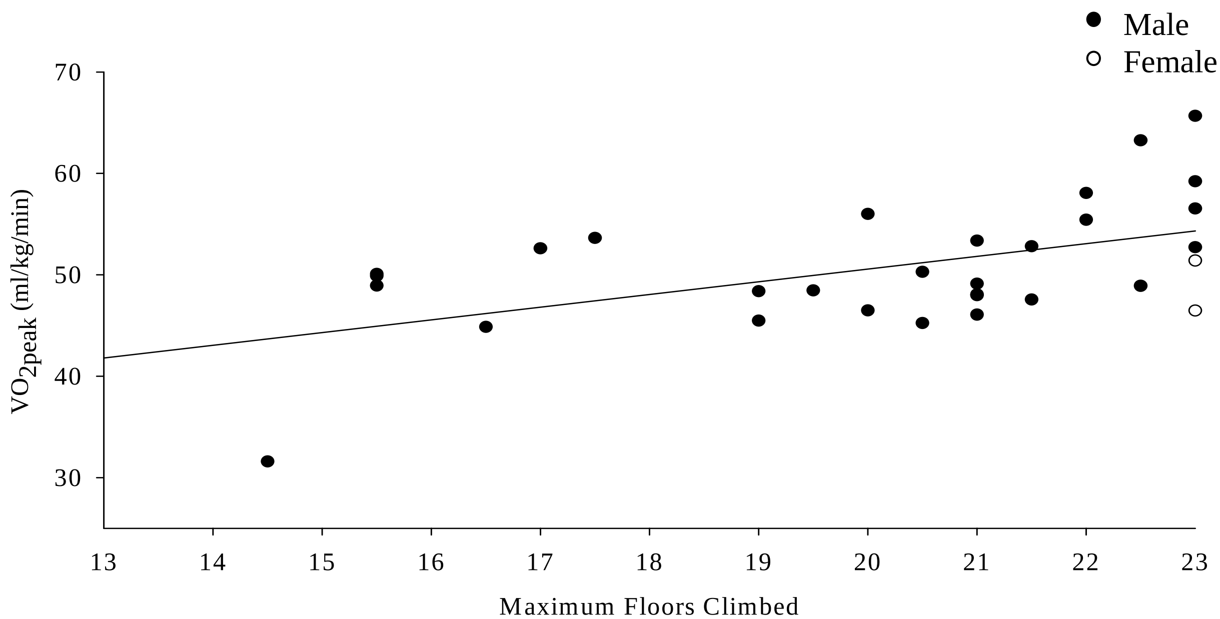

Figure 19: Relationship between VO_{2peak} and the maximum number of floors climbed ($r = 0.52$, $p < 0.05$).

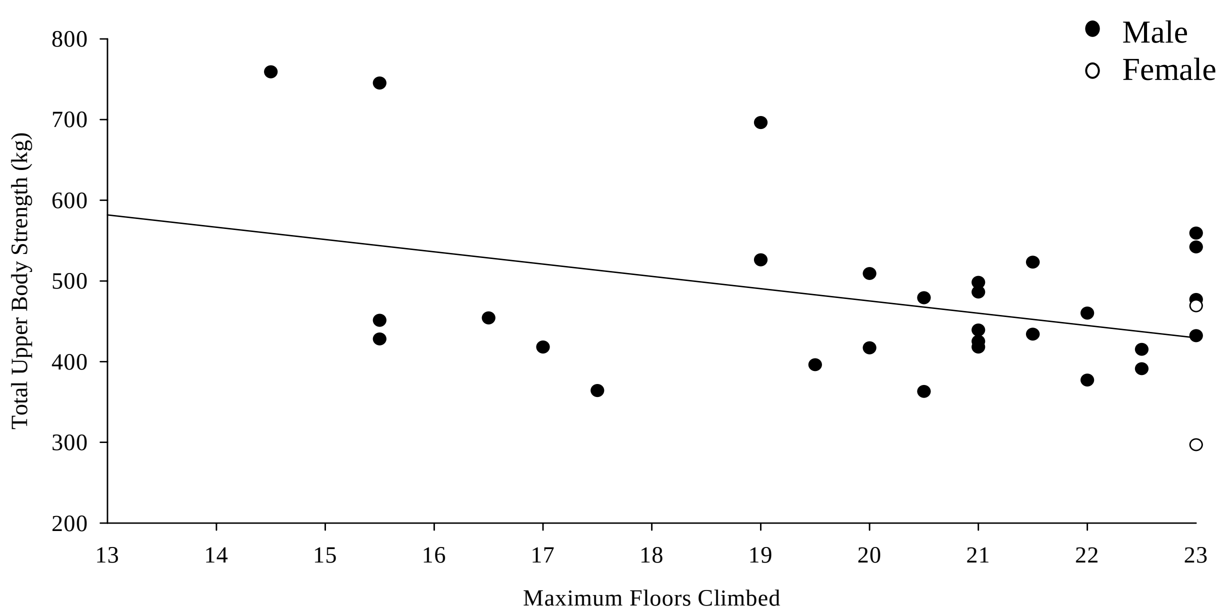

Figure 20: Relationship between total upper body strength and the maximum number of floors climbed ($r = -0.38$, $p < 0.05$).

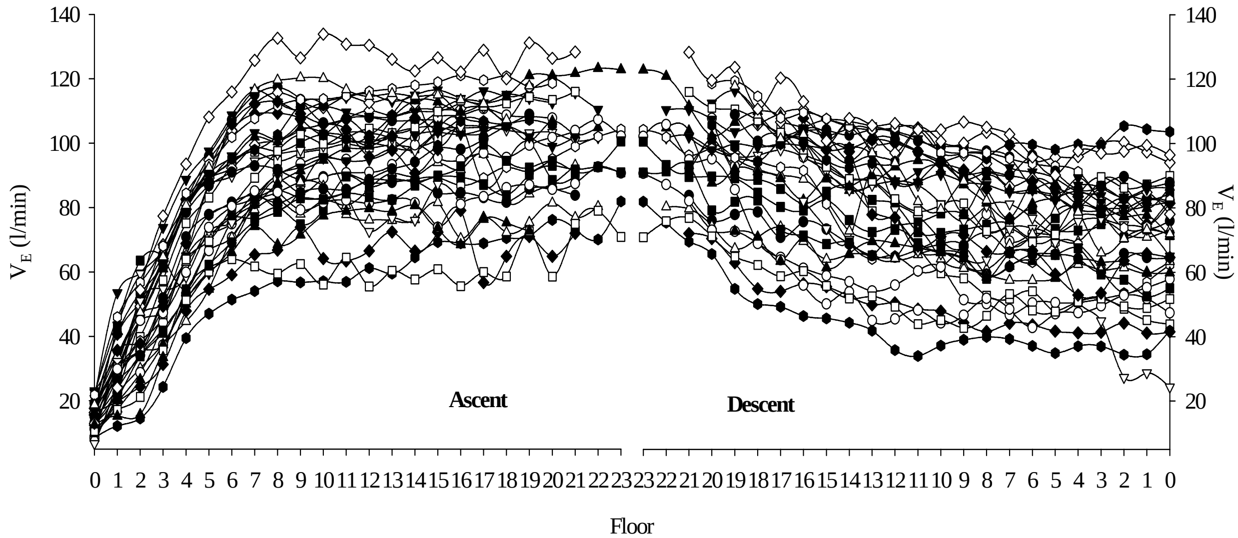

Figure 21: Individual V_E (l/min) for each firefighter during the maximal stair climb scenario.

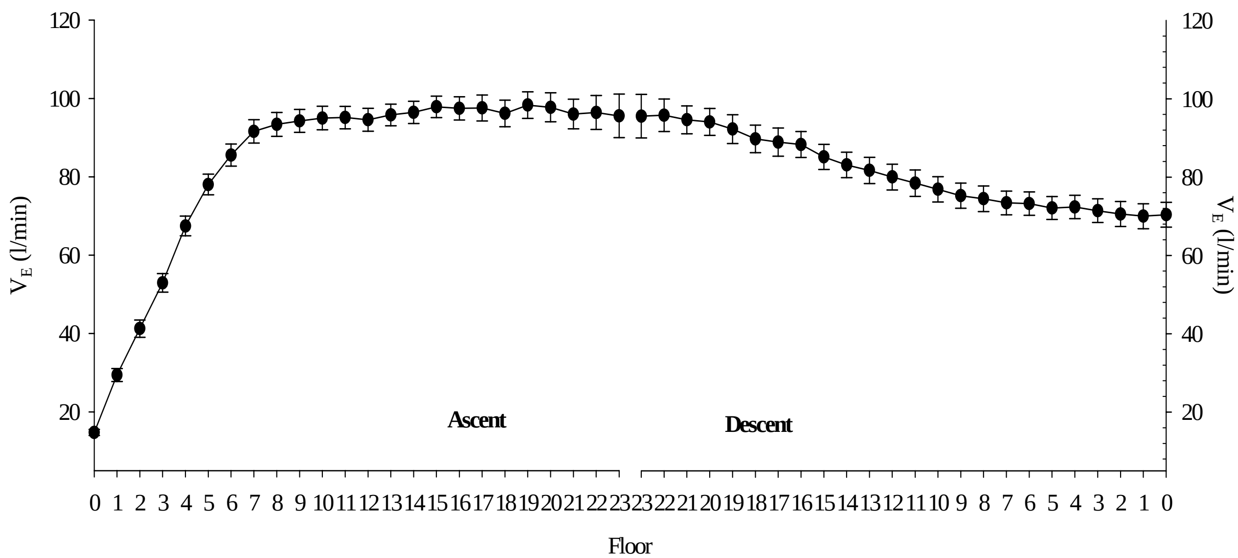

Figure 22: Average V_E (l/min) per floor during the maximal stair climb scenario. Values are mean ± S.E.M.

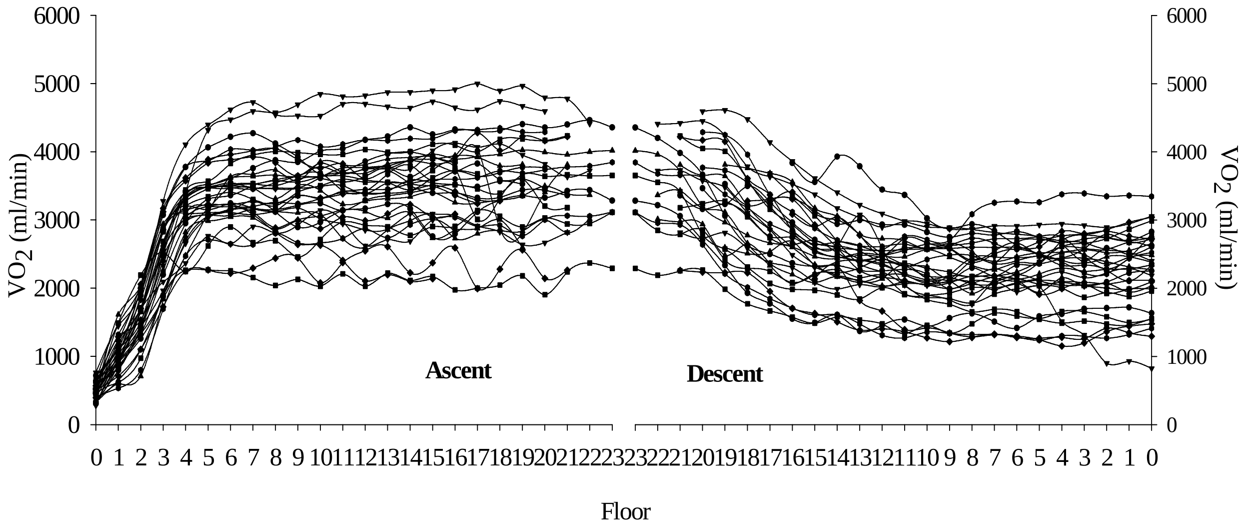

Figure 23: Absolute VO_2 (ml/min) per floor during the maximal stair climb scenario.

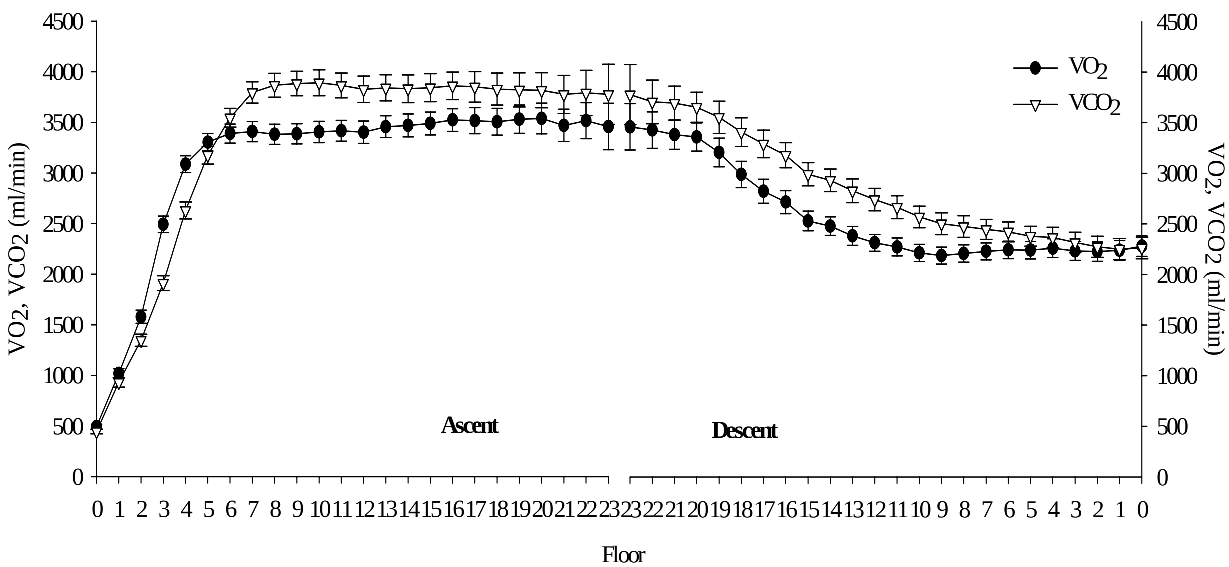

Figure 24: Average VO_2 (ml/min) per floor during the maximal stair climb scenario. Values are mean ± S.E.M.

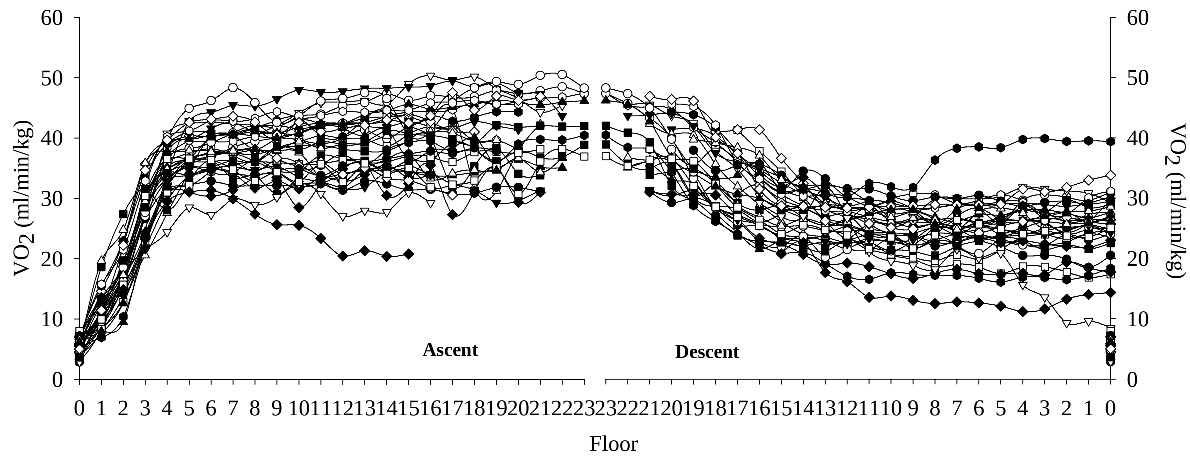

Figure 25: Relative VO_2 (ml/kg/min) for each firefighter during the maximal stair climb scenario.

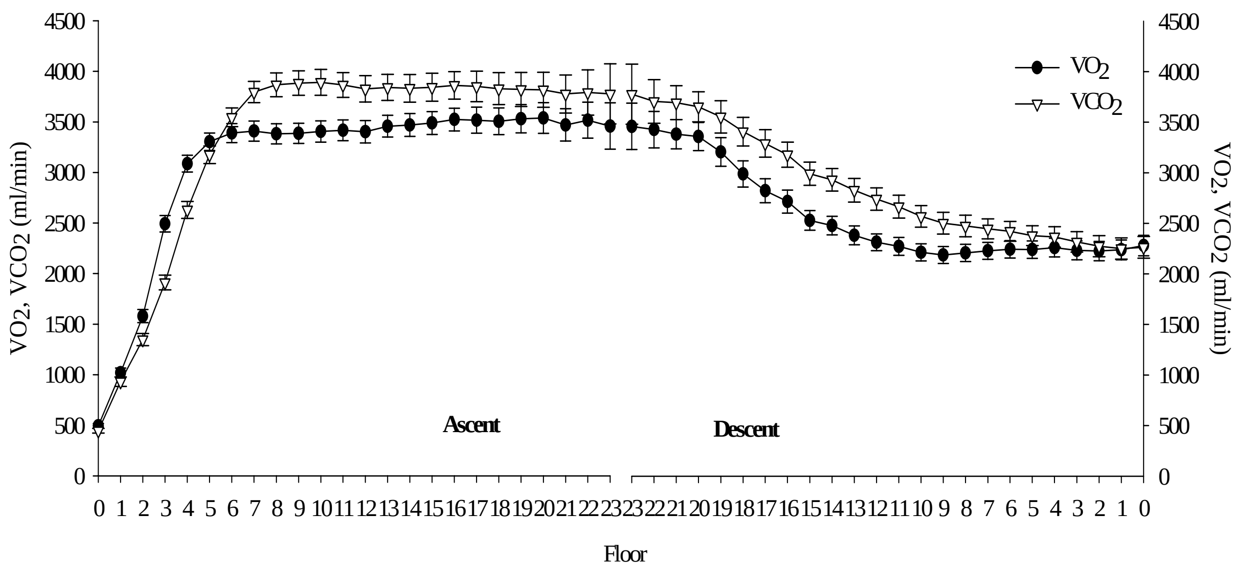

Figure 26: Average VO_2 (ml/kg/min) during the maximal stair climb scenario. Values are mean ± S.E.M.

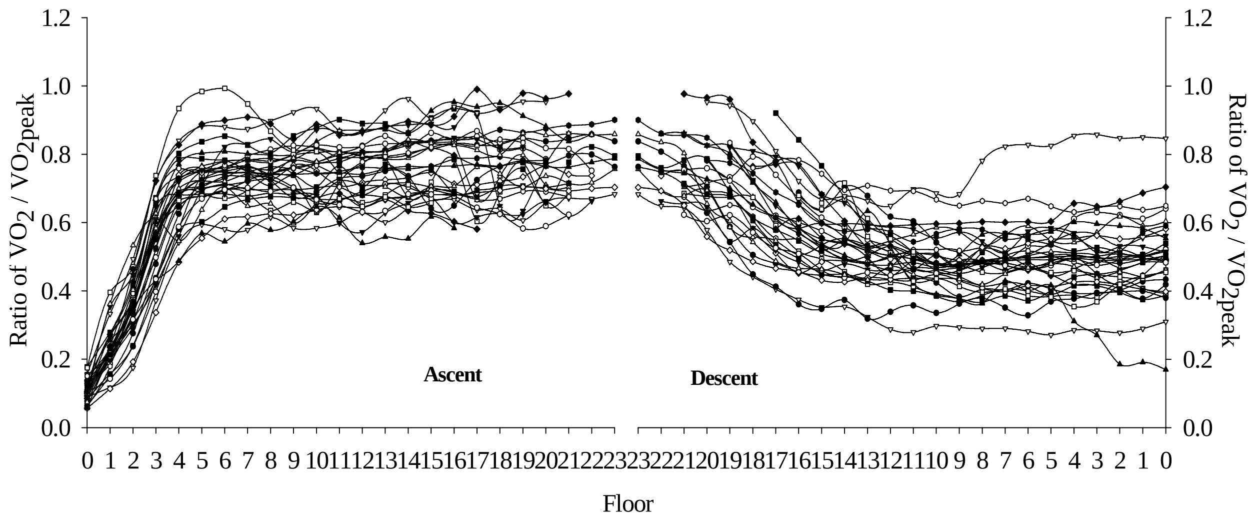

Figure 27: Individual ratios of VO_2 during the maximal stair climb to VO_{2peak} for each firefighter.

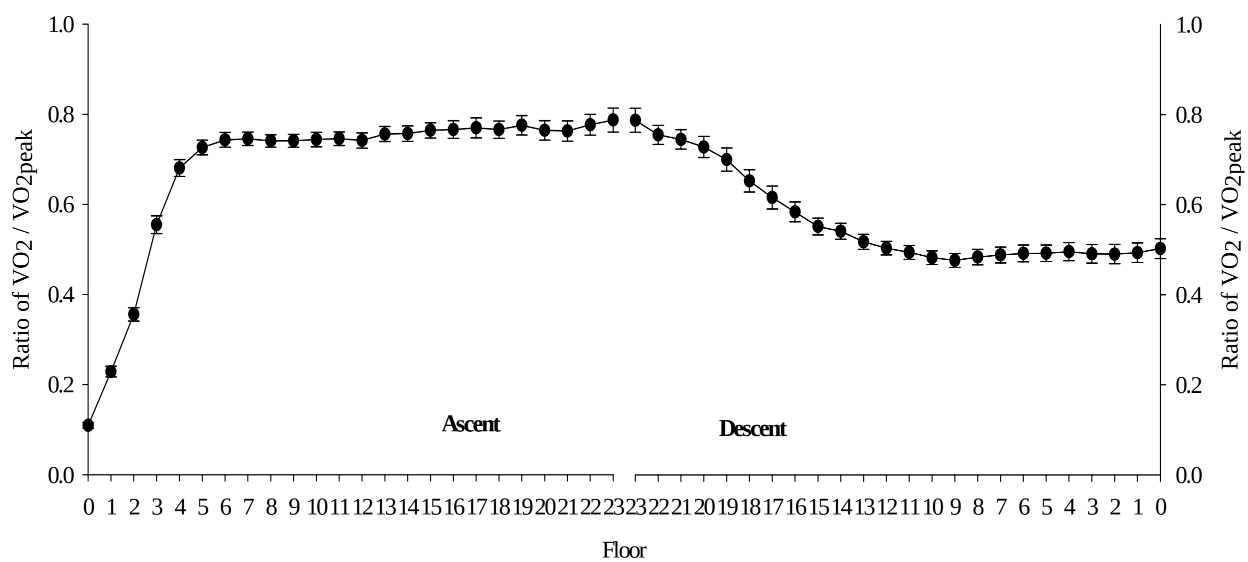

Figure 28: Average ratio of VO_2 during the maximal stair climb scenario to $VO_{2peak.}$ Values are mean ± S.E.M.

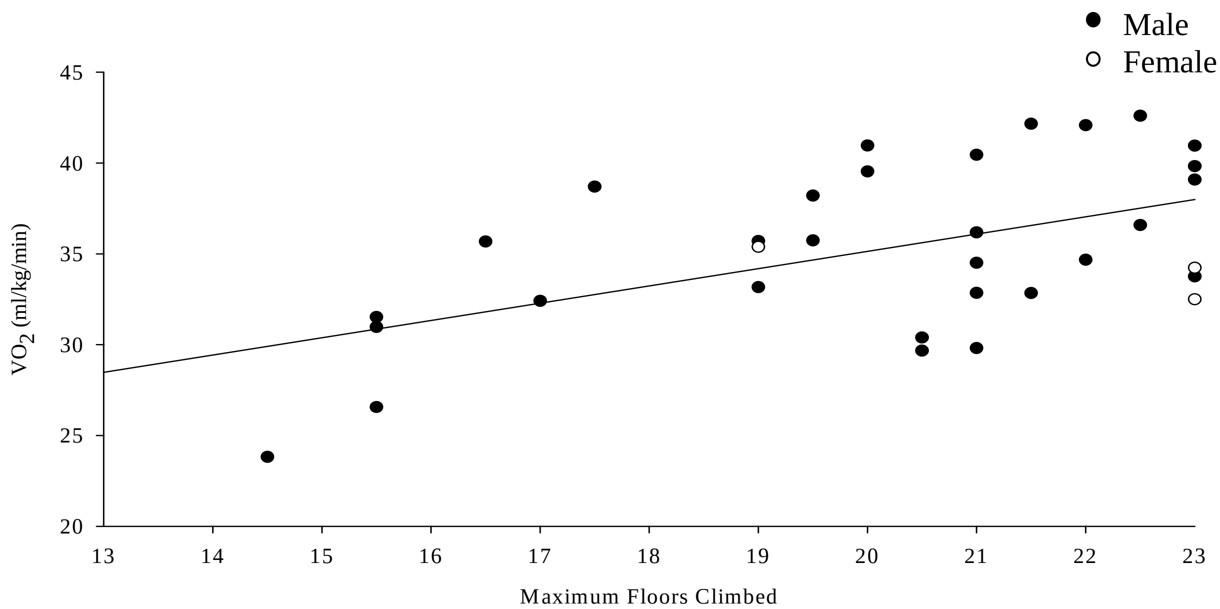

Figure 29: Relationship between average VO_2 (ml/kg/min) during the maximal stair climb task and the maximum number of floors climbed ($r = 0.53$, $p < 0.05$).

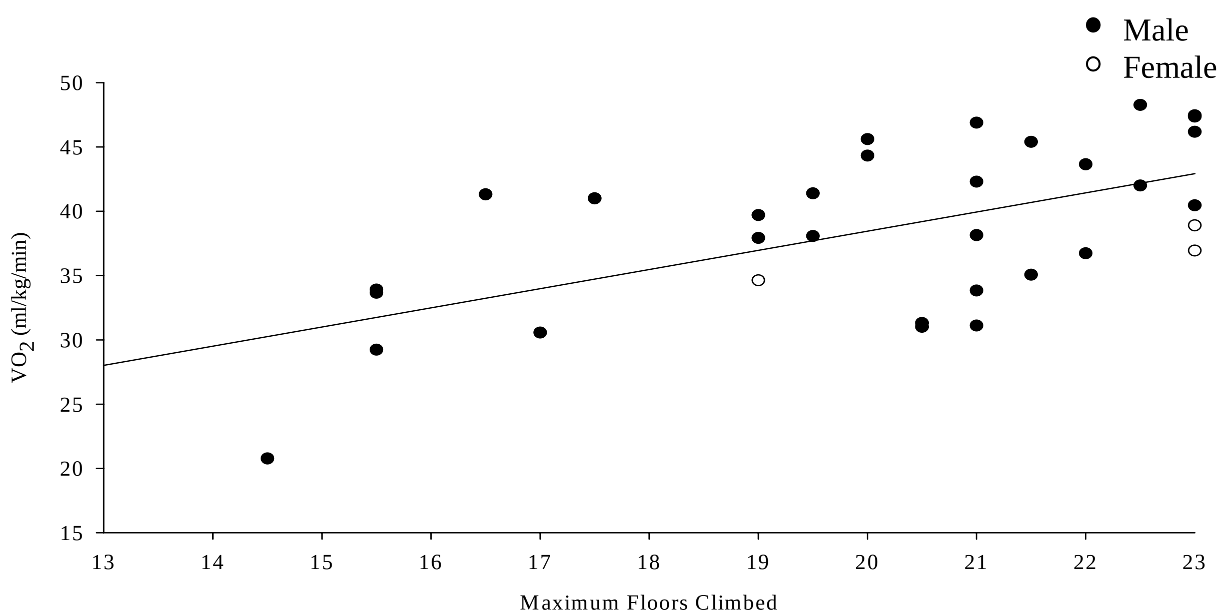

Figure 30: Relationship between VO_2 (ml/kg/min) during the last flight climbed and the maximum number of floors climbed ($r = 0.59$, $p < 0.05$).

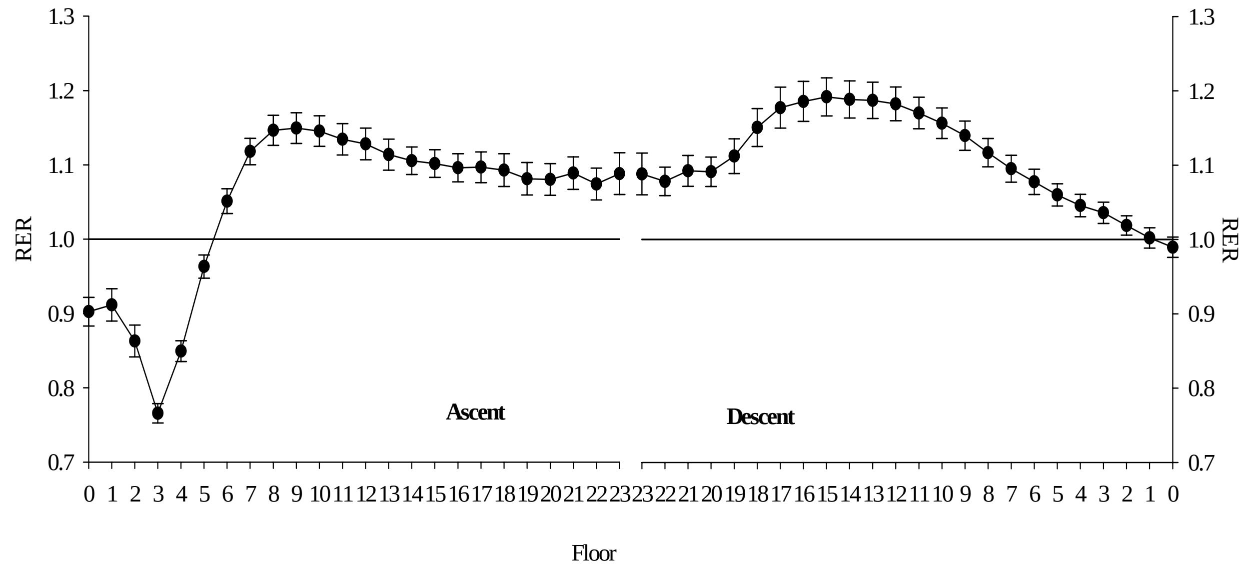

Figure 31: Average respiratory exchange ratio (RER) for each floor during the maximal stair climb. Values are mean ± S.E.M.

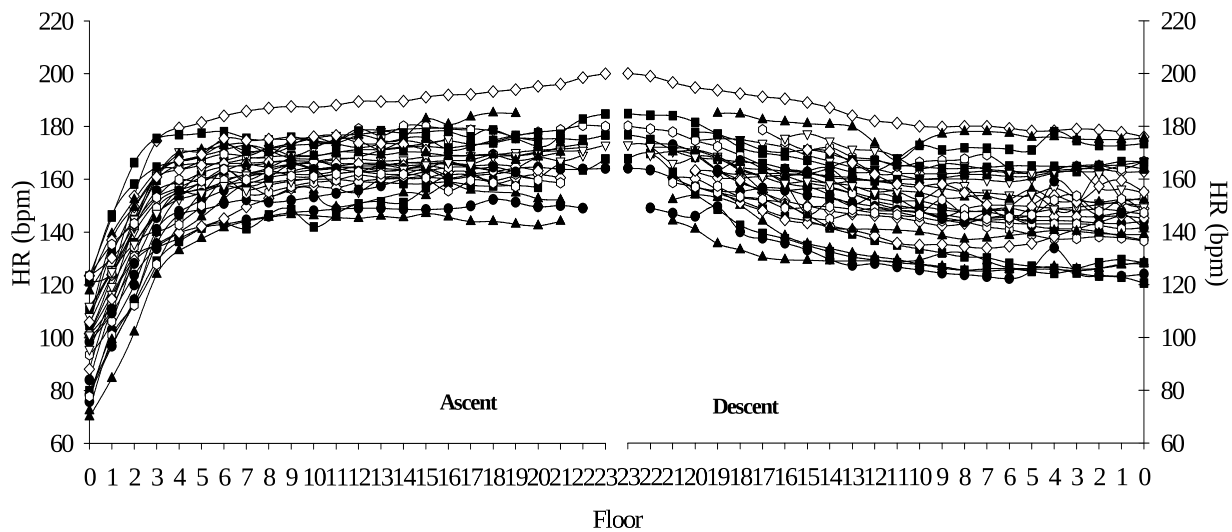

Figure 32: Individual heart rate (bpm) for each firefighter during the maximal stair climb scenario.

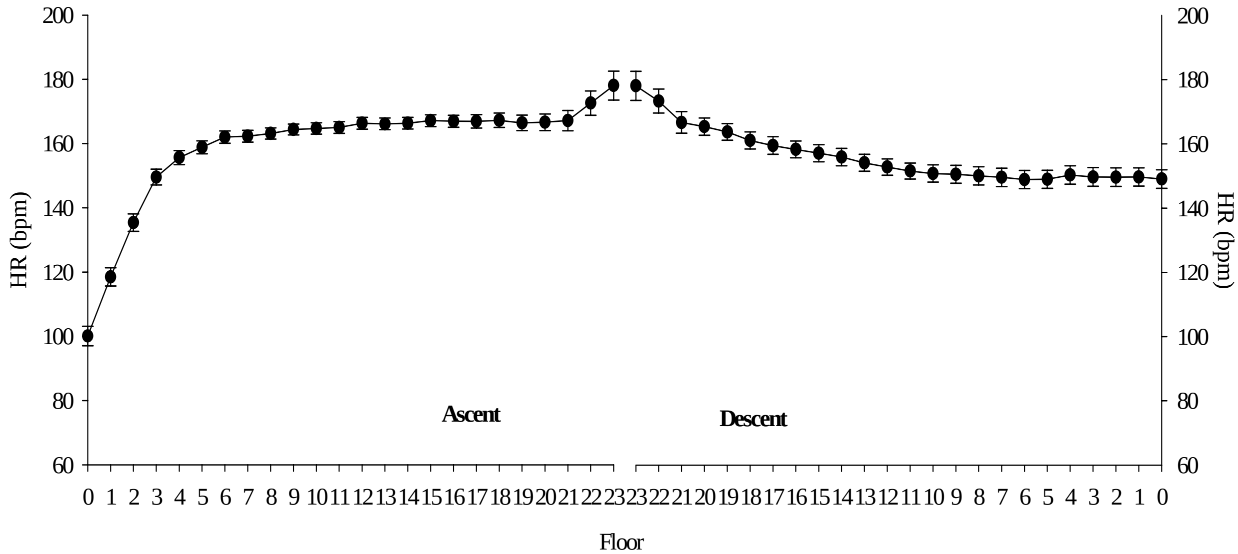

Figure 33: Average heart rate per floor during the maximal stair climb scenario. Values are mean ± S.E.M.

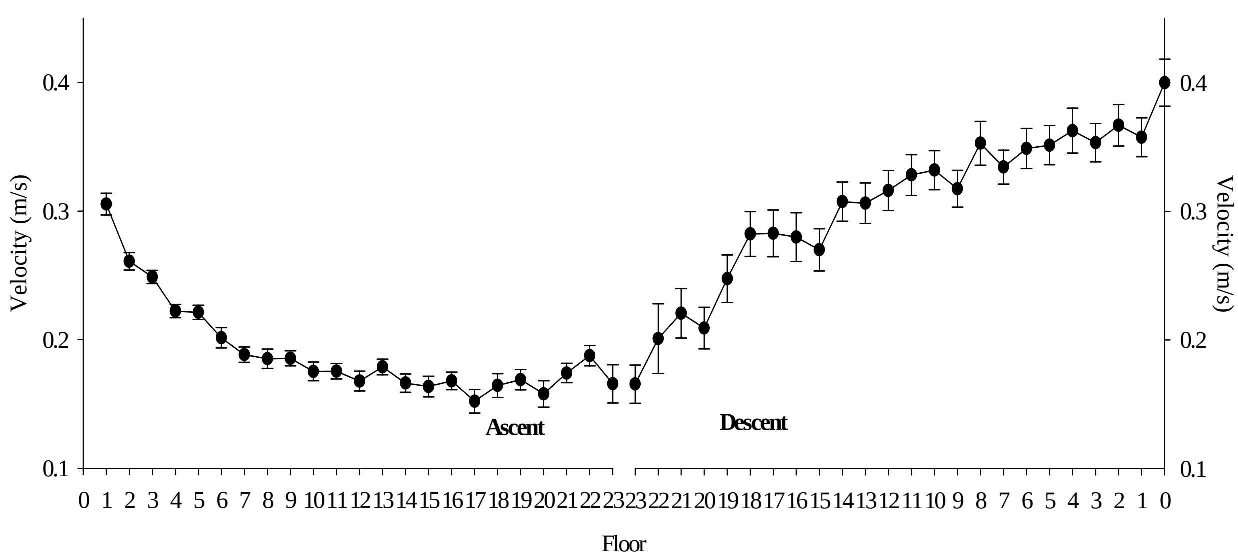

Figure 34: Average velocity per floor during the maximal stair climb scenario. Values are mean ± S.E.M.

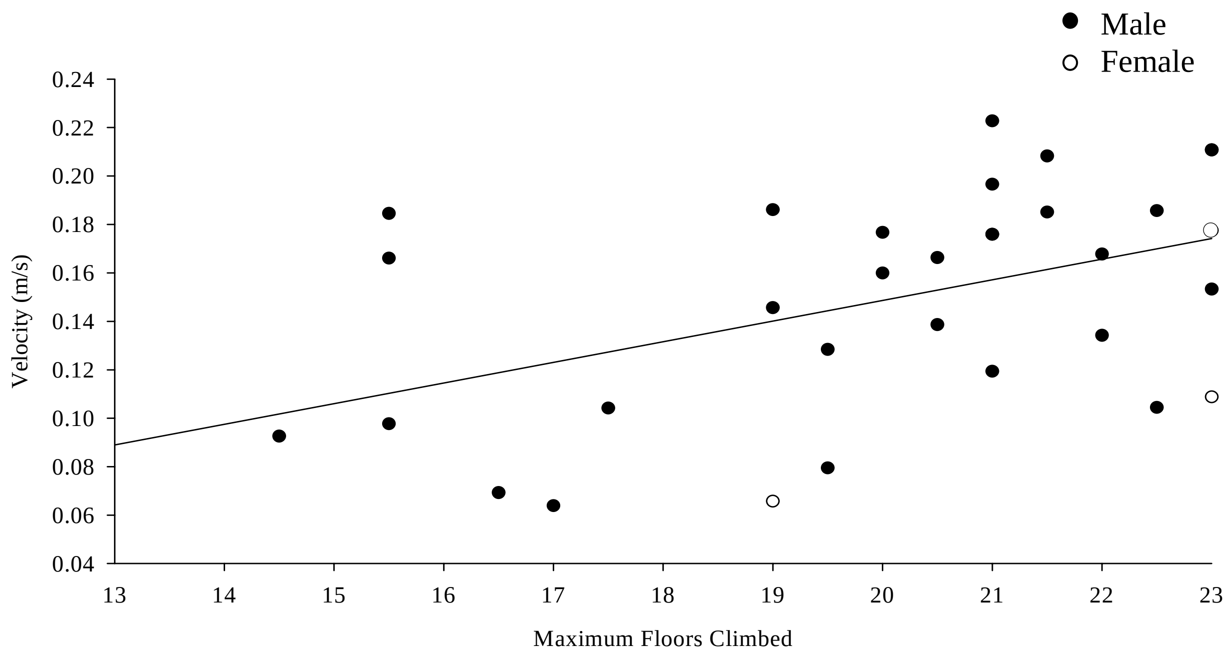

Figure 35: Relationship between velocity during the final flight climbed and the maximum number of floors climbed ($r = 0.47$, $p < 0.05$).

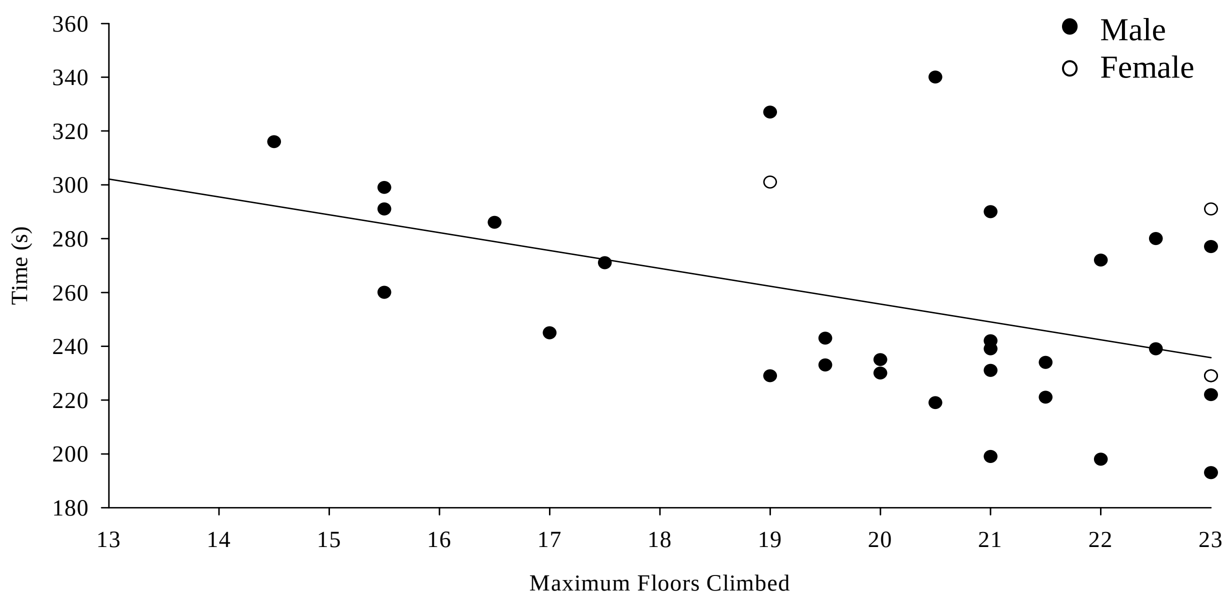

Figure 36: Relationship between the total time to climb 14 floors and the maximum number of floors climbed ($r = -0.45$, $p < 0.05$).

A summary of the air management measurements are listed in Table 4. Average starting pressure in the air cylinders was 4295 ± 204 psi (range 3870 to 4590 psi), while the mean pressures at the turn-around point (following consumption of 2365 psi from the air cylinder) and at the completion of the task were 1937 ± 201 psi (range 1505 to 2215 psi) and 1085 ± 291 psi (range 610 to 1750 psi), respectively. The average amount of air consumed during the entire maximal stair climb task was 74.9 ± 6.0% (range 61.6 to 84.3%) of the total air contained in the cylinder. Furthermore, 17 of the 36 firefighters participating in this task consumed more than 75% of their air cylinder during the maximal stair climb, indicating that their 25% low-air alarm sounded before completing the task. Total air consumption (based on the individual starting and finishing pressures for each firefighter) during the maximal stair climb scenario revealed a significant relationship with the average expired ventilation during the task ($r = 0.53$, $p < 0.05$) (Figure 37). Furthermore, firefighters' age ($r = 0.41$, $p < 0.05$) (Figure 38) and years of service as a firefighter ($r = 0.40$, $p < 0.05$) (Figure 39) showed a significant correlation with air consumption during the maximal stair climb task.

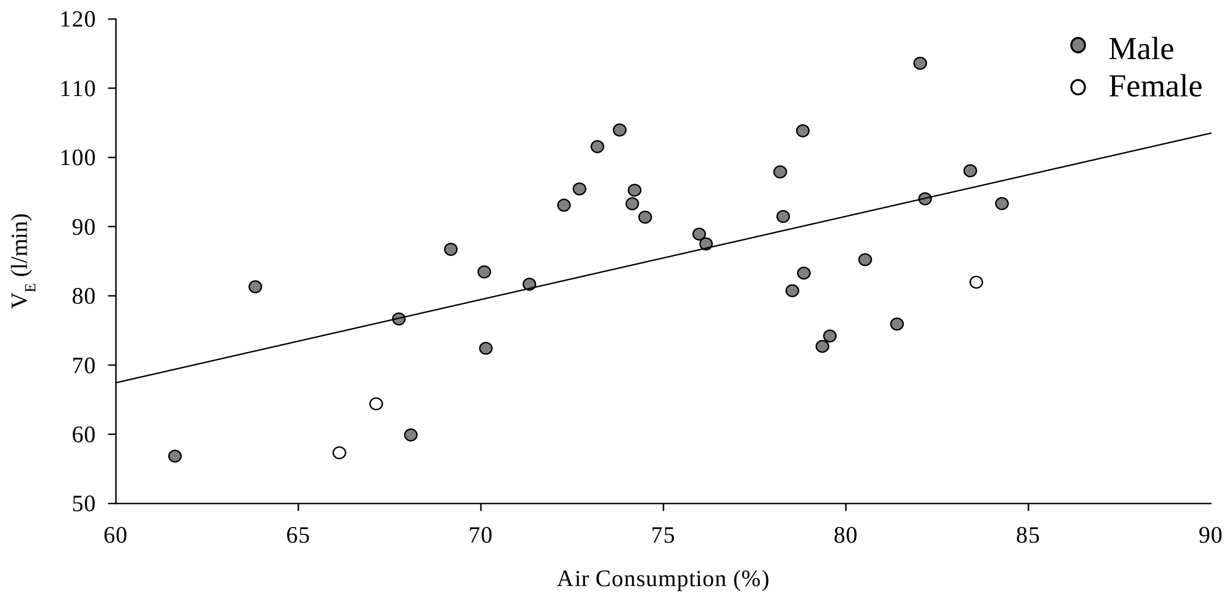

Figure 37: Relationship between average V_E and percentage of total air consumed during the maximal stair climb task ($r = 0.53$, $p < 0.05$).

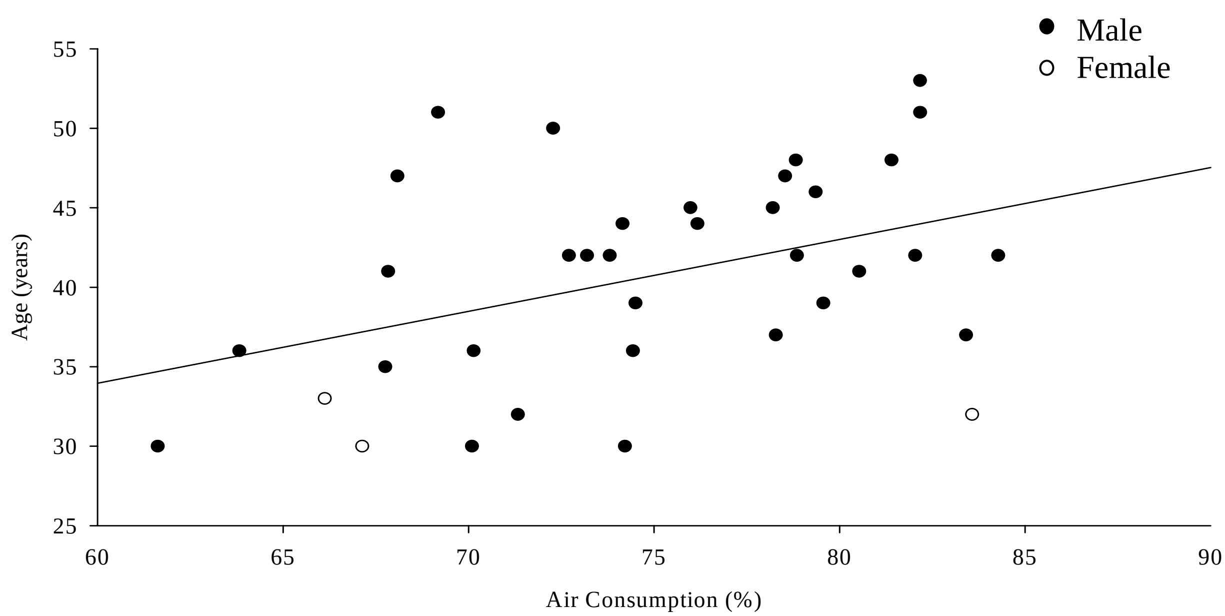

Figure 38: Relationship between firefighters' age and percentage of total air consumed during the maximal stair climb task ($r = 0.41$, $p < 0.05$).

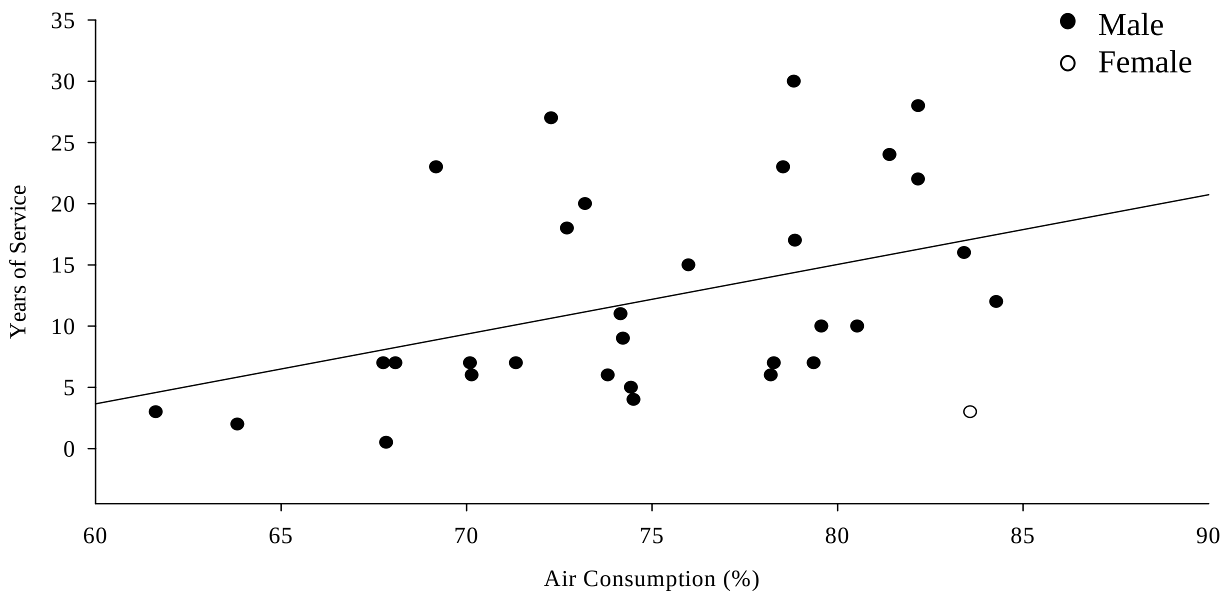

Figure 39: Relationship between years of service as a firefighter and percentage of total air consumed during the maximal stair climb task ($r = 0.40$, $p < 0.05$).

Table 4: Summary of the air cylinder pressure and total consumption during the maximal stair climb scenario.

	Pressure (psi)	**Cylinder Consumption (%)**
Start of Task	4295 ± 204	0.0
55 % Air Consumption	1937 ± 201	55.0 ± 2.9
End of Task	1085 ± 291	74.9 ± 6.0

Values are mean ± S.D.

4.4 5th Floor High Rise Scenario

The gas exchange data from 3 subjects for this scenario could not be analyzed due to technical difficulties during data collection; therefore 33 firefighters are incorporated into this portion of the analysis. Average duration for this scenario was 5 min 3 s ± 57 s. Mean expired ventilation during the entire scenario was 88.9 ± 14.4 l/min (range 60.5 to 116.3 l/min) (Figures 40 and 41). Average absolute VO_2 during the 5th floor high rise scenario was 2947 ± 461 ml/min (range 2157 to 4012 ml/min) (Figures 42 and 43), corresponding to a relative VO_2 of 33.1 ± 4.6 ml/kg/min (range 22.4 to 40.6 ml/kg/min) (Figures 44 and 45). Average oxygen consumption during this scenario corresponded to 65 ± 10% of VO_{2peak} (range 45 to 84% of VO_{2peak}) (Figures 46 and 47). Mean VCO_2 during the task was 3337 ± 547 ml/min (range 2139 to 4372 ml/min) (Figure 43), while the average respiratory exchange ratio (RER) during the entire scenario was 1.13 ± 0.12 (range 0.93 to 1.36) (Figure 48). The respiratory exchange ratio was consistently above 1.0 throughout most of this scenario suggesting an increased contribution from anaerobic metabolism. Mean heart rate during the 5th floor high rise scenario was 160 ± 14 bpm (range 127 to 187 bpm), corresponding to 88 ± 6% of HR_{peak} (range 80 to 101% of HR_{peak}) (Figures 49 and 50). A complete summary for time, V_E, absolute (ml/min) and relative (ml/kg/min) VO_2, RER, and HR for individual tasks during the 5th floor high rise task can be found in Table 5.

Table 5: Summary for time, V_E, absolute and relative VO_2, RER, and HR for individual tasks during the 5th floor high rise scenario.

Task	Time (s)	V_E (L/min)	VO_2 (ml/min)	VO_2 (ml/kg/min)	$\%VO_{2peak}$	VCO_2 (ml/min)	RER	HR (bpm)	$\%HR_{peak}$
5 Floor Stair Ascent	71.3 ± 9.6	59.2 ± 10.8	2462 ± 319	27.7 ± 3.5	55 ± 9	2209 ± 332	0.90 ± 0.09	143 ± 16	79 ± 7
Hose Drag and Room Search	128.4 ± 40.0	91.9 ± 15.4	2834 ± 447	31.9 ± 4.4	63 ± 9	3385 ± 587	1.19 ± 0.13	160 ± 13	88 ± 6
Forcible Entry	11.6 ± 3.7	86.4 ± 14.6	2876 ± 510	32.3 ± 5.0	63 ± 10	3247 ± 557	1.14 ± 0.12	161 ± 14	88 ± 6
Rescue Drag	38.0 ± 7.5	91.3 ± 12.4	3174 ± 476	35.7 ± 5.0	70 ± 10	3320 ± 493	1.05 ± 0.09	165 ± 12	91 ± 5
5 Floor Stair Descent	54.1 ± 11.3	90.4 ± 14.8	3098 ± 543	34.8 ± 5.6	68 ± 12	3463 ± 607	1.13 ± 0.11	163 ± 14	89 ± 6

Values are Mean ± S.D.

Note: Values for the 5 Floor Stair Ascent, Forcible Entry, Rescue Drag, and 5 Floor Stair Descent are averaged over the entire duration of the task.

Hose Drag and Room Search average values do not include the first room search and hose drag.

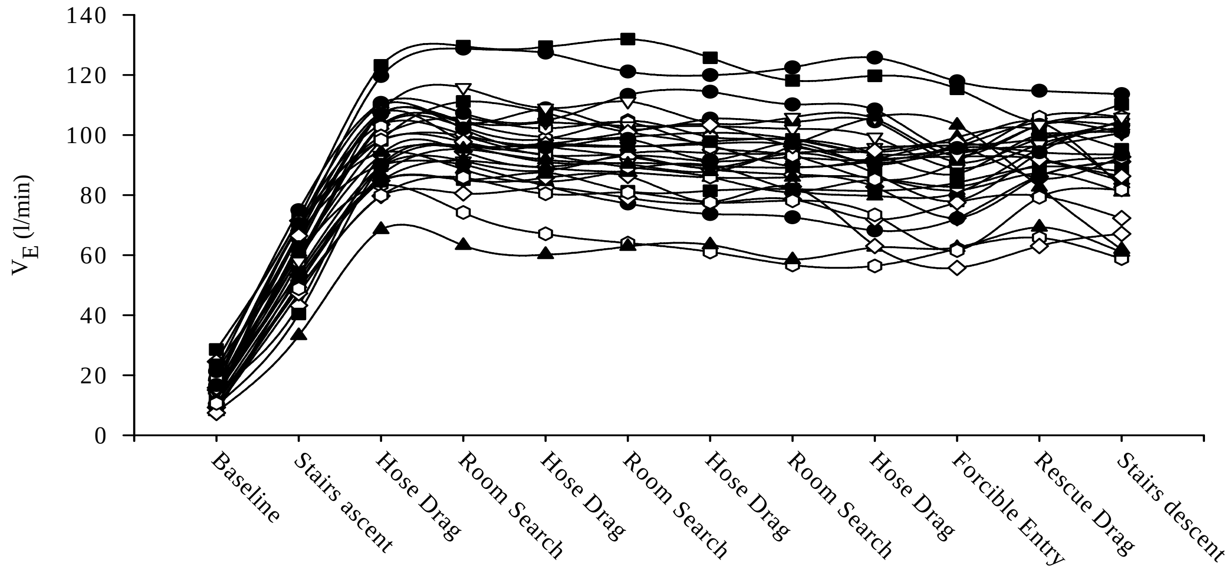

Figure 40: Individual V_E for each task during the 5th floor high rise scenario.

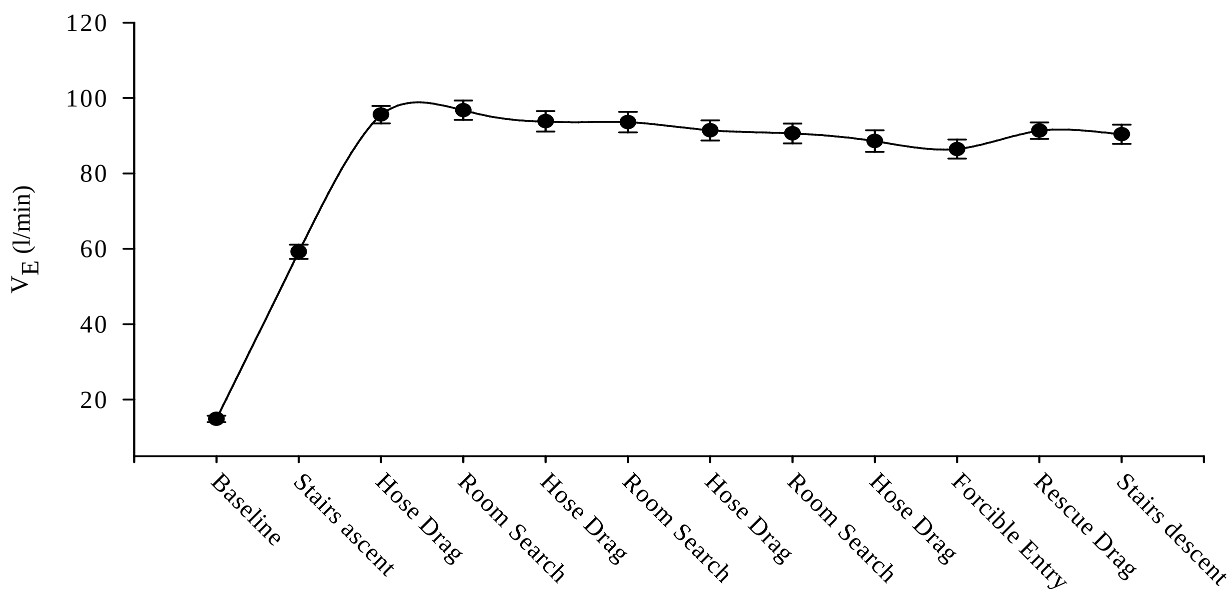

Figure 41: Average V_E for each task during the 5th floor high rise scenario.
Values are mean ± S.E.M.

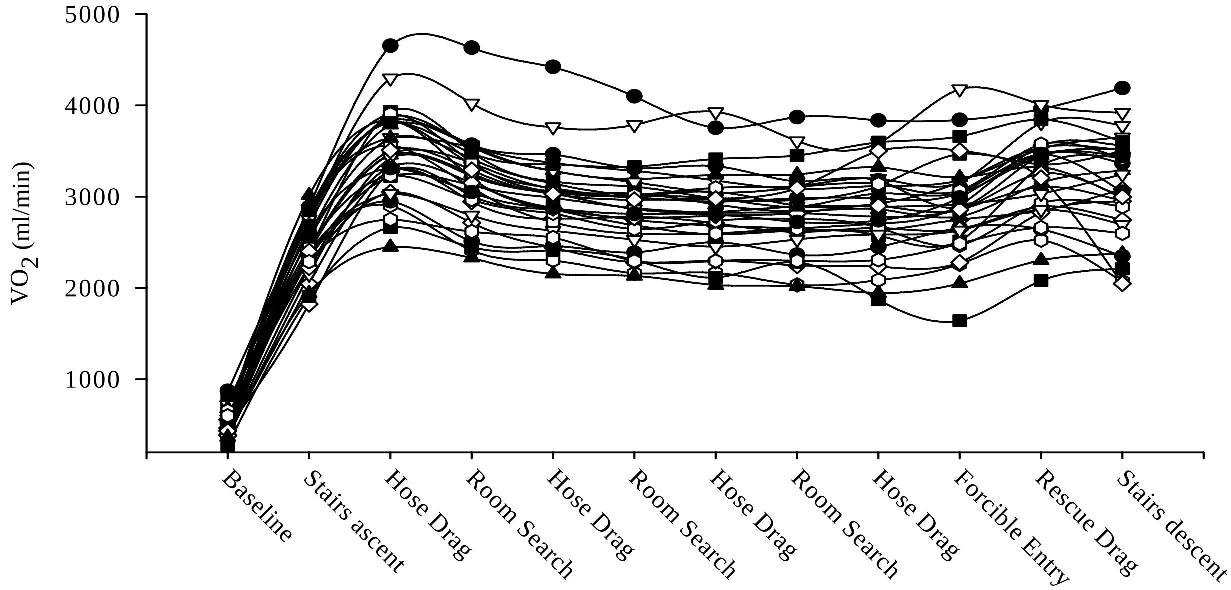

Figure 42: Absolute VO_2 (ml/min) for each task during the 5th floor high rise scenario.

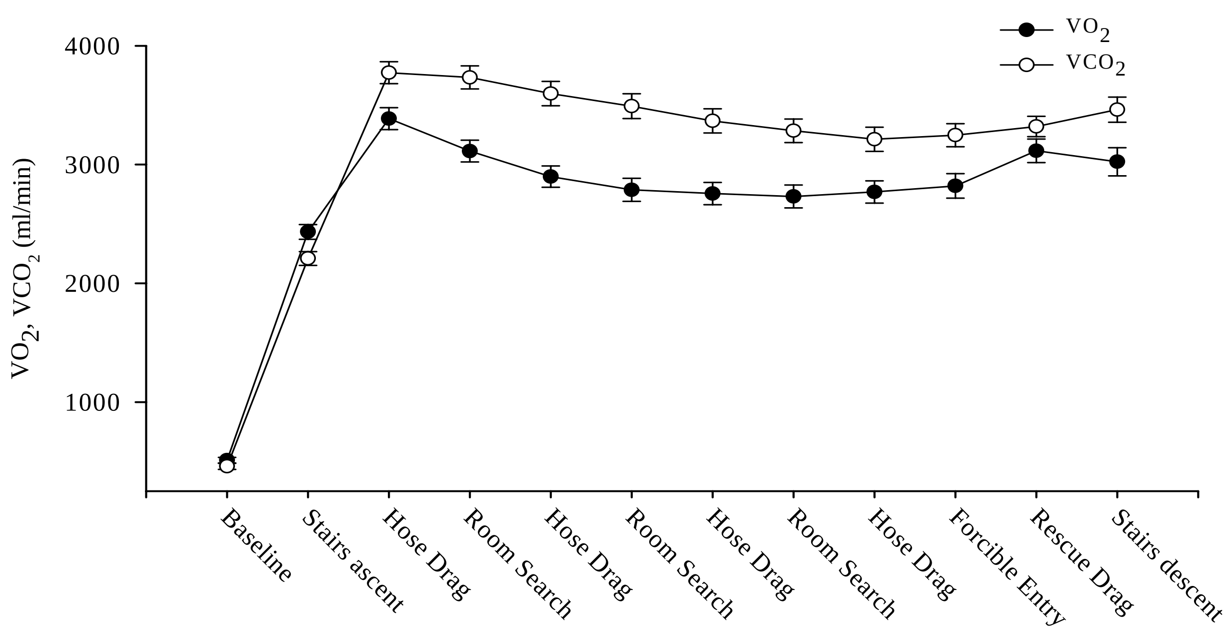

Figure 43: Average VO_2 (ml/min) and VCO_2 (ml/min) for each task during the 5th floor high rise scenario.
Values are mean ± S.E.M.

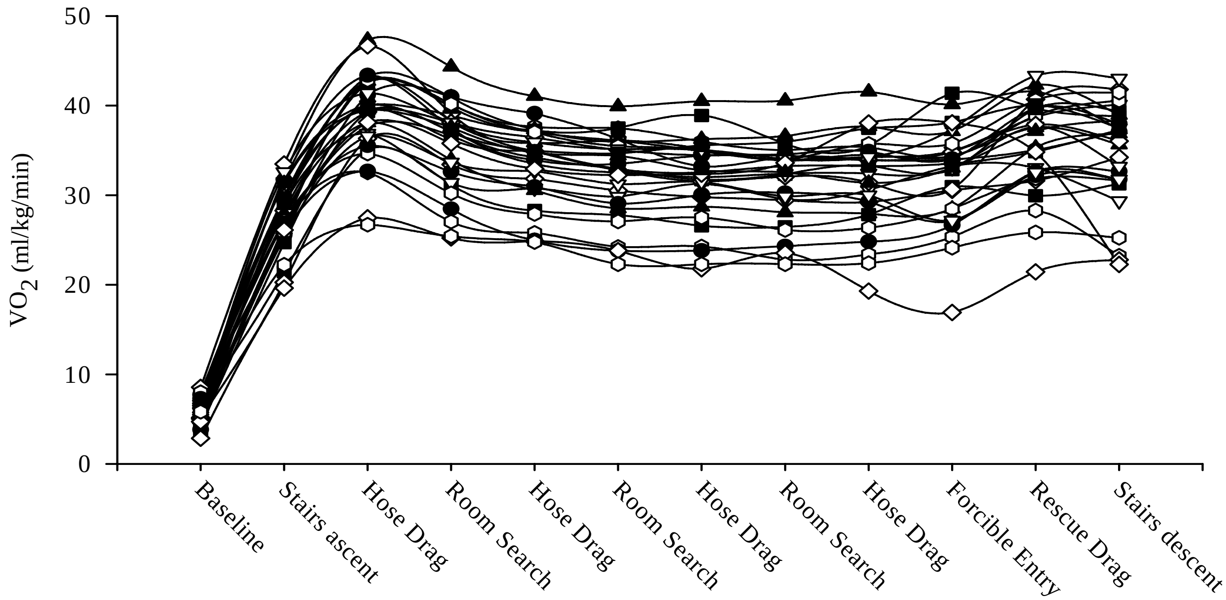

Figure 44: Relative VO_2 (ml/kg/min) values for each task during the 5th floor high rise scenario.

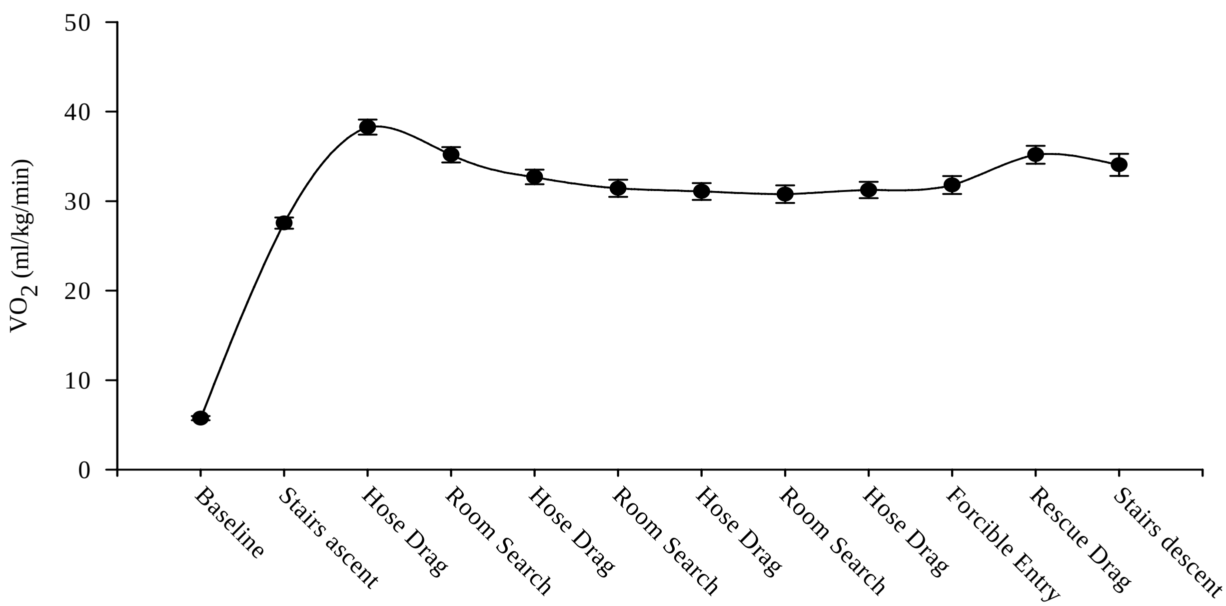

Figure 45: Average VO_2 (ml/kg/min) values for each task during the 5th floor high rise scenario. Values are mean ± S.E.M.

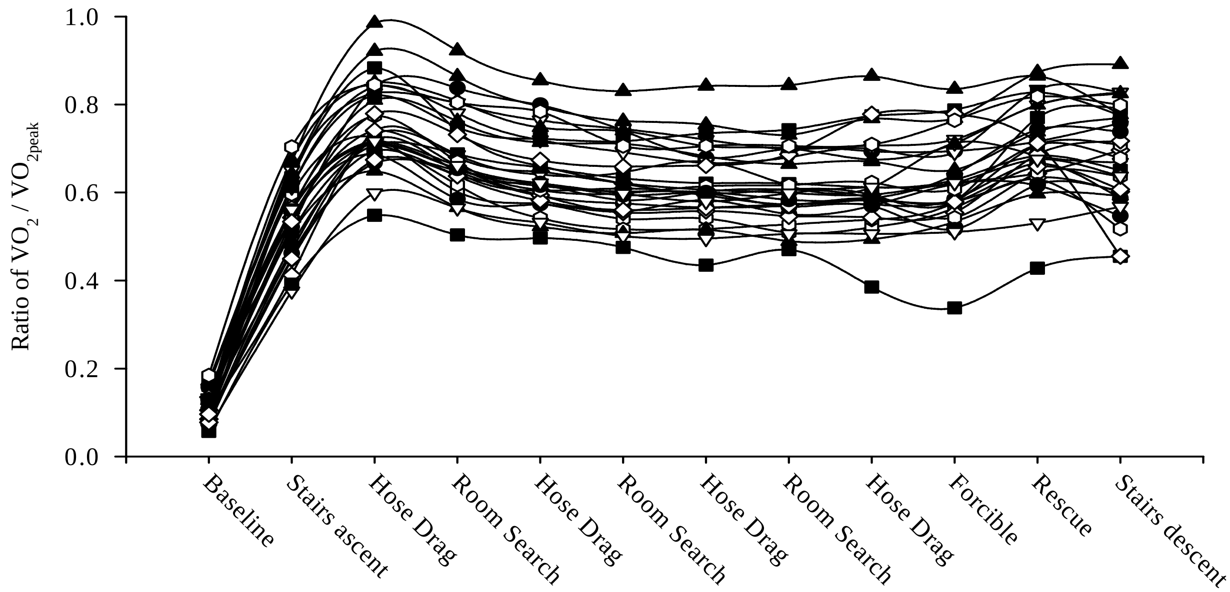

Figure 46: Individual average ratio of VO_2 during the 5th floor high rise scenario to VO_{2peak} values for each task.

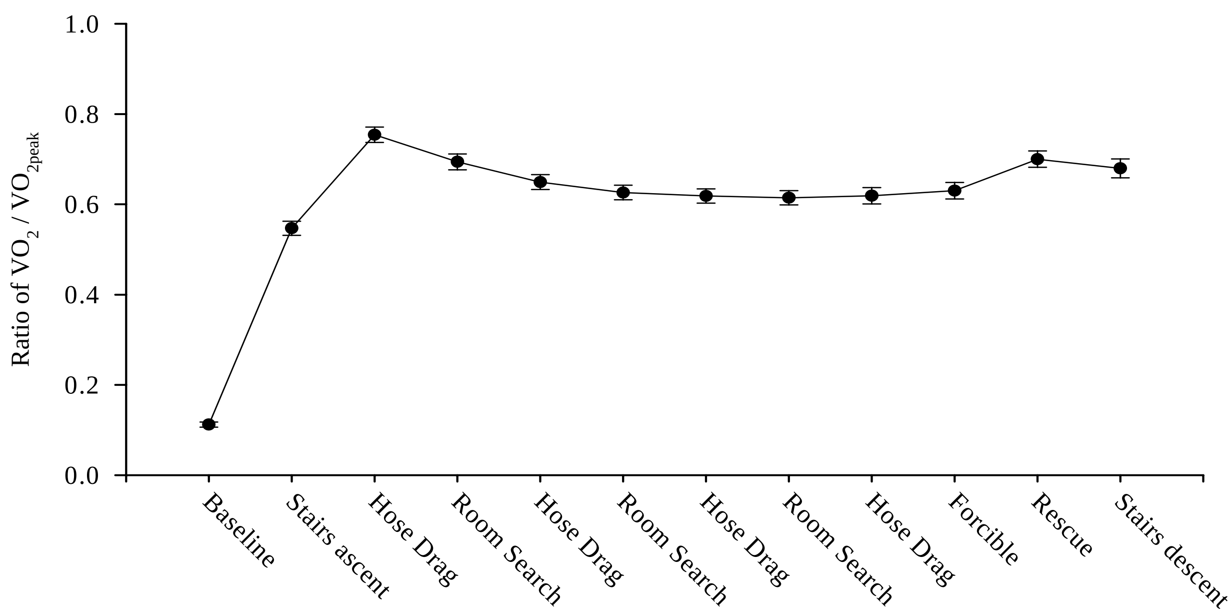

Figure 47: Average ratio of VO_2 during the 5th floor high rise scenario to VO_{2peak} values for each task. Values are mean ± S.E.M.

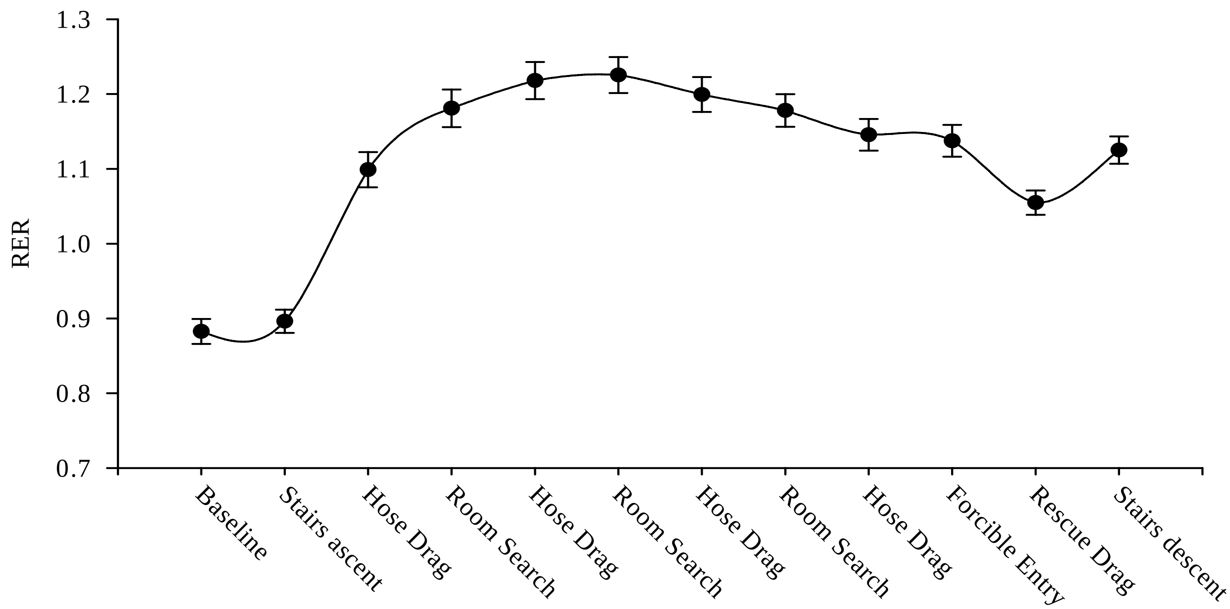

Figure 48: Average RER values for each task during the 5th floor high rise scenario. Values are mean ± S.E.M.

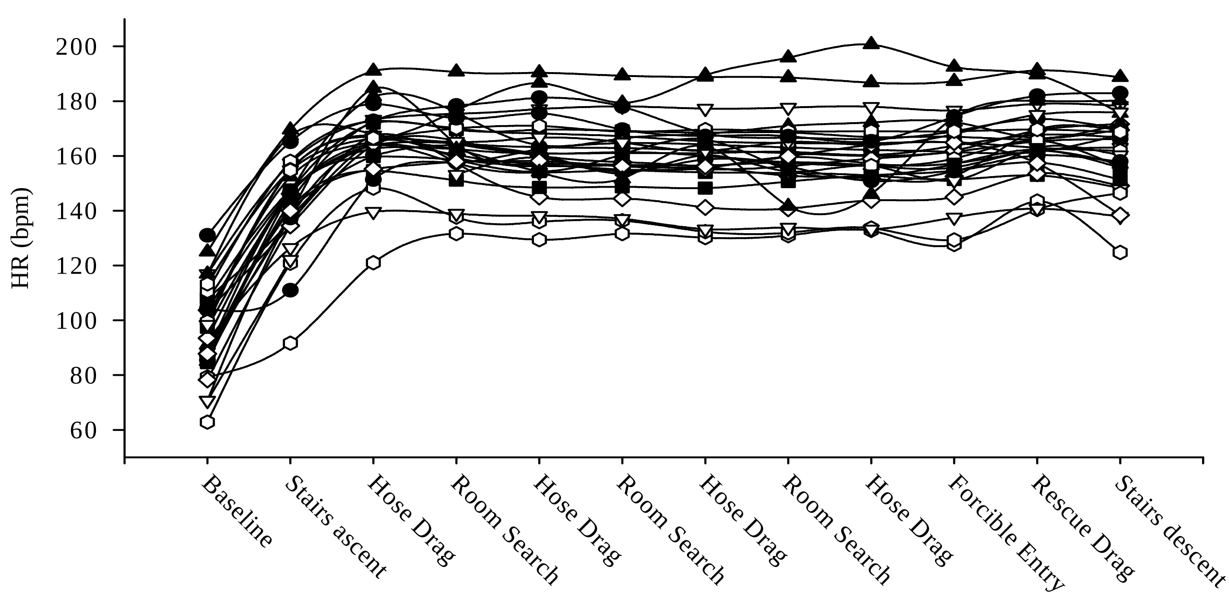

Figure 49: Individual heart rate values for each task during the 5th floor high rise scenario. Values are mean ± S.E.M.

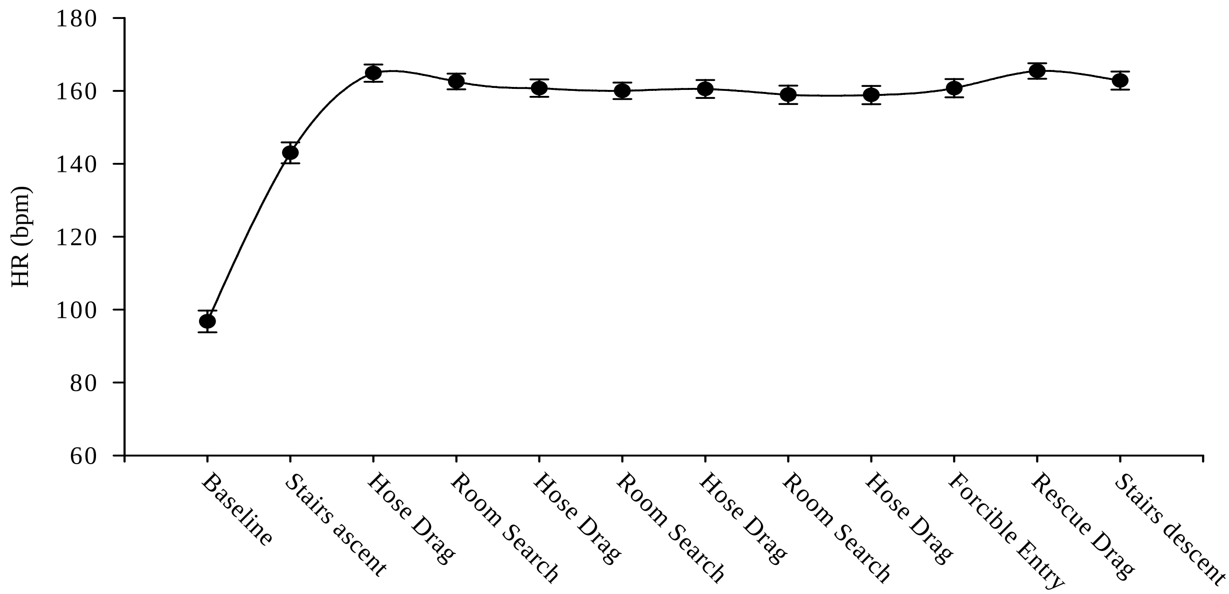

Figure 50: Average heart rate values for each task during the 5th floor high rise scenario. Values are mean ± S.E.M.

Average air cylinder pressure at the start of the 5^{th} floor high rise scenario was 4169 ± 254 psi (range 3670 to 4690 psi), while at the completion of the scenario it was 2171 ± 357 psi (range 1320 to 3020 psi). Mean air consumption from the total contained in the air cylinder during the 5^{th} floor high rise scenario was 48.0 ± 7.0% (range 33.9 to 67.6%). None of the firefighters consumed greater than 75% of their air cylinder during this task, thus, their 25% low-air alarm was never activated. Firefighters' age ($r = 0.61$, $p < 0.05$) (Figure 51) and years of service as a firefighter ($r = 0.47$, $p < 0.05$) (Figure 52) revealed significant relationships with total air consumption. Furthermore, body mass ($r = 0.36$, $p < 0.05$) (Figure 53) and average relative VO_2 during the 5^{th} floor high rise scenario ($r = -0.48$, $p < 0.05$) (Figure 54) showed significant correlations with total air consumption.

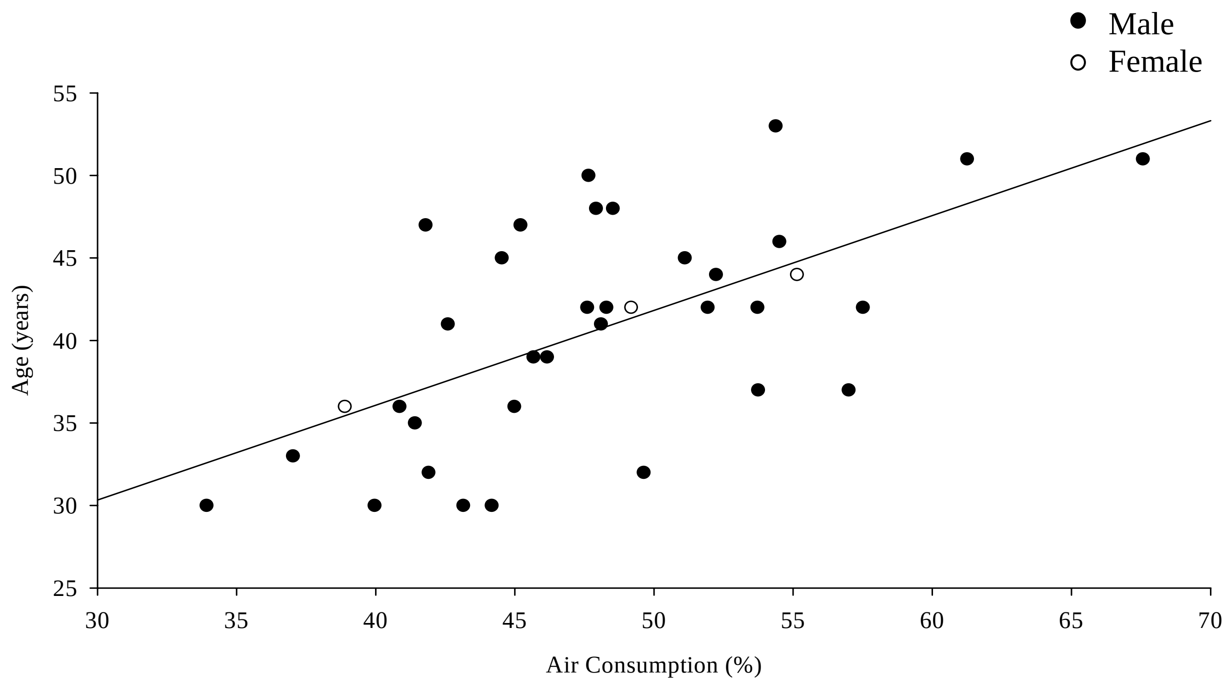

Figure 51: Relationship between firefighters' age and air consumption during the 5th floor high rise task (r = 0.61, p < 0.05).

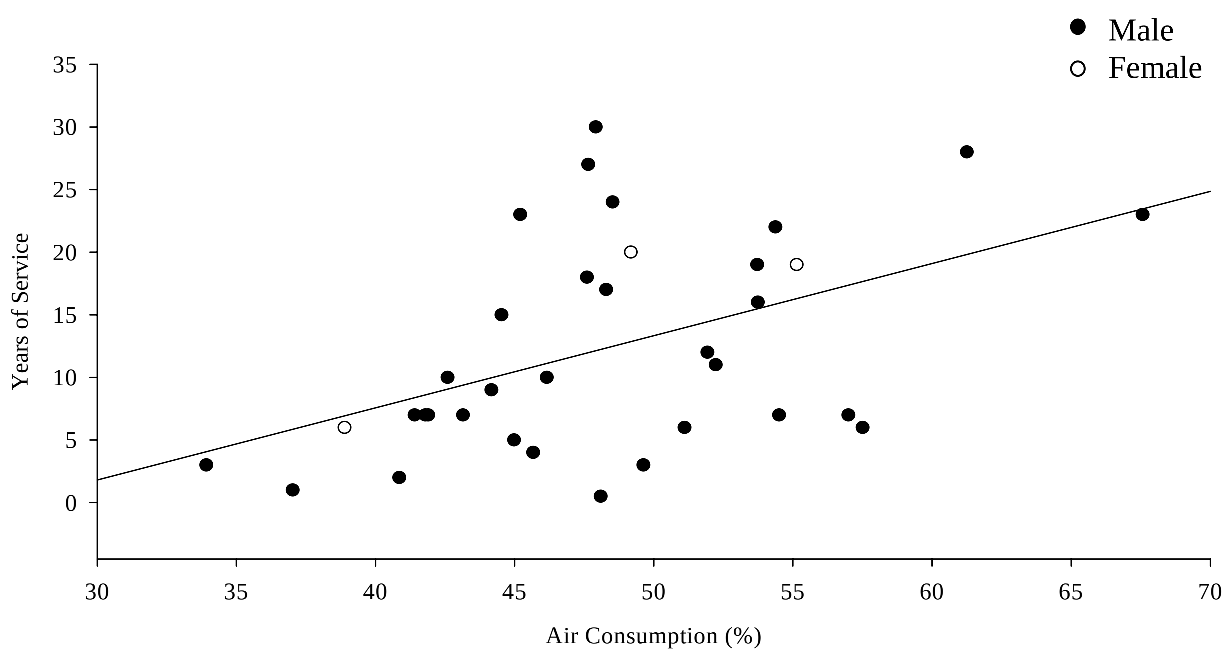

Figure 52: Relationship between years of service as a firefighter and air consumption during the 5th floor high rise scenario (r = 0.47, p < 0.05).

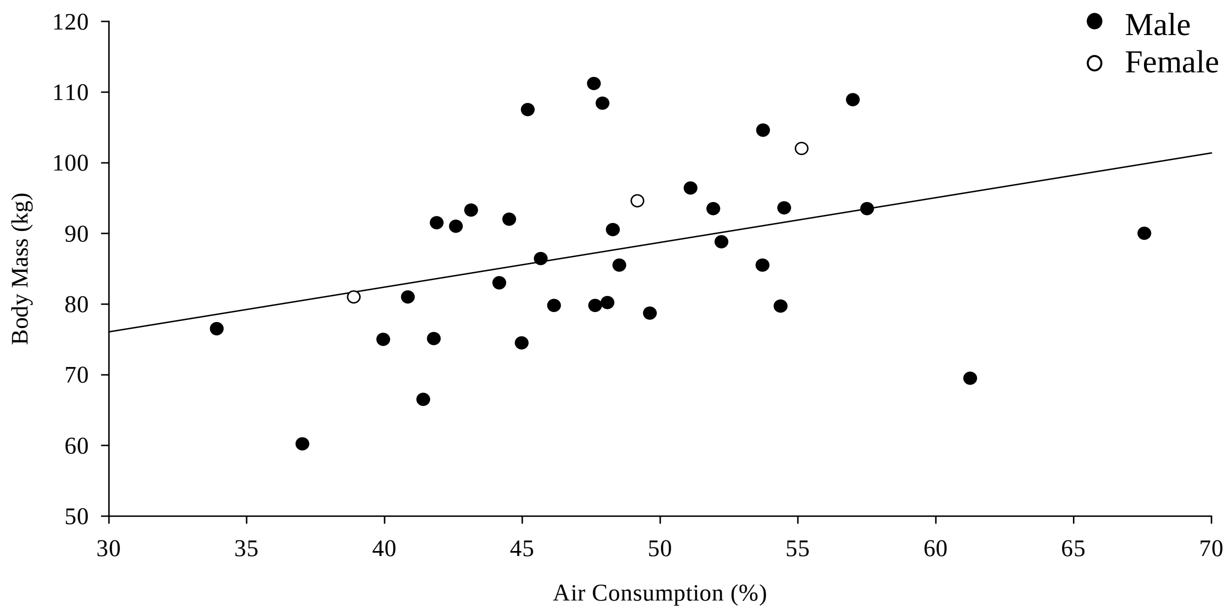

Figure 53: Relationship between body mass and air consumption during the 5th floor high rise scenario ($r = 0.36$, $p < 0.05$).

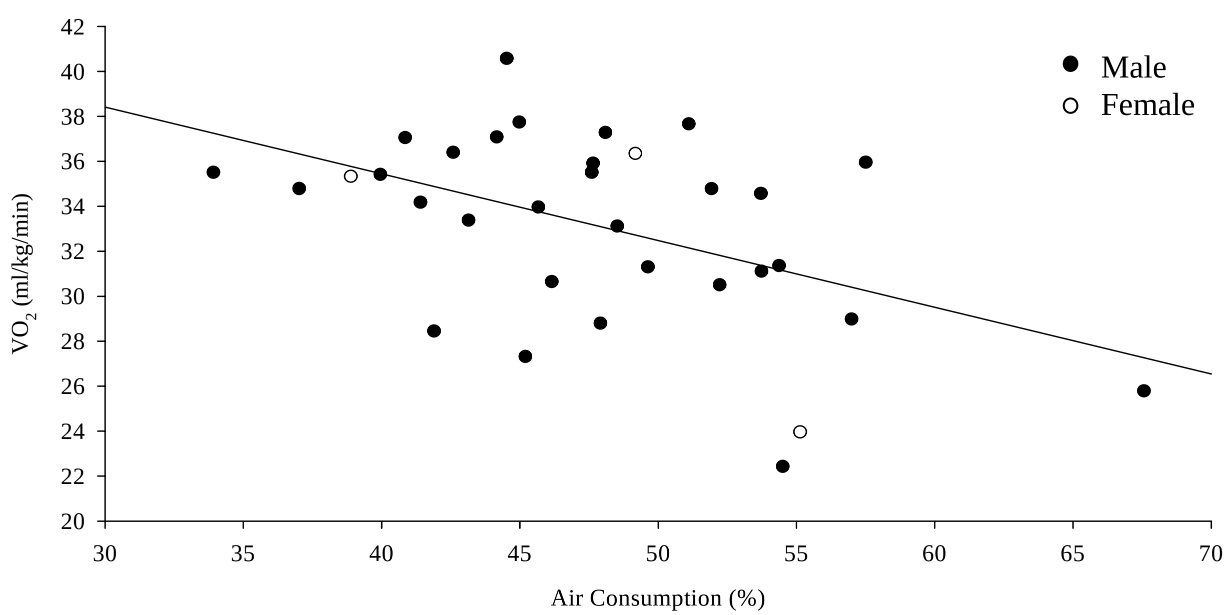

Figure 54: Relationship between VO_2 (ml/kg/min) during the 5th floor high rise scenario and air consumption ($r = -0.48$, $p < 0.05$).

4.5 Subway System Scenario

Data sets from 3 subjects were unable to be analyzed due to technical difficulties with gas collection analysis during the tests resulting in 33 firefighters being incorporated into this portion of the analysis. Mean completion time for this scenario was 12 min 5s ± 1 min 10 s. Average expired ventilation during the entire scenario was 55.5 ± 10.0 l/min (range 44.4 to 79.8 l/min) (Figures 55 and 56). Mean VO_2 during the subway scenario was 2217 ± 371 ml/min (range 1445 to 3048 ml/min) (Figures 57 and 58) and 25.2 ± 4.6 ml/kg/min (range 17.9 to 33.4 ml/kg/min) (Figures 59 and 60), corresponding to 49 ± 8% of VO_{2peak} (range 39 to 68% of VO_{2peak}) (Figures 61 and 62). Average VCO_2 during the subway scenario was 2102 ± 412 ml/min (range 1466 to 2933 ml/min) (Figure 58), while mean respiratory exchange ratio was 0.95 ± 0.09 (range 0.70 to 1.06) (Figure 63). Average heart rate during the entire scenario was 139 ± 17 bpm (range 102 to 167 bpm) (Figures 64 and 65), corresponding to 76 ± 7% of HR_{peak} (66 to 91 % of HR_{peak}). A complete summary for time, V_E, absolute (ml/min) and relative (ml/kg/min) VO_2, RER, and HR for individual tasks during the subway scenario can be found in Table 6.

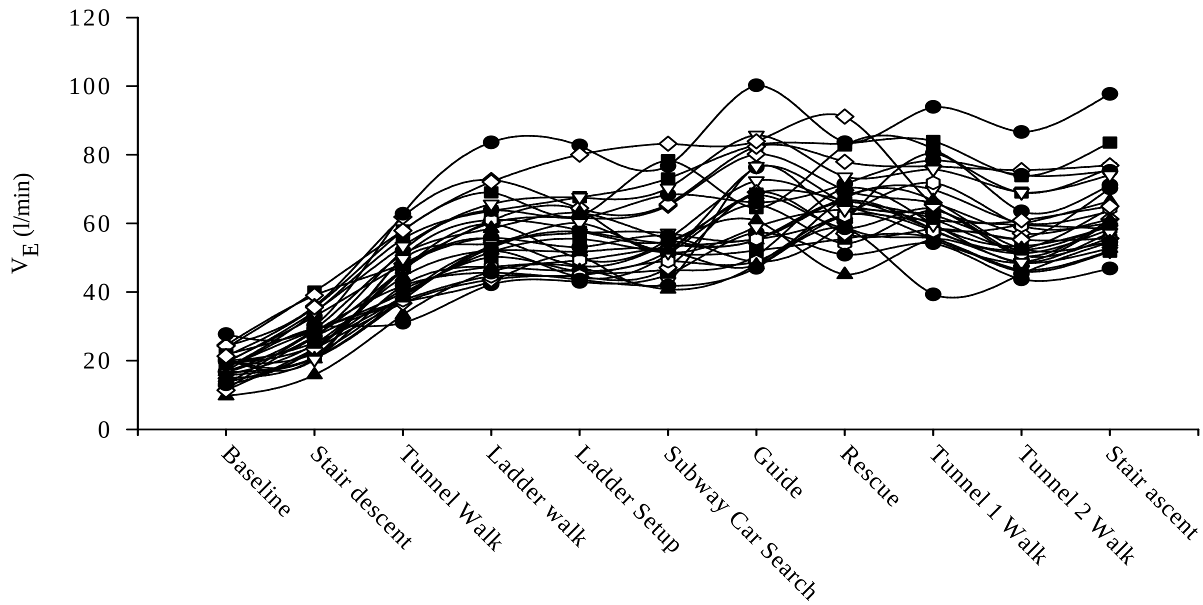

Figure 55: Individual V_E for each task during the subway scenario.

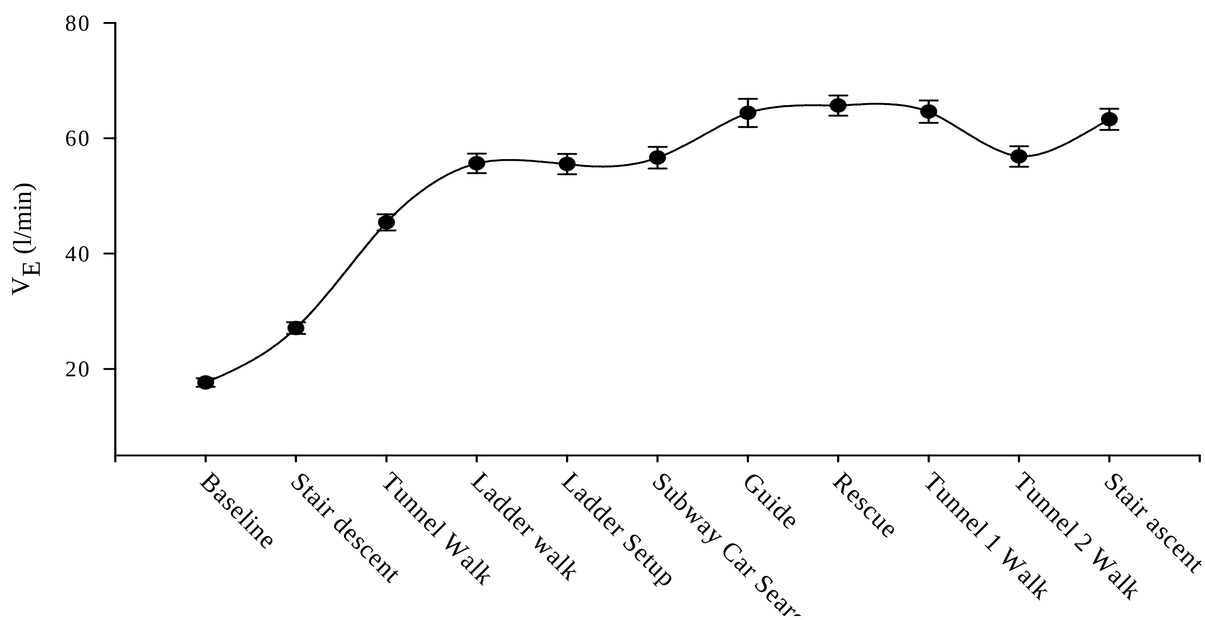

Figure 56: Average V_E for each task during the subway scenario.
Values are mean ± S.E.M.

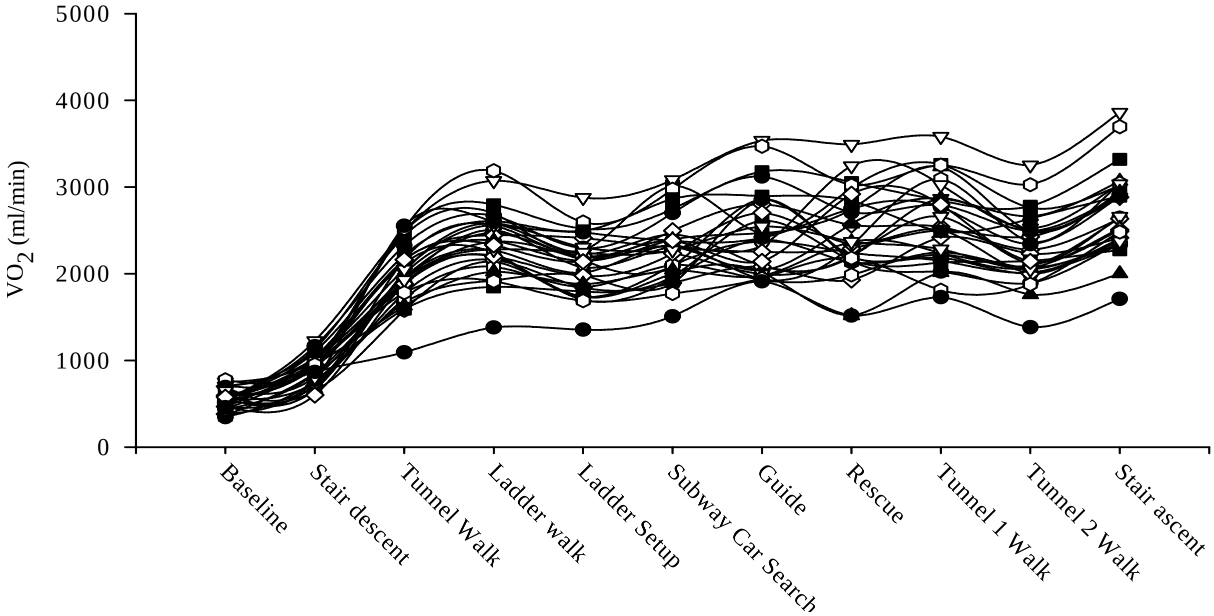

Figure 57: Individual VO_2 (ml/min) for each task during the subway scenario.

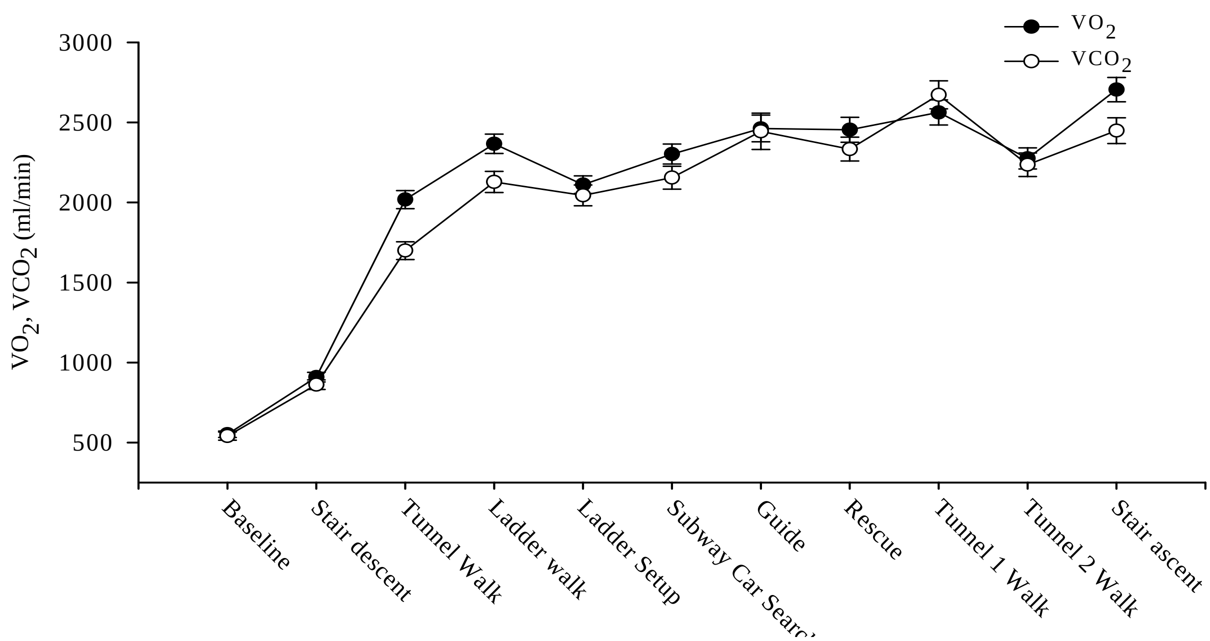

Figure 58: Average VO_2 (ml/min) and VCO_2 (ml/min) for each task during the subway scenario. Values are mean ± S.E.M.

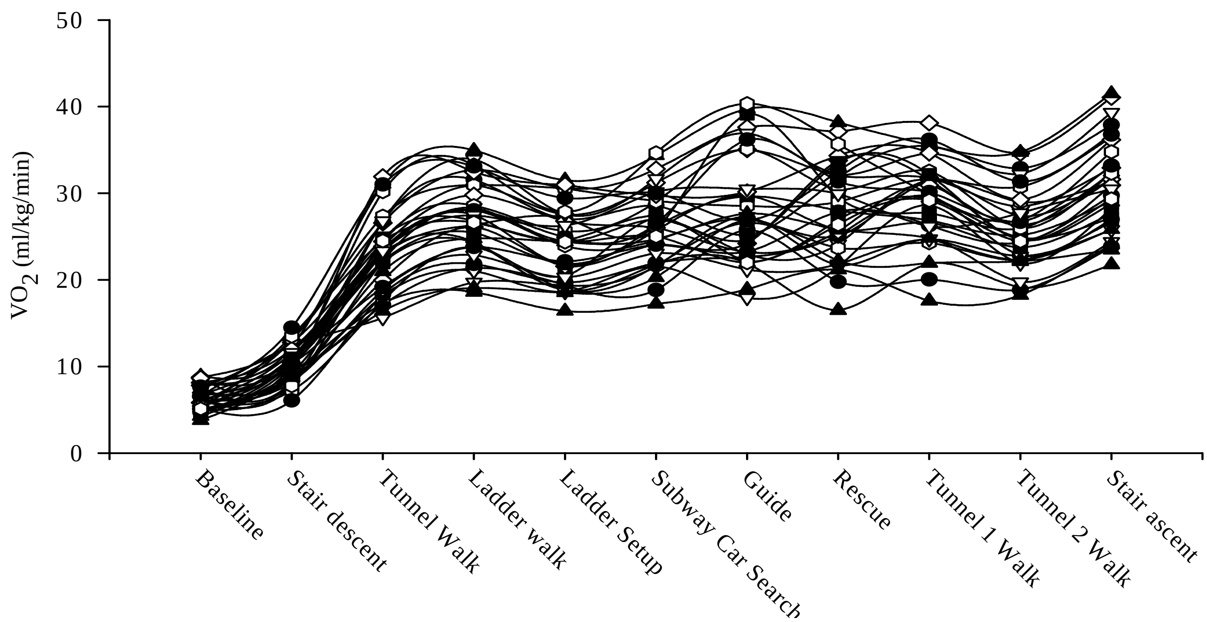

Figure 59: Individual VO_2 (ml/kg/min) for each task during the subway scenario.

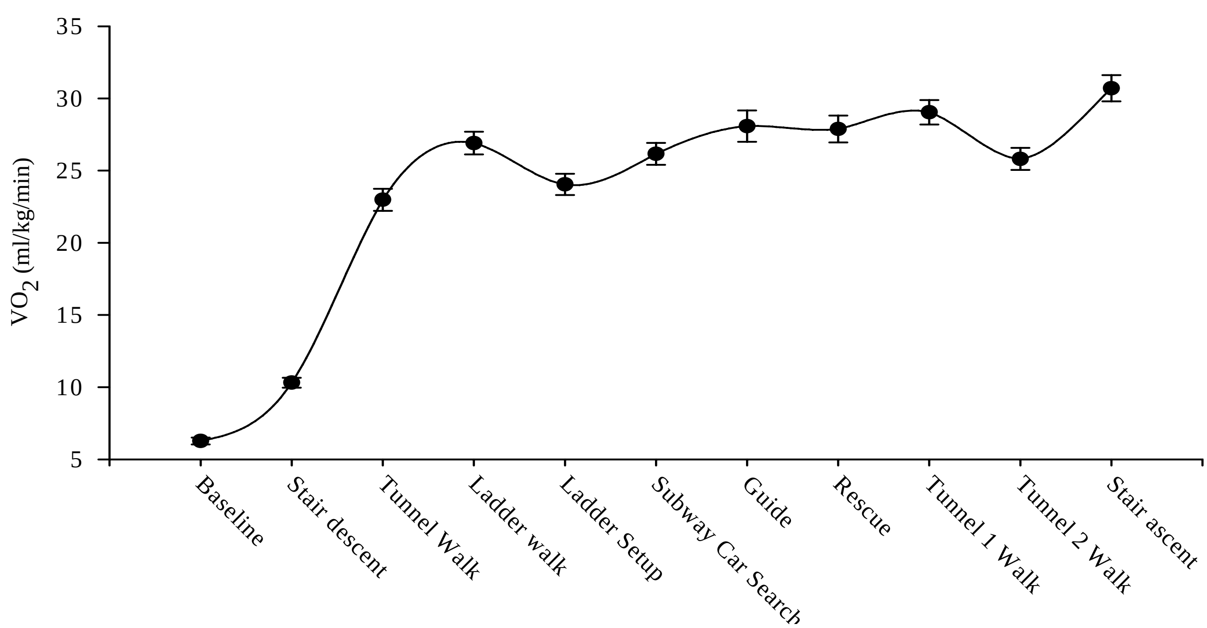

Figure 60: Average VO_2 (ml/kg/min) for each task during the subway scenario. Values are mean ± S.E.M.

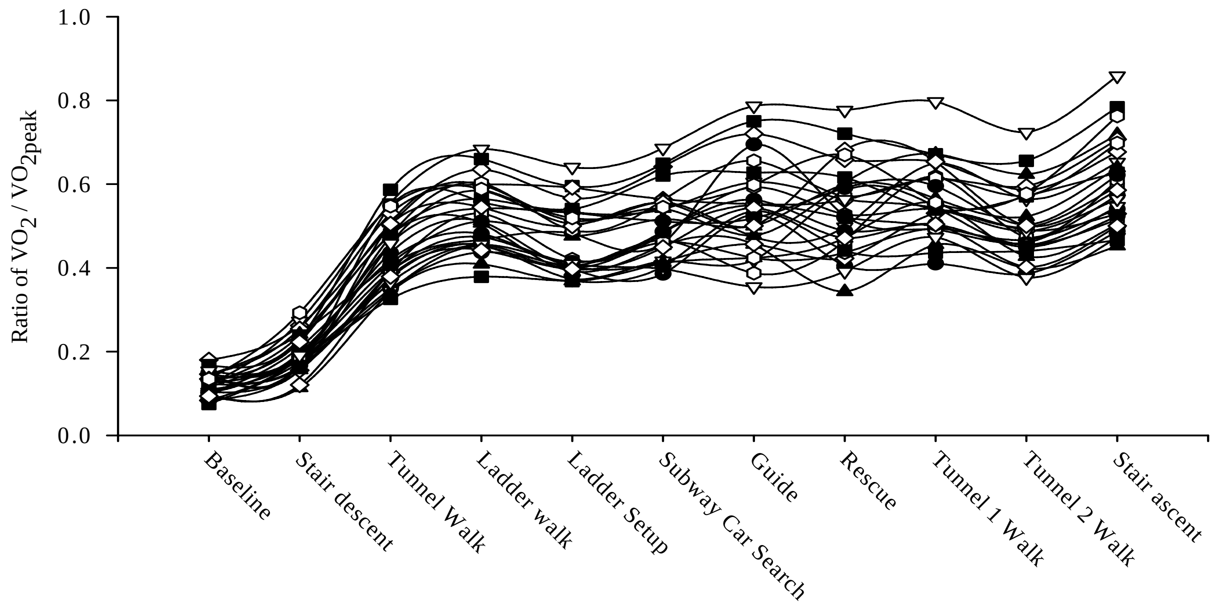

Figure 61: Individual ratio of VO_2 during the subway scenario to VO_{2peak} for each task.

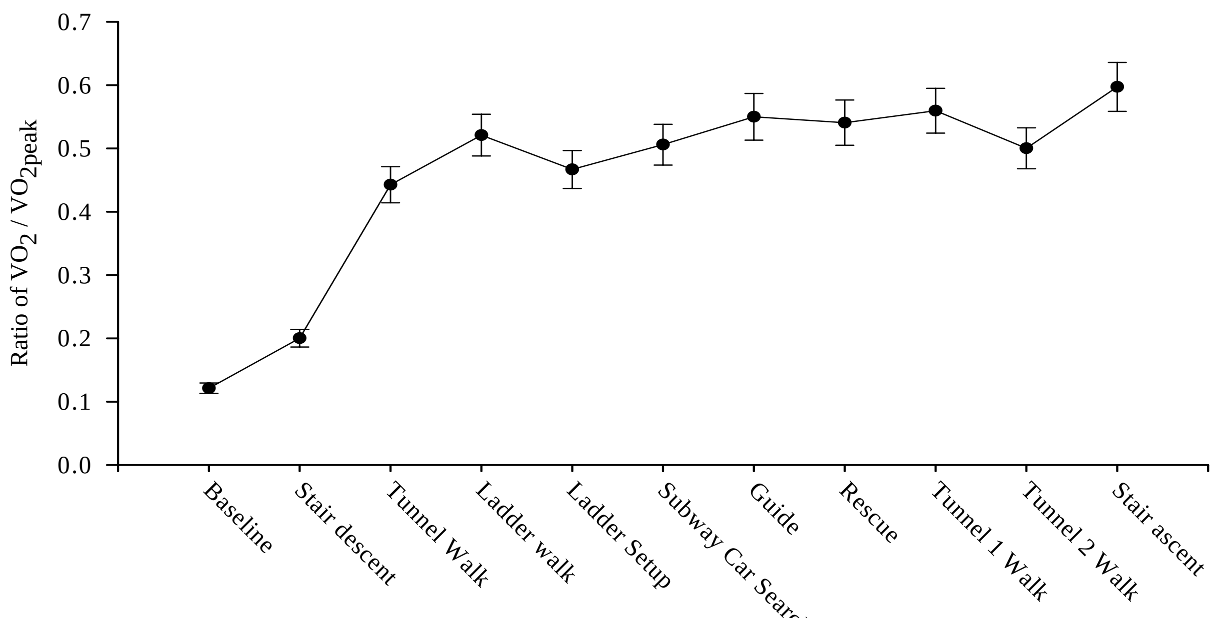

Figure 62: Average ratio of VO_2 during the subway scenario to VO_{2peak} for each task. Values are mean ± S.E.M.

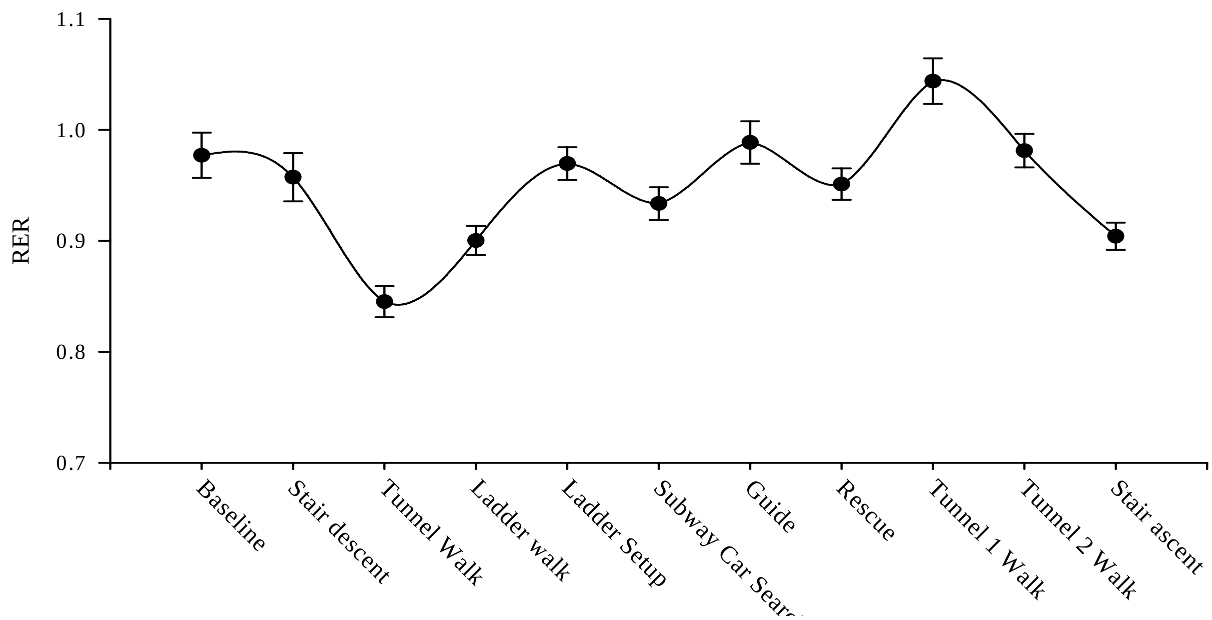

Figure 63: Average respiratory exchange ratio (RER) for each task during the subway scenario. Values are mean ± S.E.M.

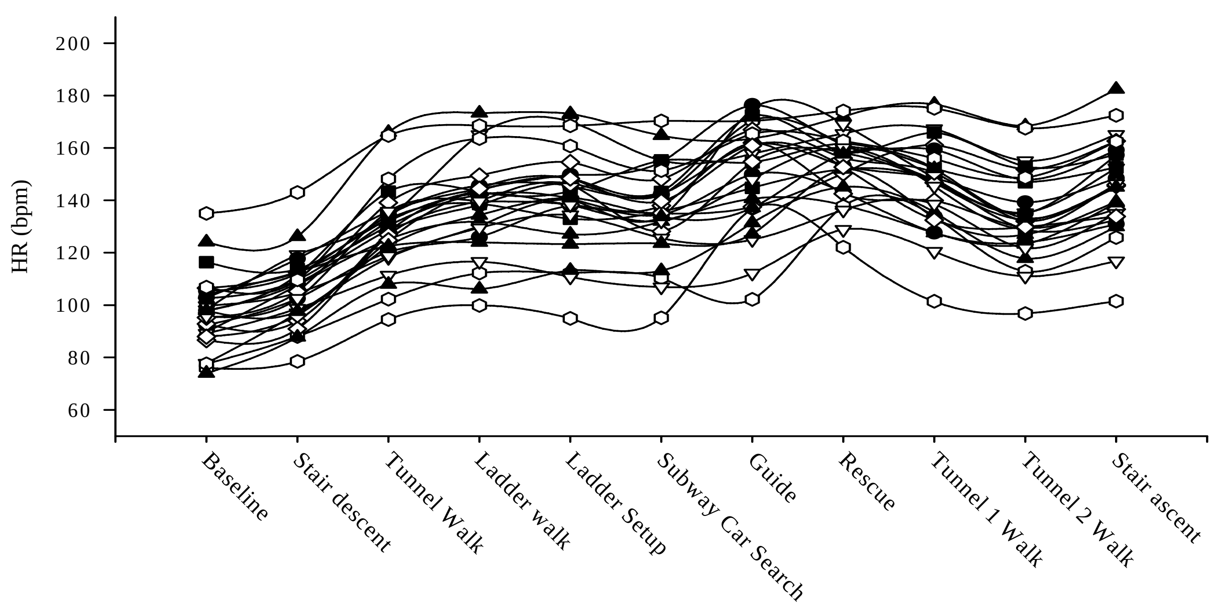

Figure 64: Individual heart rate (bpm) for each task during the subway scenario.

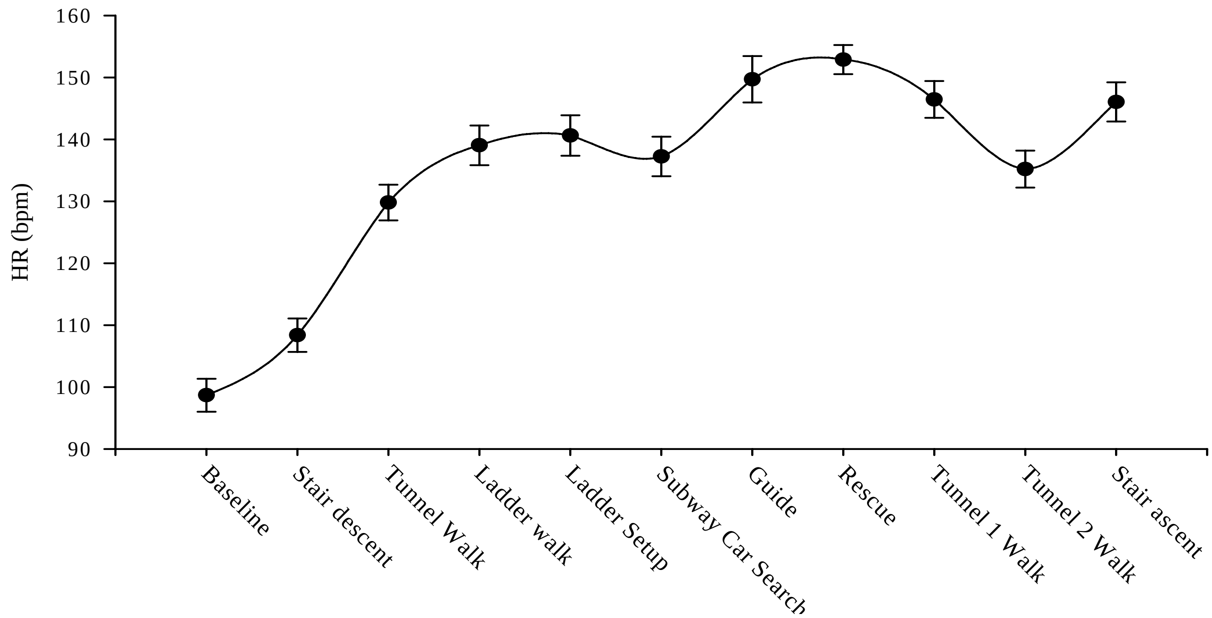

Figure 65: Average heart rate (bpm) for each task during the subway scenario. Values are mean ± S.E.M.

Table 6: Summary for V_E, absolute and relative VO_2, VCO_2, RER, and HR for each task during the subway system scenario.

Task	Time (s)	V_E (l/min)	VO_2 (ml/min)	VO_2 (ml/kg/min)	$\%VO_{2peak}$	VCO_2 (ml/min)	RER	HR (bpm)	$\%HR_{peak}$
Baseline	125 ± 3	17.6 ± 4.2	552 ± 114	6.3 ± 1.4	12 ± 2.6	541 ± 147	0.98 ± 0.12	99 ± 15	54 ± 7
Stair Descent	14 ± 4	27.1 ± 5.9	909 ± 173	10.3 ± 2.0	20 ± 4.5	862 ± 172	0.96 ± 0.13	108 ± 15	60 ± 7
Tunnel Walk	182 ± 19	45.4 ± 8.0	2018 ± 321	23.0 ± 4.4	44 ± 8	1699 ± 317	0.85 ± 0.08	130 ± 16	72 ± 7
Ladder Walk	85 ± 19	55.6 ± 9.7	2366 ± 350	26.9 ± 4.5	52 ± 8	2128 ± 377	0.90 ± 0.08	139 ± 18	76 ± 8
Setup Ladder	76 ± 16	55.5 ± 10.1	2111 ± 314	24.0 ± 4.2	47 ± 8	2044 ± 374	0.97 ± 0.08	141 ± 18	78 ± 7
Subway Car Search	51 ± 6	56.6 ± 10.8	2303 ± 359	26.2 ± 4.3	51 ± 8	2155 ± 412	0.93 ± 0.08	137 ± 18	76 ± 7
Firefighter A Rescue	45 ± 30	66.5 ± 12.5	2441 ± 518	28.2 ± 6.1	54 ± 10	2359 ± 556	0.96 ± 0.07	163 ± 13	83 ± 22
Firefighter B Guide	51 ± 12	53.0 ± 6.3	2127 ± 193	24.0 ± 3.3	47 ± 7	1934 ± 187	0.91 ± 0.08	137 ± 20	76 ± 8
Firefighter A Guide	42 ± 39	75.1 ± 10.4	2778 ± 456	32.1 ± 5.7	62 ± 9	2939 ± 528	1.06 ± 0.08	154 ± 13	79 ± 20
Firefighter B Rescue	35 ± 9	64.7 ± 6.6	2468 ± 371	27.2 ± 4.3	54 ± 9	2280 ± 238	0.93 ± 0.09	152 ± 14	84 ± 6
Tunnel 1 Walk	79 ± 8	64.6 ± 11.1	2563 ± 452	29.0 ± 4.9	56 ± 8	2672 ± 505	1.04 ± 0.12	146 ± 17	80 ± 6
Tunnel 2 Walk	142 ± 15	56.8 ± 10.3	2275 ± 379	25.8 ± 4.4	50 ± 8	2236 ± 423	0.98 ± 0.09	135 ± 17	74 ± 7
Stair Ascent	13 ± 3	63.3 ± 10.5	2705 ± 438	30.7 ± 5.2	60 ± 10	2449 ± 460	0.90 ± 0.07	146 ± 18	80 ± 6

Values are Mean ± S.D.

Average air cylinder pressure at the start of the subway scenario was 4256 ± 202 psi (range 3500 to 4560 psi), while at the completion of the scenario the air cylinder pressure was 1704 ± 245 psi (range 1180 to 2170 psi). Mean air consumption during the entire subway scenario was 59.9 ± 5.6% (range 49.4 to 72.8%). No firefighter had a total air consumption of greater than 75% of their air cylinder meaning that none of the firefighters' 25% low-air alarms were activated. Firefighters' age ($r = 0.54$, $p < 0.05$) (Figure 66) and years of service as a firefighter ($r = 0.56$, $p < 0.05$) (Figure 67) revealed a significant relationship with the total air consumed from the air cylinder during the subway scenario. Firefighters' body mass ($r = 0.61$, $p < 0.05$) (Figure 68), body mass index ($r = 0.54$, $p < 0.05$), and body fat percent ($r = 0.45$, $p < 0.05$) revealed significant individual relationships with the total air consumption during the subway scenario. Relative VO_{2peak} (ml/kg/min) ($r = -0.48$, $p < 0.05$) (Figure 69) and average VO_2 (ml/kg/min) ($r = -0.38$, $p < 0.05$) (Figure 70) during the subway scenario revealed significant individual correlations with total air consumed from the air cylinder. Mean expired ventilation during the subway scenario revealed a significant relationship with the total air consumption from the air cylinder ($r = 0.57$, $p < 0.05$) (Figure 71).

Comparing all three scenarios in terms of their physical demands, significant differences in relative VO_2 during the scenarios were seen between the maximal stair climb and both the 5th floor and subway scenarios, as well as between the 5th floor and subway scenario ($p < 0.05$). Significant differences in heart rate were observed between the maximal high rise and subway scenario, as well as the 5th floor and subway scenario ($p < 0.05$). Similar significant differences were shown with V_E between the maximal stair climb and subway scenario, as well as the 5th floor and subway scenario ($p < 0.05$) (Table 7).

Based on the linear regressions with total air consumption and years of service as a firefighter, two groups were established based on the median years of service of 10 years (range 0.5 to 30 years). Running a One-way ANOVA for total air consumption by years of service, significant differences were shown for each of the three scenarios (Table 8).

Table 7: Average values for V_E, relative VO_2, and HR for each of the scenarios

Scenario	**V_E (l/min)**	**VO_2 (ml/kg/min)**	**HR (bpm)**
Maximal Stair Climb	86.3 ± 16.7 ^{a}	35.5 ± 9.1 ^{a}	162 ± 11 ^{a}
5th Floor High Rise	88.9 ± 14.4 ^{a}	33.1 ± 4.6 ^{b}	160 ± 14 ^{a}
Subway	55.5 ± 10.0 ^{b}	25.2 ± 4.6 ^{c}	139 ± 17 ^{b}

Mean ± S.D.
Values in a column not sharing the same letter are significantly different. $p < 0.05$.

Table 8: Average air consumption for each of the scenarios grouped by years of service as a firefighter

Years of Service	**Maximal Stair Climb (%)**	**5th Floor High Rise (%)**	**Subway (%)**
0 – 10 years	72.5 ± 6.1†	45.0 ± 6.4†	56.9 ± 4.3†
> 11 years	77.8 ± 4.6	51.8 ± 6.0	64.2 ± 4.2

Mean ± S.D.
† - Significant difference from > 11 years group. $p < 0.05$.

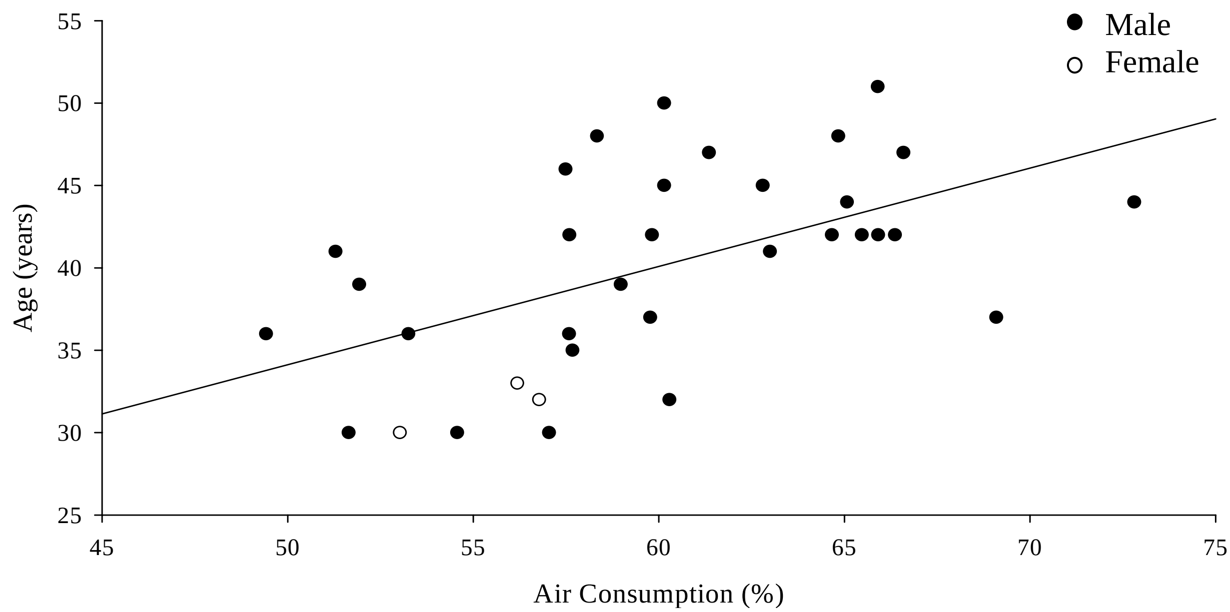

Figure 66: Relationship between firefighters' age and total air consumption from the air cylinder during the subway scenario (r = 0.54, p < 0.05).

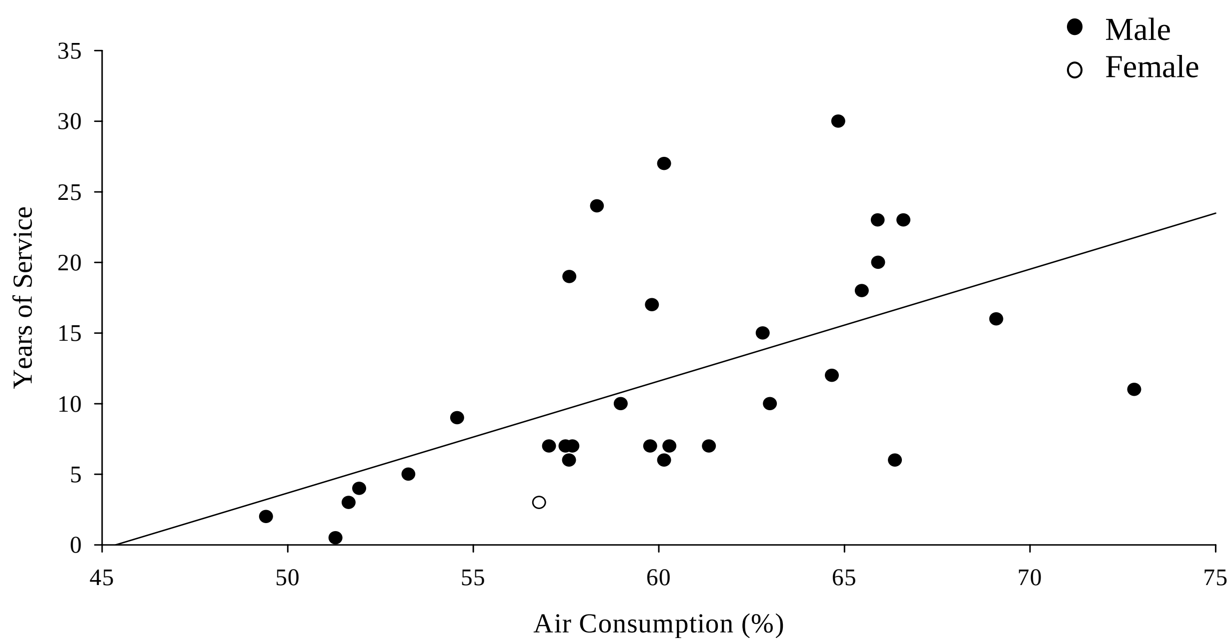

Figure 67: Relationship between years of service as a firefighter and total air consumption from the air cylinder during the subway scenario (r = 0.56, p < 0.05).

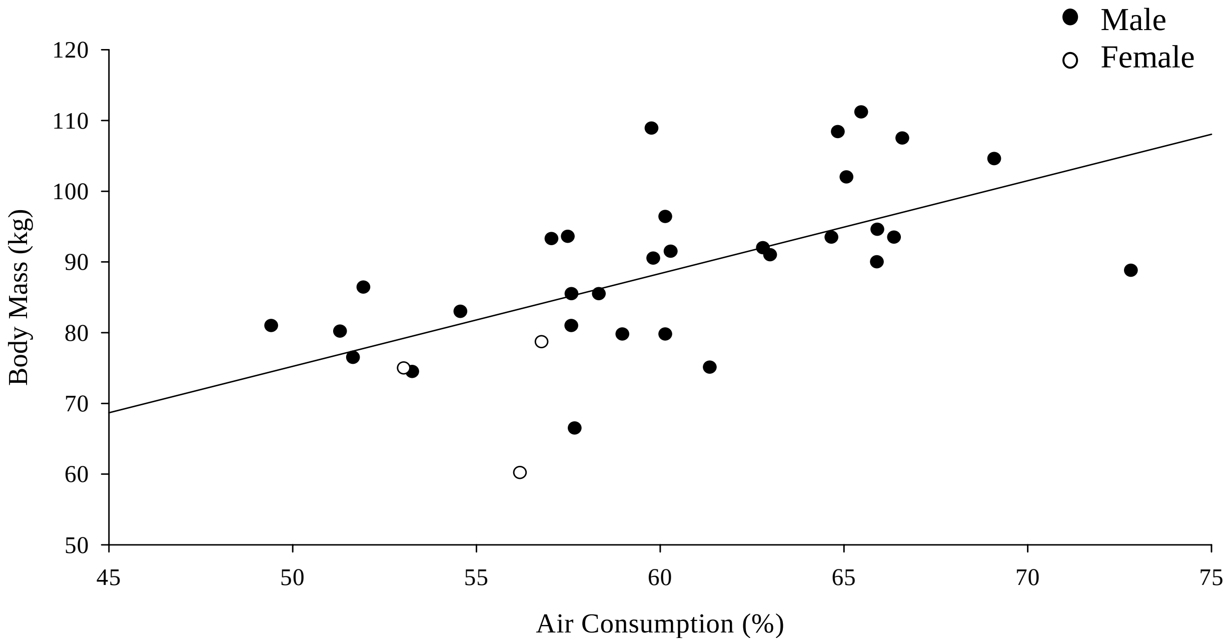

Figure 68: Relationship between body mass and total air consumption from the air cylinder during the subway scenario (r = 0.61, p < 0.05).

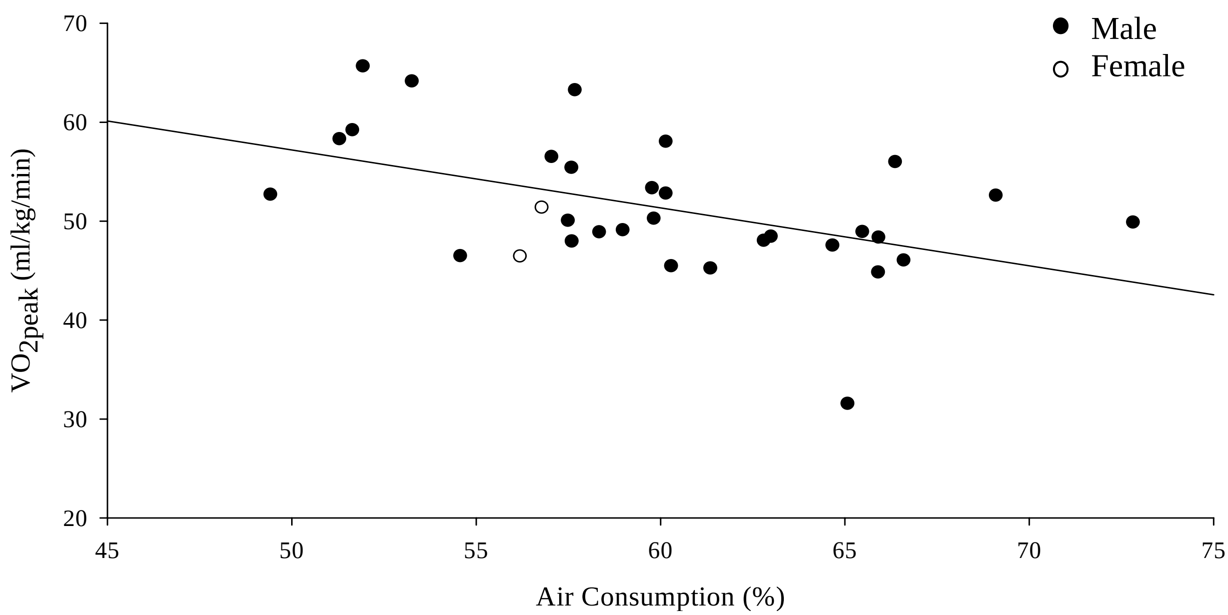

Figure 69: Relationship between relative VO_{2peak} (ml/kg/min) and total air consumption from the air cylinder during the subway scenario (r = -0.48, p < 0.05).

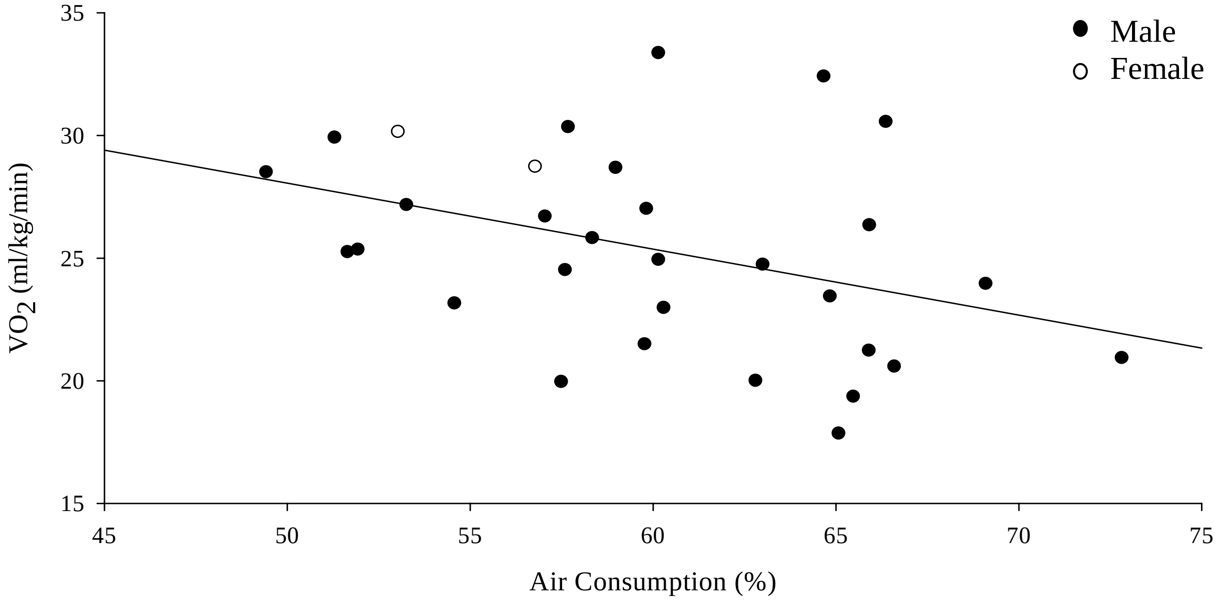

Figure 70: Relationship between average VO_2 (ml/kg/min) during the subway scenario and total air consumption from the air cylinder ($r = -0.38$, $p < 0.05$).

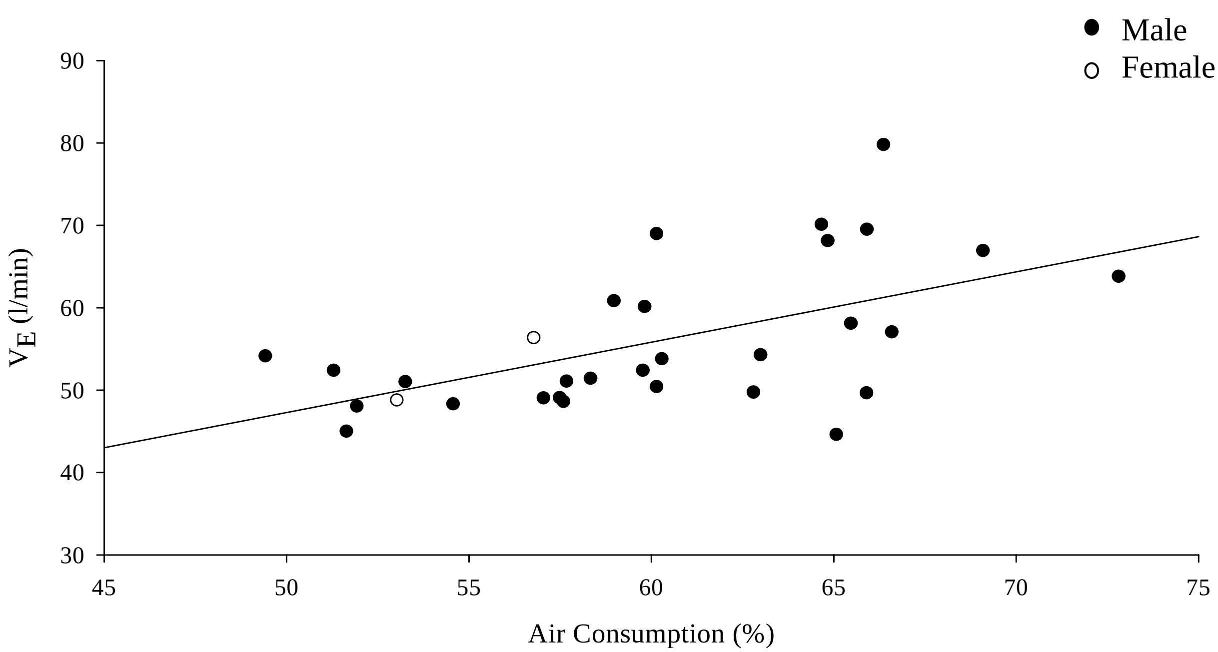

Figure 71: Relationship between V_E during the subway scenario and total air consumption from the air cylinder ($r = 0.57$, $p < 0.05$).

5.0 DISCUSSION

5.1 Summary of Main Findings

The first objective of this study was to integrate the Cosmed $K4b^2$ breath by breath gas collection system into a standard SCBA. Based on the data collected (Figures 72 and 73), the integration was successful and the modified gas collection system was functional to use in the simulated firefighting tasks field setting.

The data quantify the physical demand imposed on firefighters during three large structure firefighting scenarios. Relative VO_2 during the maximal stair climb scenario was significantly greater than both the 5th floor high rise and subway scenarios. This suggests that climbing stairs while consuming 2365 psi from an air cylinder results in an physical demand placed on the firefighter compared to the other two scenarios. These results are similar to the data reported by O'Connell, Thomas, Cady and Karwasky (1986) during five minutes of constant work rate stair climbing. Furthermore, it appears that the victim drag and rescue is the single most demanding task during the 5th floor high rise and subway scenarios, which has been suggested in previous research (Holmer et al., 2007).

Although it has been suggested (Holmer et al., 2007) and hypothesized that increased years of service as a firefighter would most likely relate to greater efficiency in air consumption in order to complete a particular task, the data show that as years of service increase firefighters appear to consume more air while completing a given task. Furthermore, increased relative VO_2 during the scenario results in a more efficient use of the firefighter's air cylinder. This suggests that those firefighters capable of producing more power per kg have improved performance and thus, decreased air consumption to complete a given task.

5.2 Determination of the Turn-around Pressure for the Maximal Stair Climb Scenario

In order to standardize performance during the maximal stair climb scenario, each firefighter was given a specific turn-around pressure for his/her individual air cylinder corresponding to a total air consumption of approximately 55%. Setting the level of air consumption for the turn-around point at 55% was determined through discussions with training officers and District Chiefs of the Toronto Fire Service as a level that would most likely result in a total air consumption of approximately 75% over the entire duration of the scenario. Due to the nature of refilling the SCBA air cylinder, the theoretical starting pressure for each cylinder is 4500 psi; however, various procedures can be used for the refilling process resulting in a wide range of starting pressures. The actual volume of air to be consumed was determined by calculating the starting pressure of a typical air cylinder and then computing the turn-around pressure following consumption of 55% from the air cylinder. After examination of the air cylinders that were to be used for the maximal stair climb scenario, starting pressures were observed from 3870 to 4590 psi with an average value of 4295 psi. Therefore, the starting pressure of a typical air cylinder was assumed to be 4300 psi resulting in a standardized turn-around air consumption of 2365 psi for each firefighter. Using this procedure meant that individuals who had lower starting pressures would consume their predetermined volume of air and be closer to the 25% low-air alarm at the turn-around point.

5.3 Firefighter Characteristics and Physical Fitness Tests

The study population included 33 male and 3 female firefighters from the Toronto Fire Service with an average age of 40.7 years. According to departmental statistics from 2006, the average age of all ranks in the Toronto Fire Service was 43.5 years, while the mean age for the rank of firefighter was 41.5 years (Toronto Fire Service, 2006). These values indicate that our study population was representative of the age range in the Toronto Fire Service.

Previously, it has been suggested that the physiological characteristics of the firefighter population are similar to that of the of the North American sedentary population (Davis, Dotson, & Santa Maria, 1982; Horowitz & Montgomery, 1993; Lemon & Hermiston, 1977a); however, the higher VO_{2peak} values reported in this study are in line with a recent study involving the Toronto Fire Service (McLellan & Selkirk, 2004; Selkirk et al., 2004), as well as additional research in this field (Donovan et al., 1999; Lusa, Louhevaara, Smolander, Kivimaki, & Korhonen, 1993). Although it has been suggested that VO_{2peak} is the primary factor in determining firefighting performance (Davis et al., 1987; Gledhill et al., 1992; Lemon et al., 1977b), it has become increasingly apparent that firefighting stresses all aspects of physical fitness (Rhea et al., 2004).

Anthropometric characteristics measured in this study were similar to those previously reported for the firefighting population (Lemon et al., 1977a). In terms of muscular strength, specifically the military press and biceps curls, Doolittle (1979) recommended that firefighters should be able to lift a minimum of 43 kg for the military press with a desirable standard of 55 kg, while the minimum standard for biceps curls was 46 kg with a desirable standard of 55 kg. In relation to the current study, the mean strength values for both the shoulder press and biceps curls are above the recommendations by Doolittle, with none of the firefighters below the recommended minimum standard for shoulder press and only 3 below the suggested standard for biceps curls. In terms of the firefighter population's overall physiological profile compared to the Canadian population, it has been reported that firefighters have higher body mass, body mass index, and greater muscular endurance (Horowitz et al., 1993).

5.4 High Rise Maximal Stair Climb Scenario

The primary goal of this study was to quantify the physiological demands and air requirements during firefighting tasks in large structures while wearing full PPE and SCBA. Although it is well understood that wearing full firefighting equipment places an additional energy demand on the firefighter, these previous studies did not incorporate breathing through the positive pressure SCBA mask (Donovan et al., 1999; Hooper, Crawford, & Thomas, 2001; Louhevaara, Ilmarinen, Griefahn, Kunemund, & Makinen, 1995). The facemask was either carried along side the firefighter or was modified to disconnect the positive pressure capabilities of the system in order to incorporate a flow monitoring device. Previous research that has kept the positive pressure characteristics of the SCBA system intact examined the effects of the SCBA on ventilatory function and maximal oxygen uptake using a motorized treadmill or electronically braked cycle ergometer, but not during simulated firefighting tasks (Butcher, Jones, Eves, & Petersen, 2006; Dreger, Jones, & Petersen, 2006; Eves et al., 2005; Petersen, Dreger, Williams, & McGarvey, 2000).

The maximal stair climb scenario was representative of a potential task given to firefighters in a high rise structure in order to ventilate the stairwell or climbing to the level of the fire if the stairwell has been compromised with smoke making the use of SCBA breathing a necessity. Mean absolute VO_2 during the scenario was 3168 ± 878 ml/min, which is similar to the oxygen uptake reported by O'Connell, Thomas, Cady, and Karwasky (1986), who examined simulated stair climbing for 5 minutes at a rate of 60 steps per minute. Although the average duration of the maximal stair climb scenario was 1 min 31 s longer than the protocol of O'Connell et al. (1986), by the 5^{th} minute of the stair climb, oxygen uptake for most firefighters had already reached a relatively constant level. Therefore, the additional minute and a half of stair climbing does not appear to have caused an additional increase in oxygen uptake. Mean relative VO_2 in this scenario was 35.5 ± 9.1 ml/kg/min, which fits in the range of previous research examining the energy cost of simulated firefighting. These studies have reported the relative VO_2 for firefighting tasks to be 30.5 ml/kg/min and up to 41.5 ml/kg/min for the most demanding tasks (Gledhill et al., 1992; Lemon et al., 1977b; Sothmann et al., 1991; Sothmann et al., 1990). However, interpreting and comparing these results must be taken with caution as differences in gas exchange equipment, firefighting task protocol, participant characteristics, and performance instructions vary between studies.

In relation to the maximal treadmill test, mean VO_2 during the maximal stair climb scenario corresponded to 70 ± 10% of VO_{2peak}. This value is within the range reported by Lemon and Hermiston (1977b), who suggested that firefighters commonly work between 60 and 80 % of their VO_{2peak}. Furthermore, Sothmann, Saupe, Jasenof, and Blaney (1992) found that the predicted VO_2 for fire suppression tasks was 63% of VO_{2peak}. As well, Sothmann et al. (1990) reported an average of 76 % of VO_{2peak} to complete 7 firefighting tasks, while O'Connell, Thomas, Cady, and Karwasky (1986) determined that 5 minutes of stair climbing required 80 % of VO_{2peak}. One limitation of using VO_2 in order to measure energy expenditure is the underlying assumption that all energy is being derived aerobically. However, during the maximal stair climb scenario the mean respiratory exchange ratio was 1.05 ± 0.15. The respiratory exchange ratio greater than 1.0 throughout most of this scenario indicates that a sizeable amount of energy was derived through anaerobic metabolism. Examining the respiratory exchange ratio throughout the entire duration of this scenario reveals an average baseline value of 0.90. During baseline data collection, firefighters were asked to wear their

SCBA mask while breathing through room air with many reporting that they experienced some difficulty inspiring through the small air port. This configuration is not what the firefighters are accustomed to and might have resulted in increased anxiety corresponding to a situation of hyperventilation, thus, increasing VCO_2 and RER. Previous research has identified that wearing a facemask can be associated with claustrophobia and a sensation of increased anxiety (Johnson, Dooly, Blanchard, & Brown, 1995; Morgan & Raven, 1985; Wilson et al., 1989).

Mean heart rate for the entire maximal stair climb scenario was 162 ± 11 bpm, corresponding to 88 ± 4% of HR_{peak}. These values are comparable with previous research examining the heart rate response in simulated firefighting tasks (Davis et al., 1982; Gilman & Davis, 1993; Sothmann, Saupe, Jasenof, & Blaney, 1992). Furthermore, Manning and Griggs (1983) reported that within the first minute of a firefighting task, heart rate increases 70 to 80% of HR_{peak} and then plateaus between 90 to 100% of HR_{peak} until the firefighting activity is completed. The high heart rate levels during firefighting tasks are a response to the cardiovascular strain, anxiety (Kuorinka et al., 1981), and the increased weight of wearing the personal protective equipment (Louhevaara et al., 1985; Louhevaara et al., 1984).

The average maximum number of floors climbed by the firefighters before consuming 2365 psi from the air cylinder was 20 ± 2.5 floors. Significant correlations with the maximum number of floors climbed was observed for age of the firefighter ($r = -0.30$, $p < 0.05$), body mass ($r = -0.30$, $p < 0.05$), body mass index ($r = -0.42$, $p < 0.05$), body fat percentage ($r = -0.44$, $p < 0.05$), relative VO_{2peak} ($r = 0.52$, $p < 0.05$), and total upper body strength ($r = -0.38$, $p < 0.05$). Based on these findings, it appears that increased body mass, which is often associated with decreased relative VO_{2peak} and increased upper body strength, may hinder a firefighter's ability to climb a considerable number of floors. Furthermore, velocity during the final floor climbed ($r = 0.45$, $p < 0.05$) and the completion time to climb 14 floors (the minimum level that all firefighters were able to achieve) ($r = -0.46$, $p < 0.05$) suggests that individuals who are capable of maintaining a consistent velocity throughout the stair climb with a corresponding increased performance time to climb 14 flights are capable of climbing a larger number of flights.

The second important objective of this study was to examine the total air consumption from the SCBA air cylinder during the three scenarios. Although technology and the creation of portable breath by breath gas collection systems have allowed researchers to examine the physiological aspects of firefighting in greater detail, at a fire scene the firefighter and incident commander must rely on the pressure information provided by the SCBA's heads-up-display. During the maximal stair climb scenario, the mean air consumption from the SCBA air cylinder was 74. 9 ± 6.0%. Furthermore, of the 36 firefighters who participated in this scenario, 17 consumed greater than 75% of their air cylinder. This resulted in activation of the 25% low-air alarm during the scenario. This information is of critical importance because the purpose of the final 25% of air in the cylinder is for emergency situations. All firefighters should be in and safely exit the fire scene at or before consuming 75% of their air cylinder in order to maintain the remaining 25% in case of an emergency scenario. Significant correlations were found with V_E ($r = 0.53$, $p < 0.05$), age of the firefighter ($r = 0.41$, $p < 0.05$), and years of service as a firefighter ($r = 0.40$, $p < 0.05$) when compared to the total air consumed from the air cylinder. This suggests that even though firefighters with more experience might be expected to perform these tasks more efficiently, it appears that with increasing age firefighters are not able to effectively utilize their air consumption and require a greater amount of air from their air cylinder in order to complete a given task. Taken together, these data suggest that the maximal stair climb scenario is a physically demanding firefighting task and that if firefighters are required to stair climb while consuming approximately 55% of their air cylinder, this will not allow them adequate air supply to conduct any further tasks and still be able to evacuate the building with a safe volume of air remaining.

5.5 5th Floor High Rise Scenario

The 5th floor high rise scenario was indicative of the type of tasks that would be required for fire suppression and victim rescue at a fire scene in the event that the stairwell was filled with smoke. Mean absolute VO_2 during this scenario was 2947 ± 461 ml/min, with an average relative VO_2 of 33.1 ± 4.6 ml/kg/min, corresponding to 65 ± 10% of VO_{2peak}. These values are within the range previously reported in the literature for the energy cost during simulated firefighting tasks (Lemon et al., 1977b; Sothmann et al., 1991; Sothmann et al., 1992). Sothmann et al. (1992) evaluated the heart rate response of firefighters during actual emergencies in order to estimate relative VO_2 values during fire suppression and found that firefighters were working at 63 % of their VO_{2peak}. This would appear to confirm that the simulated tasks implemented in this study are representative in terms of cardiovascular strain. Furthermore, each firefighter was asked to rate the scenario in terms of the nature of the tasks and the physical demand placed on the firefighter in relation to an actual emergency. Firefighters reported an average rating of 7.9 ± 1.0 out of maximum score of 10, further suggesting that the simulated firefighting tasks were representative of actual activities. Similar to the high rise maximal stair climb scenario, average heart rate for the entire scenario was 160 ± 14 bpm, corresponding to 88 ± 6% of HR_{peak}. The observed heart rate values during the 5th floor high rise scenario are similar to results previously reported and discussed earlier (Davis et al., 1982; Gilman et al., 1993; Manning & Griggs, 1983; Sothmann et al., 1992). Romet and Frim (1987) and Holmer et al. (2007) reported that the victim search and rescue appears to be the most important and physically demanding firefighting task. The results of the 5th floor high rise scenario are similar to this finding. The physiological responses during the victim rescue drag for this scenario revealed a mean absolute and relative VO_2 of 3174 ± 476 ml/min and 35.7 ± 5.0 ml/kg/min, corresponding to 70 ± 10% of VO_{2peak}. Mean respiratory exchange ratio for the victim rescue drag was 1.05 ± 0.09, with an average heart rate of 165 ± 12, corresponding to 91 ± 5% of HR_{peak}. This suggests that during fire suppression the responsibility of the firefighter to rescue a fallen victim will undoubtedly result in greater physical demand imposed on the body.

Mean respiratory exchange ratio throughout the entire scenario was 1.13 ± 0.12. Comparable to the high rise maximal stair climb scenario, RER values were consistently greater than 1.0 during the 5th floor high rise scenario indicating a considerable contribution from anaerobic metabolism. The higher RER values seen in this scenario compared to the maximal stair climb could be due to the increased upper body work required for the hose pull, room search, forcible entry, and victim rescue drag. The addition of upper body work would require increased metabolic demand and also result in more production of lactic acid and therefore, greater CO_2 production. The high VCO_2 values observed in both the maximal stair climb scenario and 5th floor high rise scenario are indicative of the anaerobic challenge of these tasks as well as a result of the physiological demands imposed while wearing the SCBA and PPE. The increased weight of the personal protective equipment and SCBA could result in greater activation of smaller muscle groups, including postural muscles to stabilize the upper body, causing an increase in production of metabolic waste products.

In terms of air management for this scenario, total air consumption from the volume contained in the air cylinder was 48.0 ± 7.0%. None of the 36 firefighters had their 25% low-air alarm activated, indicating that the duration (5 min 3 s ± 57 s) and physical nature of the tasks allowed them to consume an efficient amount of air and be able to evacuate the simulated fire scene with the recommended amount of air remaining in the cylinder. Significant correlations with total air consumption were found for the age of the firefighter ($r = 0.61$, $p < 0.05$) and years of service as a firefighter ($r = 0.47$, $p < 0.05$). Similar to the maximal stair climb scenario, it appears that although the firefighters who have been on the job for a longer period of time would be expected to be more efficient at successfully completing the tasks, increasing age results in greater consumption of air in order to complete a simulated firefighting scenario. Furthermore, firefighters' body mass ($r = 0.36$, $p < 0.05$) and relative VO_2 during the scenario ($r = -0.48$, $p < 0.05$) revealed significant relationships with total air consumption. These data suggest that firefighters with increased body mass are not capable of providing more power per kg during the simulated firefighting tasks, thus, decreasing efficient air consumption throughout the scenario.

Based on the physiological demands and air management results, the maximal stair climb scenario appears to be a greater cardiovascular challenge than the 5th floor high rise scenario. This could be due to the higher work rate maintained throughout the entire stair climb scenario, whereas in the 5th floor scenario the total mass of the firefighters' body, PPE, and SCBA was not required to be lifted a vertical distance. This situation would result in increased metabolic demand to the lower body muscles.

5.6 Subway System Scenario

The subway scenario was representative of the duration and type of tasks firefighters would be responsible to complete in conducting fire suppression and victim rescue, including the potential walking distance required underground in a subway tunnel. Immediately following the scenario, firefighters were asked to rate the scenario in terms of the nature of the tasks and the physical demand placed on the firefighter in relation to an actual emergency. Firefighters reported an average rating of 7.7 ± 1.4 out of maximum score of 10, further suggesting that the simulated firefighting tasks were representative of actual activities. In comparison to the other two scenarios, the duration of the subway scenario was longer requiring an average completion time of 12 min 5s ± 1 min 10 s. Mean absolute VO_2 during this scenario was 2217 ± 371 ml/min, with a relative VO_2 of 25.2 ± 4.6 ml/kg/min corresponding to 49 ± 8% of VO_{2peak}. These values are below those previously reported, including the range suggested by Lemon and Hermiston (1977b) between 60 and 80 % of VO_{2peak}. The decreased cardiovascular challenge observed could be due to the majority of this scenario involving walking to and from the subway car, which comprised an average of 9 min 43 s ± 53 s of total walking time. Therefore, approximately 81% of this entire scenario involved walking with almost no elevation changes that would require an increased energy demand as seen with stair climbing.

Due to the nature of this scenario where two firefighters worked in tandem to complete the simulated tasks, firefighter A completed the victim rescue drag prior to firefighter B. The results show that the cardiovascular challenge imposed to both firefighters during the victim rescue drag was similar. A difference is seen between firefighter A and B in the guide walk, where carry-over effects from the rescue would have resulted in the higher V_E, absolute and relative VO_2, VCO_2, and heart rate responses. Although these values are greater during the guide walk for firefighter A possibly due to carry-over effects, it appears that the most demanding tasks are the victim rescue drag and stair climb at the end of the scenario. These results are comparable to those reported by Holmer et al. (2007) and Romet and Frim (1987), who suggested that the victim search and rescue is the most physically demanding firefighting task. Of major importance is the finding that the final task of the subway scenario (stair ascent) reveals an increased physical demand. Although this scenario is the least challenging of the three scenarios employed, it is important to note that the addition of heat stress due to increased ambient temperatures, decreased visibility, and increased anxiety would increase the cardiovascular challenge and cause the final stair ascent to potentially be more demanding. Therefore, firefighters should be aware that, unlike the high rise scenarios, exiting the fire scene at a subway scenario will require an increased metabolic demand and this should be taken into account when managing their air during fire suppression.

In terms of air management for this scenario, mean air consumption was 59.9 ± 5.6% from the air cylinder. Despite the decreased physiological demand when compared to the 5th floor high rise scenario, total air consumption was almost 12% greater, which can be explained by the increased completion time during the subway scenario. Furthermore, none of the firefighters had total air consumption greater than 75% of their air cylinder, meaning that the 25% low-air alarm was never activated during this scenario. Similar to both of the high rise scenarios, it appears that increasing age and years of service results in greater total air consumption to complete the tasks. Additionally, increased body mass often associated with decreased relative VO_{2peak} appears to result in greater air consumption during subway scenario. Average relative VO_2 during this scenario revealed a significant correlation with total air consumption suggesting that a higher relative VO_2 produces more power per kg (total combined mass of the body and firefighting equipment) resulting in better performance (Holmer et al. (2007), subsequently relating to more efficient air consumption.

For all three scenarios, the results indicate that there are large individual differences in the energy requirements in order to complete similar type of work. When requested to perform the tasks at an equivalent pace that would be required at an actual fire scene, it appears that each firefighter will determine his/her optimal balance between the physical demand required for the task and his/her own physical capacity (Holmer et al., 2007).

6.0 LIMITATIONS

A primary limitation of this study, which is often seen when studying the firefighting population, is mainly highly fit individuals will volunteer as participants. The lower end of the spectrum in terms of physical fitness is not regularly represented in the participants volunteering for research studies. Furthermore, due to modifications with the SCBA equipment for testing purposes and the importance of maintaining a safe testing environment, firefighters were not subjected to regular fire scene conditions involving increased ambient temperatures, poor visibility, and potentially greater feelings of anxiety. The addition of heat stress and psychological factors associated with poor visibility and anxiety could influence the physiological responses of the firefighters while completing the various tasks. Due to generic sizing of the SCBA facemasks and differing facial structures of each firefighter, maintaining a perfect fit at all times with no possible air leaks is difficult to ensure. An additional limitation is that each firefighter was instructed to complete the scenarios at a pace equivalent to what they would work at during an actual fire emergency. Since work rate and pace could not be controlled for, differences in completion times for a given task are observed and may make interpreting physiological responses more difficult.

Future research should focus on attempting to recruit a representative participant population including the less physically fit firefighters. This would result in a greater overall understanding of the physiological demands and air requirements in large structure firefighting. In addition, imposing additional stressors to the testing protocol, such as a complete blackout of the visibility through the SCBA facemask and implementing entanglement boxes for the firefighters to navigate through would increase the possible psychological feeling of anxiety. Eventually, being able to modify the integrated SCBA Cosmed K4b^2 system so that it still meets all safety requirements would be extremely beneficial and could possibly allow for breath by breath gas collection during live simulated fires. This would allow a more accurate depiction of an actual fire scene including stressors placed on the body by the ambient environment.

7.0 CONCLUSIONS

The integration of the SCBA facemask with the Cosmed $K4b^2$ breath by breath gas collection system was an essential component in the process of examining the physiological demands during simulated large structure firefighting tasks. The results of this study are fundamental in quantifying the physiological demands and ventilatory requirements during high rise and subway system fire scenarios in order to establish principles for air management while breathing through the SCBA air cylinder. The data indicate that the task of stair climbing to the point of consuming 55% of a typical air cylinder can be considered one of the most demanding firefighting tasks. Based on these findings, caution must be taken by incident commanders at a fire scene when having to deploy firefighters a considerable distance up a smoke filled stairwell with the intention to perform various fire suppression and victim rescue tasks. Although the 5^{th} floor high rise and subway system scenarios did not require the same volume of air consumption, the data are instrumental in quantifying the air requirements during these firefighting tasks. It appears that increasing age requires a larger air consumption to complete a given task, and that increased body mass also results in greater air requirements. Furthermore, the ability to produce more power per given kg of total body mass, including firefighting equipment, seems to produce better performance times and more efficient air management. However, the safety of all firefighters is of major importance and individuals should be aware of their own air management to make sure they obtain a safe exit from the fire scene.

8.0 RECOMMENDATIONS

This study has quantified the air requirements during simulated firefighting tasks in large high-rise and subway structures. The results can provide the basis for modifying work cycles and adjusting air management procedures while fighting large structural fires. The data indicate that during a maximal stair climb task where a firefighter might be required to consume approximately 55% of his/her air cylinder, nearly half of the firefighters in this study would have activated their 25% low-air alarm during the descent phase increasing the potential of serious injury and possibly death. The current observations allow for advancement of basic recommendations that could be implemented to improve firefighter safety in high-rise and subway emergencies.

- To compensate for any potential emergency situations, air cylinder refill stations could be set up on various floors to make sure that firefighters do not have to travel the entire distance of the stairwell with little air remaining in order to safely exit the fire scene. This would allow firefighters who have consumed a large quantity of their cylinder during the ascent portion of the climb to descend a smaller number of flights in order to refill or exchange air cylinders.
- The creation of specialized units might provide additional safety precautions. Specialized task forces with firefighters who are in good physical fitness and specifically trained to complete particular tasks, such as a maximal stair climb, can be implemented to improve the ability of achieving a safe exit for all firefighters.
- The current data demonstrated that a ‘30’ minute air cylinder did not allow for 20-minutes of work inside a fire scene for the average firefighter. Rather, the results showed that even in simulated scenarios where the external environment was

controlled, physically demanding tasks in high-rise structures required an average air consumption of 50% from the cylinder within a six-minute period.

- Underground fire scenes appear to be a separate entity compared to residential and high rise scenarios. Incident commanders should take into account that firefighters who have just completed potentially strenuous work tasks underground will be required to climb stairs and/or a ladder to exit these types of scenes safely. The energy requirement and air use during stair climbing is high and this could put firefighters in a compromised situation if their air supply has been depleted. Similar to the high rise recommendations, implementing a cylinder refill or exchange station near the bottom of the stairs or ladder might be appropriate if a large vertical distance must be climbed to accomplish a safe exit.

9.0 REFERENCES

Armstrong, L. E., Brubaker, P. H., Whaley, M. H., & Otto, R. M. (2006). *ACSM's Guidelines for Exercise Testing and Prescription*. (7th ed.) Philadelphia, PA: Lippincott, Williams, & Wilkins.

Astrand, P. & Rodahl, K. (1986). *Textbook of Work Physiology*. (3rd ed.) New York: McGraw-Hill.

Baker, S. J., Grice, J., Roby, L., & Matthews, C. (2000). Cardiorespiratory and thermoregulatory response of working in fire-fighter protective clothing in a temperate environment. *Ergonomics, 43,* 1350-1358.

Barnard, R. J. & Duncan, H. W. (1975). Heart rate and ECG responses of fire fighters. *Journal of occupational medicine, 17,* 247-250.

Bernzweig, D. (2004). Expanding "Time to Exit" for Firefighters. *Fire Engineering*.

Brassell, L. D. & Evands, D. D. (2003). *Trends in firefighter fatalities due to structural collapse, 1979-2002*.

Butcher, S. J., Jones, R. L., Eves, N. D., & Petersen, S. R. (2006). Work of breathing is increased during exercise with the self-contained breathing apparatus regulator. *Appl.Physiol Nutr.Metab, 31,* 693-701.

Carter, J. B., Banister, E. W., & Morrison, J. B. (1999). Effectiveness of rest pauses and cooling in alleviation of heat stress during simulated fire-fighting activity. *Ergonomics, 42,* 299-313.

Cheung, S. S., McLellan, T. M., & Tenaglia, S. (2000). The thermophysiology of uncompensable heat stress. Physiological manipulations and individual characteristics. *Sports Med., 29,* 329-359.

Davis, P. O. & Dotson, C. O. (1987). Physiological Aspects of Fire Fighting. *Fire Technology, 23,* 280-291.

Davis, P. O., Dotson, C. O., & Santa Maria, D. L. (1982). Relationship between simulated fire fighting tasks and physical performance measures. *Med.Sci.Sports Exerc., 14,* 65-71.

Davis, P. O. & Santa Maria, D. L. (1975). Energy costs of wearing fire fighter's protective equipment. *International Fire Chief, 41,* 10-11.

Donovan, K. J. & McConnell, A. K. (1999). Do fire-fighters develop specific ventilatory responses in order to cope with exercise whilst wearing self-contained breathing apparatus? *Eur.J.Appl.Physiol Occup.Physiol, 80,* 107-112.

Doolittle, T. L. (1979). *Validation of physical requirements for firefighters* Seattle: Seattle Fire Department.

Dreger, R. W., Jones, R. L., & Petersen, S. R. (2006). Effects of the self-contained breathing apparatus and fire protective clothing on maximal oxygen uptake. *Ergonomics, 49,* 911-920.

Eves, N. D., Jones, R. L., & Petersen, S. R. (2005). The influence of the self-contained breathing apparatus (SCBA) on ventilatory function and maximal exercise. *Can.J.Appl.Physiol, 30,* 507-519.

Fabio, A., Ta, M., Strotmeyer, S., Li, W., & Schmidt, E. (2002). Incident-level risk factors for firefighter injuries at structural fires. *J.Occup.Environ.Med., 44,* 1059-1063.

Faff, J. & Tutak, T. (1989). Physiological responses to working with fire fighting equipment in the heat in relation to subjective fatigue. *Ergonomics, 32,* 629-638.

Ftaiti, F., Duflot, J. C., Nicol, C., & Grelot, L. (2001). Tympanic temperature and heart rate changes in firefighters during treadmill runs performed with different fireproof jackets. *Ergonomics, 44,* 502-512.

Gilman, W. D. & Davis, P. O. (1993). Fire fighting demands aerobic fitness. *NFPA Journal,* 68-73.

Gledhill, N. & Jamnik, V. K. (1992). Characterization of the physical demands of firefighting. *Can.J.Sport Sci., 17,* 207-213.

Hodous, T. K., Pizatella, T. J., Braddee, R., & Castillo, D. N. (2004). Fire fighter fatalities 1998-2001: overview with an emphasis on structure related traumatic fatalities. *Inj.Prev., 10,* 222-226.

Holmer, I. & Gavhed, D. (2007). Classification of metabolic and respiratory demands in fire fighting activity with extreme workloads. *Appl.Ergon., 38,* 45-52.

Holmer, I., Kuklane, K., & Gao, C. (2006). Test of firefighter's turnout gear in hot and humid air exposure. *Int.J.Occup.Saf Ergon., 12,* 297-305.

Hooper, A. J., Crawford, J. O., & Thomas, D. (2001). An evaluation of physiological demands and comfort between the use of conventional and lightweight self-contained breath apparatus. *Appl.Ergon., 32,* 399-406.

Horowitz, M. R. & Montgomery, D. L. (1993). Physiological profile of fire fighters compared to norms for the Canadian population. *Can.J.Public Health, 84,* 50-52.

Johnson, A. T., Dooly, C. R., Blanchard, C. A., & Brown, E. Y. (1995). Influence of anxiety level on work performance with and without a respirator mask. *Am.Ind.Hyg.Assoc.J., 56,* 858-865.

Kilbom, A. (1980). Physical work capacity of firemen. With special reference to demands during fire fighting. *Scand.J.Work Environ.Health, 6,* 48-57.

Kraemer, W. J. & Fry, A. C. (2006). Strength Testing: Development and evaluation of methodology. In P.J.Maud & C. Foster (Eds.), *Physiological Assessment and Human Fitness* (2nd ed., pp. 115-138). Champaign, IL: Human Kinetics.

Kuorinka, I. & Korhonen, O. (1981). Firefighters' reaction to alarm, an ECG and heart rate study. *J.Occup.Med., 23,* 762-766.

Lemon, P. W. & Hermiston, R. T. (1977a). Physiological profile of professional fire fighters. *J.Occup.Med., 19,* 337-340.

Lemon, P. W. & Hermiston, R. T. (1977b). The human energy cost of fire fighting. *J.Occup.Med., 19,* 558-562.

Louhevaara, V., Ilmarinen, R., Griefahn, B., Kunemund, C., & Makinen, H. (1995). Maximal physical work performance with European standard based fire-protective clothing system and equipment in relation to individual characteristics. *Eur.J.Appl.Physiol Occup.Physiol, 71,* 223-229.

Louhevaara, V., Smolander, J., Korhonen, O., & Tuomi, T. (1986). Maximal working times with a self-contained breathing apparatus. *Ergonomics, 29,* 77-85.

Louhevaara, V., Smolander, J., Tuomi, T., Korhonen, O., & Jaakkola, J. (1985). Effects of an SCBA on breathing pattern, gas exchange, and heart rate during exercise. *J.Occup.Med., 27,* 213-216.

Louhevaara, V., Tuomi, T., Korhonen, O., & Jaakkola, J. (1984). Cardiorespiratory effects of respiratory protective devices during exercise in well-trained men. *Eur.J.Appl.Physiol Occup.Physiol, 52,* 340-345.

Louhevaara, V. A. (1984). Physiological effects associated with the use of respiratory protective devices. A review. *Scand.J.Work Environ.Health, 10,* 275-281.

Lusa, S., Louhevaara, V., Smolander, J., Kivimaki, M., & Korhonen, O. (1993). Physiological responses of firefighting students during simulated smoke-diving in the heat. *Am.Ind.Hyg.Assoc.J., 54,* 228-231.

Manning, J. E. & Griggs, T. R. (1983). Heart rates in fire fighters using light and heavy breathing equipment: similar near-maximal exertion in response to multiple work load conditions. *J.Occup.Med., 25,* 215-218.

McLellan, T. M. & Selkirk, G. A. (2004). Heat stress while wearing long pants or shorts under firefighting protective clothing. *Ergonomics, 47,* 75-90.

Morgan, W. P. & Raven, P. B. (1985). Prediction of distress for individuals wearing industrial respirators. *Am.Ind.Hyg.Assoc.J., 46,* 363-368.

National Fire Protection Association (2006). *Firefighter Skills.*

O'Connell, E. R., Thomas, P. C., Cady, L. D., & Karwasky, R. J. (1986). Energy costs of simulated stair climbing as a job-related task in fire fighting. *J.Occup.Med., 28,* 282-284.

Petersen, S. R., Dreger, R. W., Williams, B. E., & McGarvey, W. J. (2000). The effects of hyperoxia on performance during simulated firefighting work. *Ergonomics, 43,* 210-222.

Raven, P. B., Bradley, O., Rohm-Young, D., McCLure, F. L., & Skaggs, B. (1982). Physiological response to "pressure-demand" respirator wear. *Am.Ind.Hyg.Assoc.J., 43,* 773-781.

Raven, P. B., Davis, T. O., Shafer, C. L., & Linnebur, A. C. (1977). Maximal stress test performance while wearing a self-contained breathing apparatus. *J.Occup.Med., 19,* 802-806.

Rhea, M. R., Alvar, B. A., & Gray, R. (2004). Physical fitness and job performance of firefighters. *J.Strength.Cond.Res., 18,* 348-352.

Romet, T. T. & Frim, J. (1987). Physiological responses to fire fighting activities. *Eur.J.Appl.Physiol Occup.Physiol, 56,* 633-638.

Saupe, K., Sothmann, M., & Jasenof, D. (1991). Aging and the fitness of fire fighters: the complex issues involved in abolishing mandatory retirement ages. *Am.J.Public Health, 81,* 1192-1194.

Selkirk, G. A. & McLellan, T. M. (2004). Physical work limits for Toronto firefighters in warm environments. *J.Occup.Environ.Hyg., 1,* 199-212.

Smith, D. L., Petruzzello, S. J., Kramer, J. M., & Misner, J. E. (1996). Physiological, psychophysical, and psychological responses of firefighters to firefighting training drills. *Aviat.Space Environ.Med., 67,* 1063-1068.

Sothmann, M., Saupe, K., Raven, P. B., Pawelczyk, J. P., Davis, P. O., Dotson, C. O. et al. (1991). Oxygen consumption during fire suppression: error of heart rate estimation. *Ergonomics, 34,* 1469-1474.

Sothmann, M. S., Saupe, K., Jasenof, D., & Blaney, J. (1992). Heart rate response of firefighters to actual emergencies. Implications for cardiorespiratory fitness. *J.Occup.Med., 34,* 797-800.

Sothmann, M. S., Saupe, K. W., Jasenof, D., Blaney, J., Donahue Fuhrman, S., Woulfe, T. et al. (1990). Advancing age and the cardiorespiratory stress of fire supression: determining a minimum standard for aerobic fitness. *Human Performance, 3,* 217-236.

Teitlebaum, A. & Goldman, R. F. (1972). Increased energy cost with multiple clothing layers. *J.Appl.Physiol, 32,* 743-744.

Toronto Fire Service (2006). *Toronto Fire Service Statistics*.

United States Fire Administration (2002). Firefighter injuries in structures. *Federal Emergency Management Agency, 2,* 1-2.

United States Fire Administration (2006). *Firefighter fatalities in the United States in 2005* Emmitsburg, MD.

Walton, S. M., Conrad, K. M., Furner, S. E., & Samo, D. G. (2003). Cause, type, and workers' compensation costs of injury to fire fighters. *Am.J.Ind.Med., 43,* 454-458.

White, M. K. & Hodous, T. K. (1988). Physiological responses to the wearing of fire fighter's turnout gear with neoprene and GORE-TEX barrier liners. *Am.Ind.Hyg.Assoc.J., 49,* 523-530.

Wilson, J. R., Raven, P. B., Morgan, W. P., Zinkgraf, S. A., Garmon, R. G., & Jackson, A. W. (1989). Effects of pressure-demand respirator wear on physiological and perceptual variables during progressive exercise to maximal levels. *Am.Ind.Hyg.Assoc.J., 50,* 85-94.

APPENDIX A

Results from the mechanical calibration procedure are shown in Figure 72. At very low ventilations, a large percent error was observed between the Cosmed measured values and the predicted calibrator values, ranging from 11% to 16%. Expired ventilation values were reasonable through the middle flow rates up to 90 l/min, with percent errors ranging from 0.5% to 6%. After calibrating the flow turbine at 15, 22.5, and 30 l/min to determine the accuracy of the measured VO_2 values using the integrated SCBA Cosmed system, percent error values ranged from -1.77% to 2.36%. As well, VCO_2 was compared between measured and predicted values and ranged in percent error from -4.30% to 0.29%. Although the ventilation error is large at certain flow rates, it appears that VO_2 and VCO_2 values measured by the integrated SCBA Cosmed system are within a reasonable range (Figure 73). Values highlighted in teal in Figure 73 represent the measured SCBA Cosmed values, whereas the values in bold depict the percent error between the SCBA Cosmed system and the predicted values from the mechanical calibrator. Predicted values are shown in the top portion of the spreadsheet, with ambient environment characteristics and dead space manually inputted.

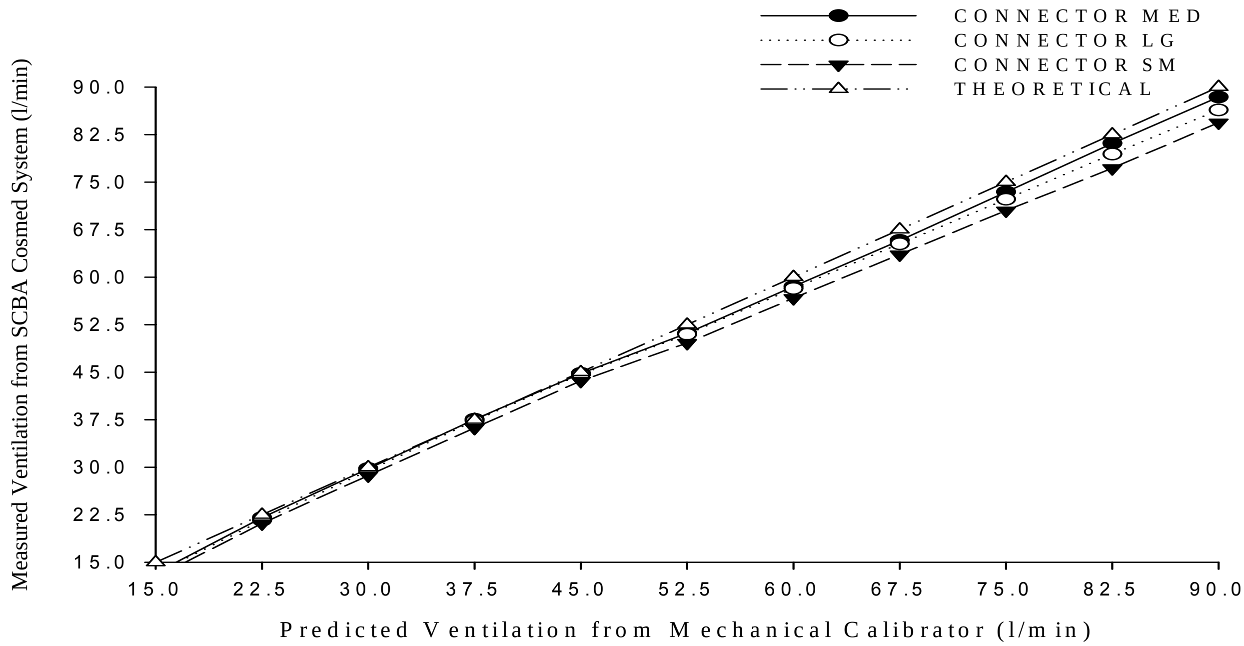

Figure 72: Determination of the SCBA Cosmed integrated system comparing the measured minute ventilation with the predicted minute ventilation from the mechanical calibrator.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Calibrator Report for COSMED											
2												
3												
4			Room Temperature °C	22		Calibrator side Dead Space mL			350			
5			Barometric Pressure mmHg	730		Room Air side Dead Space mL			0			
6			RH %	56								
7												
8	Calibrator						BTPS	BTPS				
9	V L/SEC	fb	VT	VE	VO2STPD	VCO2 STPD	O2exp	CO2exp	FeO2	FeCO2	FetO2	FetCO2
10	Setting	b/min	L	L/min	mL/min	mL/min	ml	ml	%	%	%	%
11	**0.50**	5	3.00	15	**540**	**593**	558	151	16.59	4.48	16.02	5.07
12	**0.75**	7.5	3.00	22.5	**810**	**889**	558	151	16.59	4.48	16.02	5.07
13	**1.00**	10	3.00	30	**1079**	**1185**	558	151	16.59	4.48	16.02	5.07
14	**1.25**	12.5	3.00	37.5	**1349**	**1482**	558	151	16.59	4.48	16.02	5.07
15												
16												
17	COSMED	Date	2007 08 08		ATP to BTPS exp	1.123281	calculated	1.123161				
18					BTPS to STPD	0.791337	calculated	0.791422				
19	**0.50**	5.16	3.16	16.29	547	585	525	144	16.63	4.57	16.07	5.06
20	ATP normalized for fb		2.81	14.06	***530***	***567***	*STPD normalized for fb*					
21		% error	**-6.27**	**-6.27**	***-1.77***	***-4.30***	**-5.91**	**-4.30**	**0.20**	**1.91**	**0.32**	**-0.24**
22	**0.75**	7.53	3.31	24.97	832	895	552	151	16.65	4.56	16.06	5.09
23	ATP normalized for fb		2.95	22.13	***829***	***891***	*STPD normalized for fb*					
24		% error	**-1.64**	**-1.64**	***2.36***	***0.29***	**-1.11**	**0.29**	**0.35**	**1.77**	**0.25**	**0.33**
25	**1.00**	9.94	3.32	33.00	1086	1180	554	151	16.69	4.55	16.07	5.10
26	ATP normalized for fb		2.95	29.54	***1092***	***1187***	*STPD normalized for fb*					
27		% error	**-1.52**	**-1.52**	***1.20***	***0.15***	**-0.73**	**0.16**	**0.61**	**1.52**	**0.34**	**0.49**

Figure 73: Spreadsheet for determination of percent error between measured SCBA Cosmed variables and predicted values from the mechanical calibrator.

APPENDIX B

Table 9: Summary for V_E, absolute and relative VO_2, VCO_2, RER, HR, Velocity, and Power for each flight during the maximal stair climb scenario.

Floor	V_E (L/min)	VO_2 (ml/min)	VO_2 (ml/kg/min)	% VO_{2peak}	VCO_2 (ml/min)	RER	HR (bpm)	Velocity (m/s)	Power (W)
BL	14.7 ± 4.5	495 ± 193	5.5 ± 1.3	11 ± 3	446 ± 135	0.90 ± 0.11	100 ± 17	N/A	N/A
1	29.4 ± 9.5	1020 ± 267	11.4 ± 3.0	23 ± 7	932 ± 268	0.91 ± 0.12	119 ± 15	0.31 ± 0.05	377.7 ± 71.8
2	41.2 ± 12.6	1579 ± 371	17.5 ± 3.4	36 ± 8	1348 ± 345	0.86 ± 0.12	135 ± 15	0.26 ± 0.04	321.8 ± 57.2
3	52.9 ± 13.6	2493 ± 466	27.7 ± 4.3	55 ± 11	1912 ± 416	0.77 ± 0.07	150 ± 14	0.25 ± 0.03	307.7 ± 51.5
4	67.4 ± 14.4	3087 ± 473	34.4 ± 4.0	68 ± 10	2629 ± 483	0.85 ± 0.08	156 ± 12	0.22 ± 0.03	274.6 ± 47.4
5	78.0 ± 15.1	3303 ± 494	36.8 ± 3.9	73 ± 9	3175 ± 499	0.96 ± 0.09	159 ± 11	0.22 ± 0.03	274.1 ± 56.2
6	85.5 ± 16.3	3390 ± 541	37.7 ± 4.1	74 ± 9	3545 ± 535	1.05 ± 0.10	162 ± 11	0.20 ± 0.05	249.6 ± 64.5
7	91.6 ± 17.2	3409 ± 570	37.9 ± 4.4	75 ± 8	3795 ± 608	1.12 ± 0.10	162 ± 10	0.19 ± 0.03	233.4 ± 52.5
8	93.4 ± 17.5	3382 ± 571	37.6 ± 4.5	74 ± 7	3866 ± 677	1.15 ± 0.12	163 ± 9	0.19 ± 0.04	229.7 ± 62.3
9	94.3 ± 16.9	3387 ± 572	37.6 ± 4.5	74 ± 8	3884 ± 697	1.15 ± 0.12	164 ± 9	0.19 ± 0.03	229.5 ± 49.2
10	95.0 ± 17.3	3405 ± 606	37.8 ± 5.2	74 ± 9	3891 ± 738	1.15 ± 0.12	165 ± 10	0.18 ± 0.04	217.3 ± 57.8
11	95.1 ± 16.5	3417 ± 590	38.1 ± 5.3	75 ± 8	3865 ± 708	1.13 ± 0.12	165 ± 10	0.18 ± 0.03	216.3 ± 45.7
12	94.5 ± 16.7	3403 ± 637	37.9 ± 6.0	74 ± 9	3827 ± 751	1.13 ± 0.12	166 ± 10	0.17 ± 0.04	206.6 ± 57.4
13	95.8 ± 15.9	3457 ± 619	38.5 ± 5.8	76 ± 9	3841 ± 740	1.11 ± 0.12	166 ± 9	0.18 ± 0.04	220.3 ± 46.9
14	96.4 ± 16.4	3469 ± 649	38.7 ± 6.1	76 ± 10	3832 ± 784	1.11 ± 0.11	166 ± 10	0.17 ± 0.04	205.4 ± 53.5
15	97.9 ± 15.9	3489 ± 653	38.8 ± 5.9	76 ± 9	3842 ± 793	1.10 ± 0.11	167 ± 10	0.16 ± 0.05	201.6 ± 58.0
16	97.5 ± 16.7	3523 ± 636	39.3 ± 5.5	77 ± 11	3860 ± 768	1.10 ± 0.11	167 ± 10	0.17 ± 0.04	206.2 ± 47.6
17	97.6 ± 17.8	3517 ± 697	39.7 ± 6.2	77 ± 12	3851 ± 812	1.10 ± 0.11	167 ± 10	0.15 ± 0.05	185.5 ± 61.9
18	96.2 ± 17.6	3506 ± 687	39.9 ± 5.9	77 ± 10	3829 ± 821	1.09 ± 0.11	167 ± 11	0.16 ± 0.05	200.3 ± 65.5
19	98.3 ± 17.3	3531 ± 713	40.0 ± 6.0	78 ± 11	3821 ± 860	1.08 ± 0.11	166 ± 11	0.17 ± 0.04	205.8 ± 53.8
20	97.7 ± 17.7	3538 ± 723	40.0 ± 6.2	76 ± 10	3817 ± 834	1.08 ± 0.10	167 ± 12	0.16 ± 0.05	192.9 ± 62.6
21	96.0 ± 16.5	3470 ± 692	40.0 ± 6.4	76 ± 10	3776 ± 818	1.09 ± 0.10	167 ± 13	0.17 ± 0.03	209.0 ± 44.5
22	96.4 ± 15.0	3517 ± 617	42.4 ± 5.1	78 ± 8	3790 ± 773	1.07 ± 0.07	173 ± 13	0.19 ± 0.03	216.4 ± 25.6
23	95.5 ± 15.7	3459 ± 648	43.4 ± 4.4	79 ± 8	3777 ± 839	1.09 ± 0.08	178 ± 12	0.17 ± 0.04	186.9 ± 49.5

Note: BL = Baseline