THESIS

PHYSIOLOGICAL STRAIN OF FIREFIGHTERS EXPOSED TO A LIVE FIREFIGHTING EXERCISE

Submitted by

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In partial fulfillment of the requirement

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2009

COLORADO STATE UNIVERSITY

April 6, 2009

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY KYLE RUSSELL BARNES ENTITLED PHYSIOLOGICAL STRAIN OF FIREFIGHTERS EXPOSED TO A LIVE FIREFIGHTING EXERCISE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

PHYSIOLOGICAL STRAIN OF FIREFIGHTERS EXPOSED TO A LIVE FIREFIGHTING EXERCISE

The physiological demands of occupations such as live urban or wildland firefighting are an important determinant of occupational safety, and can inform decisions about employee recruitment, screening, and training. To this end, the present study describes the physiological strain which attends live burn exercises in an urban firefighter academy.

Fourteen firefighters from the Northern Colorado Fire Consortium Fire Academy participated in this investigation. The firefighter cadets' clinical characteristics were as follows (mean ± SD): age 28.8 ± 5.7 years; height 1.8 ± 0.1 m; mass 83.8 ± 12.9 kg; body mass index (BMI) 26.3 ± 3.0; maximal aerobic capacity 45.0 ± 4.4 ml/kg/min, 3.77 ± 0.6 L/min. Participants were studied during two live burn sessions separated by four days. The mean (± SD) duration of fire exposures was 9.6 ± 1.5 and 9.32 ± 2.6 minutes for day one and two, respectively. The pre-burn heart rates were 92.7 ± 18.0 bpm and 96.4 ± 13.8 bpm in days one and two, respectively. The mean pre-burn blood pressures were 117/68 ± 18.7/9.1 and 122/76 ± 11.0/8.9, respectively. The mean pre-burn blood lactate was 3.3 ± 1.9 mmol/L on day one and 2.7 ± 1.0 mmol/L on day two.

Post-burn mean (± SD) heart rates were 156.8 ± 20.9 and 156.2 ± 18.5 bpm for day one and two, respectively. Mean post-burn blood pressure was 139/61 ± 9/7/16.8 on day one and 131/68 ± 8.9/17.7 on day two. Post-burn lactate was 7.2 ± 3.3 and 5.3 ± 2.3 mmol/L, on day one and day two, respectively. Mean minute ventilation (VE) achieved during the fire exercise were 83.4 ± 13.5 and 85.1 ± 23.5 L/min on day one and two. These calculated VE values represent 90.0± 18.9 and 85.8 ± 25.6 % of $V_E$max, respectively.

The foregoing data suggest that a live burn training exercise elicits a significant physiological strain as seen in both pre- and post-burn data. Elevated heart rates and lactate values near 4.0 mM/L, the onset of blood lactate accumulation (OBLA), prior to entry into the fire indicate an anticipatory response by the firefighters. Additionally, post-burn lactate double that at pre-burn, heart rates near 85 percent their age predicted max, and minute ventilations above 80 L/min (or 85+% VEmax) indicate a significant physical challenge the firefighters undergo during the live fire exercise.

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ACKNOWLEDGEMENTS

The completion of this project represents the culmination of many days and months of time and effort from many different people to get me to this point. Therefore, my appreciation and thanks goes out to the Northern Colorado Fire Consortium, particularly Glenn Levy and Brad Kobielusz from the Poudre Fire Authority for convincing each of the fire chiefs from each department to sign on and agreeing to this study; as well as the firefighter cadets who participated as subjects in this study. To my thesis committee, for their support and advice through this entire process, particularly Dr. Matt Hickey for the unprecedented amount he has done for me in my graduate career. A special thanks goes to Tiffany Lipsey for not only her idea for this study, but her unwavering help and support from the data collection to my defense. To my parents and brother: you have taught me the value of hard work, dreaming big, and being a man of hope, love, and faith. I appreciate and love you more than you will ever know. Lastly, I must thank my Lord and Savior Jesus Christ—through Him all things are possible.

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CHAPTER I

INTRODUCTION

The primary source of power for the production of work comes from the contraction of skeletal muscle. However, a variety of ways of reducing or eliminating the requirements for muscle power have been developed. Such techniques typically involve utilizing mechanical advantage provided by tools, levers, engines and similar labor-saving devices. Today with the help of robots and computers, technology has allowed many companies to become a nearly hands-free environment, and work-site occupational demands have, in many settings, declined considerably. Perhaps not surprisingly, fewer workers are likely to be capable of working a full day of manual labor (Sharkey & Davis, 2008).

In addition to changes in occupational environments, labor saving devices around the home allow most Americans to go about their day with minimal physical effort. Unfortunately, there are consequences to these luxuries: degenerative diseases associated with inactivity and overweight, such as heart disease—the number one killer in the United States—are epidemic (National Institute on Aging, 2007).

Despite the foregoing, physically demanding jobs still exist in a number of fields, including mining, forestry, agriculture, construction and public safety (Sharkey & Davis, 2008). In sport, athletes train daily to compete at the highest level possible. For those jobs that involve rigorous physical effort on a daily basis, it may be useful to start considering those employees as ‘occupational athletes’. Given this, employers should provide the necessary time and training to their ‘athletes’ which allow them to complete their jobs in the safest and most efficient manner possible.

Any worker must possess certain physical characteristics to be successful in occupations that are physically demanding. Recent data classify more than two-thirds of Americans over the age of 20 years of age as overweight (BMI > 25) or obese (BMI > 30), both of which are likely to be detrimental to work performance and health in those occupational settings that require significant physical work capacity (Statistics, 2008). Firefighters for instance, must combine both physical strength and stamina, thus they need to train the heart as much as every other muscle. In this context, aerobic fitness or VO_2max is defined as the ability to take in, transport, and use oxygen, and thus captures both cardiovascular and skeletal muscle work capacity. Two variables directly related to aerobic fitness, but measured in different units are aerobic capacity and aerobic power. Aerobic capacity is measured in liters of oxygen consumed per minute (L/min), whereas aerobic power is measured in oxygen consumed per unit of body weight (ml/kg/min) (Sharkey & Davis, 2008). Aerobic capacity is an indicator of the maximal size of the aerobic motor (the heart and skeletal muscle), however, it is related to body size, so larger people in general have higher values. Aerobic capacity is related to performance in non-weight bearing sports, such as rowing and swimming. Aerobic power is related to performance in weight-bearing sports, like running and Nordic skiing. When relating it to occupational athletes, aerobic capacity may be important in some fields, but aerobic power is a better indicator of work capacity in fields like firefighting. Work capacity is defined as a workers' ability to accomplish production goals without excessive fatigue and without becoming a hazard to themselves or coworkers (Sharkey & Davis, 2008). A 2003 study found in wildland firefighting, aerobic power is inversely related (r = -0.87) to the time it takes to reach a safety zone (B. Ruby, Ledbetter, Armstrong, & S, 2003). Simply put, this data suggests that those individuals with high aerobic power are better equipped to retreat to safety than their less fit counterparts. For a fire chief, their first priority is always the safety of their own firefighters, before saving infrastructure or even victims. Therefore, understanding the physiological strain firefighters undergo when exposed to live fires will help us better understand what types of physical training will be best that will allow them to work safely at a higher capacity for longer periods of time.

Statement of the Problem

Determine the physiological strain put on to firefighters as they are exposed to a live fire training drill.

Specific Aims

Specific Aim #1

Measure the physiologic strain put on firefighters exposed to live fire as measured by:

a. Blood lactate levels
b. Heart rate
c. Blood pressure
d. Time exposure to fire
e. Respiratory minute volume

Hypothesis

The physiological strain of a live burn exercise will require heart rate, blood pressure, blood lactate, and minute ventilation beyond that of which the firefighters could sustain in a full working day.

CHAPTER II

LITERATURE REVIEW

WORK PHYSIOLOGY

Work physiology (′wərk ′fiz·ē′äl·ə·jē) is an aspect of occupational health and safety that takes into account metabolic cost, measurement and prevention of work strain, and other ergonomic factors in the design of tasks and workplaces (Astrand, Rodahl, Dahl, & Stromme, 2003). The main objective of the work physiologist is to enable working individuals to accomplish their tasks without undue fatigue so that at the end of the working day, they are left with sufficient vigor to enjoy their leisure time (Astrand, Rodahl, Dahl, & Stromme, 2003).

With the development of mechanization, automation, and many work-saving devices in both the home and work, modern technology has eliminated much of the occupational and non-occupational physical work. However, some physically demanding jobs still exist in a number of occupations including mining, commercial fishing, forestry, agriculture, transportation, construction and public safety (Astrand, Rodahl, Dahl, & Stromme, 2003; Sharkey & Davis, 2008). There is an increasing tendency in all occupations to reduce or eliminate physical strain, while simultaneously increasing productivity. Technology has accelerated the tempo of most industrial operations while cutting out the need for physical labor. In addition, the relative short work week has created a setting where there is less need for workers in industrial settings. The outcome has resulted in work that is more physically and mentally monotonous than demanding (Astrand, Rodahl, Dahl, & Stromme, 2003; Sharkey & Davis, 2008).

Although the physical demands of occupations have changed over time, the importance of work physiology research has not. The Harvard Fatigue Laboratory was a first of its kind exercise physiology laboratory with its initial focus being on various components of physiology in industrial settings. The importance of the Harvard Fatigue Laboratory's impact on the origin, emergence, and establishment of the discipline of exercise physiology in the United States is immeasurable. The Harvard Fatigue Laboratory was established in the basement of the Harvard Graduate School of Business in 1927. During its twenty year tenure over 330 books and articles were published by over 150 authors and co-authors (Chapman, 1990). Essentially the godfathers of exercise physiology were found in this Laboratory—David Bruce Dill, Arlie Bock, Lawrence J. Henderson, Steven Horvath, R.E. Johnson, and Ancel Keys. Classic studies on agricultural fieldwork (sharecroppers), high altitude mining operations, and laborers working on the Hoover Dam are among the most notable fieldwork completed by the Harvard Fatigue Lab personnel. With such success, the activities of the Laboratory became a template for each of these men as they spread across the country to establish their own labs following the closure of the lab in 1947. The three main interests of the Laboratory were "physiological, psychological and sociological specifically geared toward industrial workers" (Dill, 1967). Today, few labs still exist that focus on physiology in occupational settings; especially those that serve as civil servants such as firefighters, law enforcement and military. It goes without saying that fifty years after the closure of the Harvard Fatigue Laboratory, its influence is still seen in the field of physiology today. However, for those that protect our homes, streets, and country; it may be good to return to the roots of this field and serve them in some way that we can make their jobs and lives safer while they protect ours. Therefore, the task facing the work physiologist in the field today is to assess the strain imposed on the worker by the working environment and determine ways to properly train employees.

COMPONENTS OF PHYSICALLY DEMANDING JOBS

Work is considered physically demanding when it requires high energy expenditure, intense muscular effort, or a combination of the two (Sharkey & Davis, 2008). Workers in heavy industry, construction, agriculture, mining, forestry, firefighting, law enforcement, and the military are often required to engage in strenuous effort. These occupations and others require strength and endurance at least some of the time while on the job. Other components can make work difficult and stressful, such as the vigilance required of air traffic controllers, or the repetition of an assembly line worker (Sharkey & Davis, 2008). However, the two major components that define physically demanding jobs are energy expenditure and muscular effort.

Energy Expenditure

To perform work, the body requires the energy that is released during the metabolism of fat, carbohydrate, and protein. Several studies have classified the energy expenditure needed for various common jobs (Table 1) (Durnin, 1967; Durnin & Passmore, 1967; B. C. Ruby, Schoeller, Sharkey, Burks, & Tysk, 2003; B. C. Ruby et al., 2002). For example, when oxygen and energy demands are low, such as office work at a desk, this is considered light work. Light work generally is not limited by the ability to take in, transport and use oxygen (aerobic fitness). However, when oxygen and energy needs are moderate or high (over 5 kcal per minute) work production is directly related the ability to sustain aerobic energy production (Durnin & Passmore, 1967).

Table 1: Physical Work Classification: Energy Expenditure

Classification	Caloric cost	Oxygen cost	Examples
Light	< 2.5 kcals/min	< 0.5 L/min	Desk work
Moderate	2.5 - 5	0.5 - 1.0	Chores, repairs, walking
Heavy	5 - 7.5	1.0 - 1.5	Chain sawing, shoveling
Very Heavy	7.5 - 10.0	1.5 - 2.0	Chopping wood, digging
Extremely Heavy	> 10.0	> 2.0	Hiking uphill with pack, jogging

Adapted from U.S. Department of Labor, 1968, D*ictionary of occupational titles* (Washington D.C.: U.S. Government Printing Office) and P.O. Astrand et al., 2003, *Textbook of Work Physiology*, 4th ed. (Champaign, IL: Human Kinetics).

Moderate levels of work (2.5 – 5 kcal per minute) can be demanding when done for long periods and when environmental factors such as heat and humidity increase the physiological stress on the worker. Heavy and very heavy work place an even greater burden on the worker, requiring more frequent rest breaks. Extremely heavy work (above 10 kcal per minute or 2 liter per minute of oxygen) occurs in the military, law enforcement, and structural firefighting (Sharkey & Davis, 2008). This type of work can be sustained for prolonged periods of time by highly trained workers and occupational athletes specifically conditioned for the task, but can only be done sporadically by those with lower fitness levels. Several studies have demonstrated that highly fit (VO_2max > 55ml/kg/min) workers can work at nearly 50 percent of their aerobic fitness for an eight hour work day, whereas unfit (VO_2max < 45 ml/kg/min) workers can only sustain 30 percent of their max aerobic fitness for this duration (Figure 1) (Astrand, Rodahl, Dahl, &

Stromme, 2003; United States Bureau of Employment Security., Eckerson, & United States Employment Service., 1966; United States Employment Service., 1965).

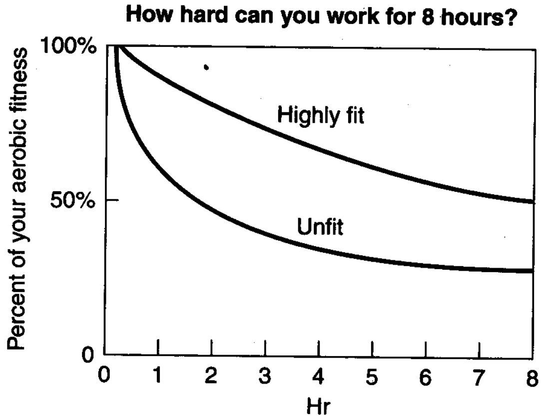

Figure 1: Fitness and work capacity (B.J. Sharkey, 2002, *Fitness and Health,* 5th ed., Champaign, IL: Human Kinetics)

According to Sharkey and Davis (2008), when hard work is required, people with a low level of aerobic fitness ($VO_2max \leq 45$ ml/kg/min) are able to sustain only 25 percent of their maximum work capacity over an eight hour work day. Those of average fitness (VO_2max 45 to 55 ml/kg/min) can work at about 33 percent, whereas those with above-average fitness ($VO_2max \geq 55$ ml/kg/min) can maintain 40 percent of their capacity for eight hours. Only highly conditioned and motivated workers can sustain levels as high as 50 percent or greater of their aerobic fitness level for eight hours.

There are some occupations that require workers to engage in bouts of extremely heavy work interspersed with periods of rest. For example, police officers spend hours behind the wheel of their patrol car, but can be called on for an all-out effort of catching and subduing a suspect. Structural firefighters work hard to extinguish a fire for bouts of five to twenty minutes, and then recover while their self-contained breathing apparatus (SCBA) is fitted with a bottle of fresh air.

When the demands of a job require energy expenditure that is extremely high, it may exceed the aerobic capacity of some workers. When this happens, workers use more energy from nonoxidative, or anaerobic, metabolism. This is not to say that aerobic metabolism does not occur before this point, just simply that a shift has occurred where a greater percentage of the metabolism is of the nonoxidative type. An associated consequence of this fate is the accumulation of metabolites (hydrogen ions) and the development of metabolic acidosis, causing muscles to fatigue (more on this in section covering *Anaerobic Processes / Lactate Production, Distribution, and Disappearance* under Physical Performance Demands below). Anaerobic energy production is highly inefficient, producing only three units of energy (adenosine triphosphate or ATP) from every one molecule of glucose that traverses the entire glycolytic pathway. Oxidative or aerobic energy production produces approximately 36 ATP from the same amount of glucose. For this reason as well as the accumulation of metabolic byproducts, anaerobic energy production can only be maintained for brief periods.

Muscular Fitness

Muscular fitness consists of strength, muscular endurance, and power. Strength is the ability to lift heavy objects; muscular endurance is the ability to do repetitive contraction with lesser weights; and power is the ability to do work rapidly *(Sharkey, 2002).* Dynamic muscular strength is clearly related to work capacity when the work requires the lifting of very heavy loads or the use of heavy tools. *Selected*

Characteristics of Occupations by Worker Traits and Physical Strength, a publication by the United States Department of Labor, describes and arranges data on physical demands, working conditions, and training time for each job defined in the Dictionary of Occupational Titles. Table 2 defines the physical work classification of muscular work (Astrand, Rodahl, Dahl, & Stromme, 2003; United States Bureau of Employment Security., Eckerson, & United States Employment Service., 1966; United States Employment Service., 1965).

Table 2: Physical Work Classification: Muscular

Work Classification	Lifting lb (kg)	Carrying lb (kg)
Very Light	Up to 10 (4.5)	Small objects
Light	Up to 20 (9.1)	Up to 10 (4.5)
Medium	Up to 50 (22.7)	Up to 25 (11.3)
Heavy	Up to 100 (45)	Up to 50 (22.7)
Very Heavy	Over 100 (45)	Over 50 (22.7)

Adapted from U.S. Department of Labor, 1968, *Dictionary of Occupational Titles* (Washington, D.C.: U.S. Government Printing Office) and P.O. Astrand et al., 2003, *Textbook of Work Physiology*, 4th ed. (Champaign, IL: Human Kinetics)

Construction workers engage in heavy work when they lift and carry lumber and concrete bags weighing over 100 pounds or lift heavy frame walls. Structural firefighters wear personal protective clothing and breathing apparatuses (SCBAs) that may weigh upwards of 50 or 60 pounds. In addition to this burden, they carry hoses and tools, and climb steps or ladders, in the course of firefighting. Clearly a combination of physical strength and endurance is optimal for such occupational demands.

Energy and Muscular Requirements

Not all work is physically demanding. Many factory jobs have been made less difficult with mechanical devices to reduce energy and muscular demands. The backbreaking work of the longshoreman or stevedore has been eliminated with cranes and cargo boxes (Sharkey & Davis, 2008). Forestry, once one of the most demanding of occupations, is now made easier with mechanized tree harvesters that cut, delimb, and stack trees. But mechanized aids are not available for all occupations, such as firefighting, construction and the military.

The energy and muscular requirements of hard work can be determined from published studies or estimated in the field. One such study, done by Passmore and Durnin (1955) defined the energy requirements of various work tasks (Table 3). This study built upon Wilbur Atwater's classic study at the end of the 19th century that influenced many areas of American life, especially the awareness of the food calorie as a unit of measure both in terms of consumption and metabolism, (Darby, 1994; Passmore & Durnin, 1955).

Table 3: Energy Requirements of Work Tasks

Work task	Kcal/min	Work Task	Kcals/min
Light Work		Medium Work	
Desk Work	2.5	Paving Roads	5.0
Standing, light activity	2.6	Gardening, weeding	5.6
Driving	2.8	Walk 3.5 mph (road/field)	5.6, 7.0
Washing clothes	3.1	Stacking lumber	5.8
Walking indoors	3.1	Chainsawing	6.2
Making bed	3.4	Laying stone	6.3
Drive motorcycle	3.4	Using pick or shovel	6.7
Metalworking	3.5	Shoveling (miners)	6.8
House painting	3.5	Walking downstairs	7.1
		Heavy Work	
Walk downhill 2.5 mph (-5, 10, 15% grade)	3.5, 3.7, 4.3	Shoveling snow	7.5
Cleaning windows	3.7	Chopping wood	7.5
Carpentry	3.8	Hike with 45 lb (20kg) pack	7.5
Farm chores	3.8	Crosscut sawing	7.5, 10
Sweep floors	3.9	Walking uphill 3.5 mph (+5, 10, 15% grade)	8, 11, 15
Plastering walls	4.1		
Auto repair	4.2	Tree falling (ax)	8.5, 12
Ironing	4.2	Gardening, digging	8.6
Raking, hoeing	4.7	Very Heavy Work	
Mix cement	4.7	Walking upstairs	10+
Mopping floors	4.9	Jogging	10

Energy cost depends on efficiency and body size. Add 10% for each 15 lb (6.8 kg) over 150 lb (68 kg); subtract 10% for each 15 lb below 150 lb.

Adapted from Human Performance Laboratory, University of Montana, 1964-present, R. Passmore and J. Durnin, 1955, "Human energy expenditure," *Physiological Review* 35: 801-824, and E. Roth, 1968, *Compendium of human responses to the aerospace environment: Volume III* (Washington D.C., National Aeronautics and Space Administration).

Their rationale was that as industry changes, with machines increasingly doing the work formerly done by manual labor, as well as the increase demand for production and shortened work week, a reassessment of human energy expenditure in the work place was needed (Passmore & Durnin, 1955). Energy expenditure can be estimated from working heart rates or by indirect calorimetry. Muscular requirements can be estimated by observing the loads lifted and carried, and work rates can be estimated by recording the number of lifts per minute. Table 4 lists the energy and muscular requirements for selected occupations taken from Dictionary of Occupational Titles (Astrand, Rodahl, Dahl, & Stromme, 2003; United States Bureau of Employment Security., Eckerson, & United States Employment Service., 1966; United States Employment Service., 1965). However, because few occupations maintain a single work rate over a given day, a range of values is provided by the authors.

Table 4: Occupational Work Classification

Occupation	Energy (kcal/min)	Muscular demand*	Comments
Farm Labor	4.0 - >7.5	Medium	Pick, carry, load
Construction	4.0 - 10.0	Heavy	Hand tools, lift, carry
Mining	4.0 - 7.5	Light - Heavy	Pick, shovel
Law enforcement	2.5 - 10.0+	Very light - very heavy	Run, subdue
FIREFIGHTING			
Structural	7.5 - 10.0	Medium - very heavy	Climb, chop, lift, carry
Wildland	6.5 - 10.0	Heavy - very heavy	Dig line, carry hose
MILITARY			
Army, Marines	2.5 - 10.0+	Medium - very heavy	Hike, climb, carry
Navy, Air Force	2.5 - 7.5	Medium - heavy	Lift, carry, load

* See lifting and carrying loads in Table 2 above

Adapted from *Hard Work* (Champaign, IL: Human Kinetics)

For repeated lifting, as in moving loads or working with hand tools, energy and muscular requirements combine to set the limits of work capacity. Workers with a high level of aerobic fitness can work at a higher work rate than those with lower levels; therefore they can do more muscular contractions per minute. However, individuals with greater strength than others can lift a load that is a lower percentage of their maximal strength; therefore stronger workers can lift more with each repetition. Thus having an ideal combination of aerobic capacity and strength is ideal for physically demanding tasks. Figure 2 shows that highly fit workers (aerobic fitness = 55 ml/kg/min) can work at a higher rate (measured by muscular contractions per minute) than unfit workers (aerobic fitness = 45 ml/kg/min) while lifting a load at a given percentage of their maximum strength (Sharkey, 2002). Combinations of work rate and percentage of maximum strength that fall to the right of the line represents the fitness level that cannot be sustained for a full working day.

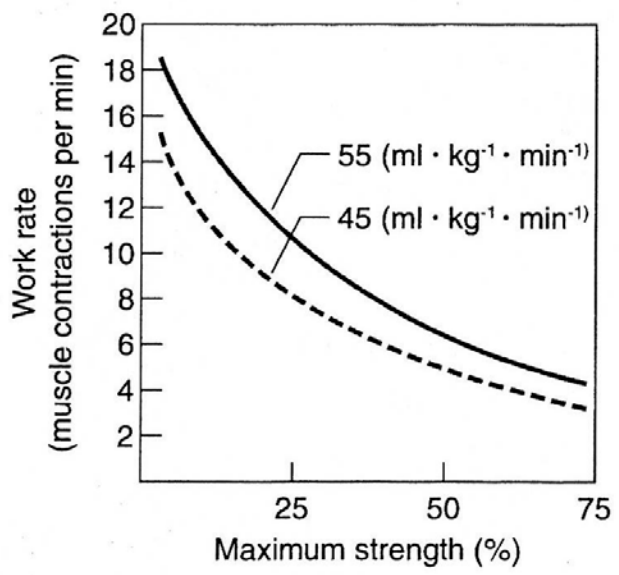

Figure 2: Strength, aerobic fitness, and work rate (B.J. Sharkey, 2002, *Fitness and Health*, 5th ed., Champaign, IL: Human Kinetics)

FACTORS AFFECTING WORK PERFORMANCE

The relationship between work rate and work capacity is affected by a complicated interaction of many factors, which must be taken into consideration (Figure 3) (Astrand, Rodahl, Dahl, & Stromme, 2003). The ability to perform physical work depends on the ability of the muscle cell to transform chemical energy in food into mechanical energy for muscular work. This in turn depends on the ability of the physiological functions that deliver fuel and oxygen to working muscle.

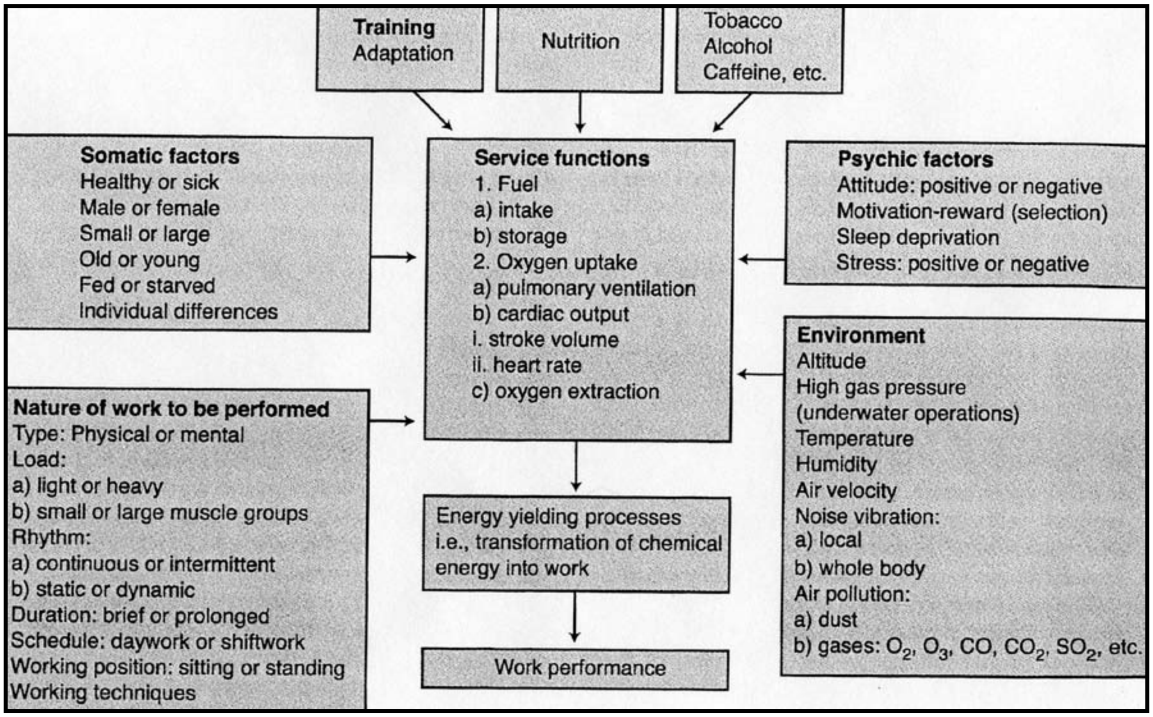

Figure 3: Factors affecting work performance (P.O. Astrand et al., 2003, *Textbook of Work Physiology*, 4th ed. (Champaign, IL: Human Kinetics)

Many of these physiological functions depend on somatic factors such as sex, age, body composition, state of health, and other individual factors. Additionally, physical performance is influenced by psychological factors, most notably motivation, attitude at work, and stress levels. Several of these factors are in turn affected by training and adaptation. One set of famous experiments originally done on factory workers between 1924 and 1932 at the Hawthorne Works factory outside of Chicago studied the effects of lighting on worker productivity. Their original findings were that worker productivity improved as illumination increased in the facility (Roethlisberger & Dickson, 1939).

Later however, they found it was not the lighting, but instead a phenomenon coined the *Hawthorne effect (Landsberger, 1958)*. The Hawthorne effect was originally defined as a short-term improvement caused by observing worker performance. Since then the idea has been broadened to people being more productive when appreciated or when watched.

Physical performance is also greatly influenced by factors in the external environment. For example, air pollution affects physical performance directly by increasing airway resistance and thereby decreasing pulmonary ventilation (Horino, 1977). The same applies to alcohol and tobacco use, both of which cause acute and long-term changes that negatively impact work capacity (John, Riedel, Rumpf, Hapke, & Meyer, 2006; Price & Hicks, 1979). Noise is a stress that not only damages hearing but also elevates heart rate and affects other physiological parameters that reduce physical performance (Horino, 1977; Karlqvist, Harenstam, Leijon, & Scheele, 2003; Matticks, Westwater, Himel, Morgan, & Edlich, 1992). Cold weather can reduce physical performance due to numbness of the hands or lowered core body temperature. Additionally, the effects of bulky cold-weather clothing can slow-down normal simple functions of a work day (Gray, Consolazio, & Kark, 1951; Nelson, Shelley, Horvath, Eichna, & Hatch, 1948; Pascoe, Bellingar, & McCluskey, 1994). Heat can greatly reduce endurance because more blood is taken to the surface of the skin to cool the body instead of being used to transport oxygen to the muscles forcing workers to perform at lower levels for shorter periods of time throughout the day (Altareki, Drust, Atkinson, Cable, & Gregson, 2008). Additionally high sweat rate can lead to dehydration in workers unless they are hydrating adequately (Latzka et al., 1998). Hyperbaria is a relatively new and unique problem encountered in a select few occupations. High gas pressures, encountered in underwater operations such as offshore oil exploration or even in some mining operations need to be considered (Le Pechon, 2006). Conversely, work in hypobaric environments, especially for workers not acclimatized can limit work performance, especially in unfit workers (McCall & Frierson, 1997). Work in space represents another set of problems not encountered anywhere on Earth. In fact, significant muscle atrophy has been noted after only five days in space (Vandenburgh, Chromiak, Shansky, Del Tatto, & Lemaire, 1999). Much of what is known about the consequences of zero gravity environments has come from short-duration flights; for long-term manned space flight, many important questions remain unresolved. Last, the nature of the work to be performed—separate from work intensity and duration—is important when considering one’s capacity to do physical work. In a general sense, all life functions operate in a rhythmic and dynamic fashion. A person’s daily life run on a work-rest-work schedule at fairly regular and relatively short intervals. Even the simplest of motor skills in a person’s life operates this way, as muscles are required to contract then relax then contract again, and so on. These brief periods of work (muscular contraction) are interspersed with periods of rest or recovery (muscular relaxation). This routine provides some rest during the actual work period so the worker can avoid fatigue or exhaustion. Work position is important as studies have shown that working in a standing position represents a greater circulatory strain than does working in a sitting position (Hettinger & Rodahl, 1960; Horino, 1977). However, working in a standing position that allows the worker to move and thus vary the load on individual muscle groups and facilitate circulation is preferable (Hettinger & Rodahl, 1960). Working technique is another factor that affects work performance. The monotony of working on an assembly line or other operation can be a stress for some people, physically and mentally, for others it may provide relief as they can perform their job almost innately while thinking about something completely different. Finally, the work schedule, whether it be a nine-to-five job or shift work, is garnering attention as a problem impacting work performance, possibly due to circadian rhythms entrained by external cues, called Zeitgebers (Nakata et al., 2001; Saijo, Ueno, & Hashimoto, 2008).

DETERMINANTS OF AEROBIC CAPACITY

Physical Characteristics of Workers

The average worker in the United States is taller and heavier than ever before. In 1960, men averaged 5 feet 8 inches in height and women averaged 5 feet 3 inches; today men and women are 1 ½ and 1 inches taller, respectively. The average weight for men has increased from 166.3 pounds in 1960 to 191 pounds in 2002. For women that weight has increases from 140.2 pounds in 1960 to 164.3 pounds in over the same time period (NCHS, 2003-2004). It would make sense that because we are taller on average we would also weigh more, however, the added weight has been predominantly adipose tissue and not muscle. Data on body mass index (BMI), a ratio of weight to height (BMI = weight (kg) / height^2 (m)), shows an increase in American adults from 25 in 1960 to 28 in 2002 (NCHS, 2003-2004). Both the World Health Organization (WHO) and the National Institute of Health (NIH) define a BMI of 25 to 29.9 kg/m^2 as overweight, and a BMI above 30 as obese. Recent data classify more than 66 percent of American adults over 20 years of age as overweight or obese (NCHS, 2003-2004).

Aerobic Fitness

Aerobic fitness or VO_2max is defined as the ability to take in, transport, and use oxygen. Two other variables directly related to aerobic fitness, but measured in different units are aerobic capacity and aerobic power. Aerobic capacity is measured in liters of oxygen consumed per minute (L/min), whereas aerobic power is measured in oxygen consumed per unit of body weight (ml/kg/min) (Sharkey & Davis, 2008). Aerobic capacity is an indicator of the maximal size of the aerobic motor (heart, lungs, blood, muscle), however, it is related to body size, so larger people in general have higher values. Aerobic capacity is related to performance in non-weight bearing sports, such as rowing and swimming. Aerobic power is related to performance in weight-bearing sports, like running and Nordic skiing. When relating it to occupational athletes, aerobic capacity may be important in some fields, but aerobic power is a better indicator of work capacity in fields like firefighting.

Gender

Before puberty, boys and girls differ little in their aerobic fitness, but from here forward females fall behind. Young women average ten to twenty percent lower in aerobic fitness compared to men, depending on their activity level. More highly trained female endurance athletes are only ten percent (or less) below elite males in VO_2max and performance times (Helgerud, 1994). Until the 1970's, women were discouraged, or even banned, from competing in hard work or distance races longer than one-half mile. "Experts" were afraid that females couldn't handle the physical strain of the event. However, today women run marathons and 100-mile endurance races, compete in the

Ironman triathlon, as well as other events that require a high level of aerobic fitness. Over time, women are proving that not only can they complete, but they are closing the time difference between men and women in these events as well.

Age

Generally, aerobic fitness declines with age after the age of 30 to 40 depending on the individual. At the age of 60, VO_2max is about 75 percent of the level at age 20. The rate of decline approaches 8 to 10 percent per decade for inactive people, regardless of their initial fitness level. Those who remain active can cut that decline in half (4 to 5 percent per decade), and those who activity train for aerobic fitness events have an even slower rate of decline (2 to 3 percent per decade) (F. Kasch, Wallace, Van Camp, & Verity, 1988). It should be noted that some studies have shown that aerobic fitness can improve even after the age of 70 (F. Kasch, Boyer, Van Camp, Verity, & Wallace, 1990).

Body Composition

Aerobic fitness is measured per unit of body weight. Therefore if fat increases, fitness decreases or vice-versa. Most of the decrements seen in fitness over time are due to an increase in body weight which correlates strongly with inactivity. One study found that both body fat and lean body weight were significantly (statistically) correlated to total work performance in wildland firefighters (Sharkey, 1981).

Muscular Fitness

In the early 1970's, few, if any, women were wildland firefighters. As a result, researchers developing a test for work capacity in firefighters saw no need to include a test for muscular fitness. Instead they focused on aerobic power, believing it to be the limiting factor in work performance. When the test for aerobic fitness was implemented in 1975, it also coincided with the entry of more women to the firefighting workforce. Soon after, crew chiefs became concerned that some firefighters (most of whom were women) lacked sufficient strength to perform their job (Sharkey & Davis, 2008). Sharkey (1981) performed a large field study (N = 121) analyzing the relationship between muscular fitness and performance and found that measures of strength, muscular endurance, as well as lean body weight, were indeed significant predictors of work performance (Sharkey, 1981).

PHYSICAL PERFORMANCE DEMANDS

Aerobic Processes

See section on *Energy Expenditure* under Components of Physically Demanding Jobs above.

Anaerobic Processes / Lactate Production, Distribution, and Disappearance

It is well documented that skeletal muscle is a major producer of lactate in the body. In fact, Otto Fritz Meyerhof, a German physiologist and biochemist, shared the 1922 Nobel Prize for medicine or physiology with English physiologist Archibald Vivian Hill for research on the chemical reactions of metabolism in muscle, specifically focusing on the glycogen-lactic acid cycle. However, in the last 35 years our understanding of lactate metabolism has changed dramatically. The traditional view has been that lactate is a waste product that is produced in skeletal muscle during anaerobic exercise, responsible for such unwanted effects as muscle soreness and fatigue. Conversely, it is now clear that lactate is a normal metabolic intermediate, even under aerobic conditions. Some studies have shown that under fully aerobic conditions, as much as 50 percent of the glucose metabolized is converted to lactate (Connett, Gayeski, & Honig, 1984; Gladden, 1991).

Lactate is now known to be exchanged among several tissues, including skeletal muscle, heart, liver, and brain (Juel & Halestrap, 1999). The transmembrane transport of lactate is mediated by a family of monocarboxylate transporters (MCT). In addition to lactate transport, it is apparent that they play a role in pH regulation of skeletal muscle, as MCT co-transport protons (Juel & Halestrap, 1999). Skeletal muscle contains both MCT1 and MCT4 isoforms. The amount of MCT1 is correlated with the aerobic capacity of the muscle fiber, possibly because MCT1 has been found in mitochondrial membranes (Brooks, Fahey, & Baldwin, 2005). Consequently, there is more MCT1 in type I than type II muscle fibers. MCT4 on the other hand is found in all muscle fiber types (Juel & Halestrap, 1999). These transporters are bidirectional, meaning that they are able to transport lactate in both directions across cell membranes depending on the hydrogen ion (H^+) and lactate gradient (C. M. Donovan & Pagliassotti, 2000).

There are several alternatives to the fate of lactate once produced. In addition to being an important metabolic intermediate for the muscle cell itself, lactate is a very important molecule for the transfer of energy substrates from one muscle cell to another.

Once a glucose molecule is phosphorylated, it is trapped inside the muscle cell; it cannot be released from the cell until it is converted to pyruvate or lactate. Following uptake of lactate in the heart or liver, lactate can be converted back to pyruvate. From that point, there are two alternative routes: (1) The pyruvate can be oxidized (primary fate in the heart), or (2) it can be used as a substrate for synthesis of glucose and glycogen; also known as gluconeogenesis (primary fate in the liver).

The effects of lactate accumulation on blood and tissue pH are misunderstood. The hydrolysis of one ATP produces one proton. However, during oxidative phosphorylation, all the products of ATP hydrolysis—adenosine diphosphate (ADP), inorganic phosphate (Pi), and H^+—are reutilized. Therefore, there is no net accumulation of H^+ in aerobic metabolism. Contrary to popular belief, during anaerobic glycolysis lactate accumulation is not the source of intracellular pH decrease (Busa & Nuccitelli, 1984). Lactate, like pyruvate, has a carboxylic acid function group. Functional groups of carboxylic acid each have their own acid dissociation constant (pK_a) which is the pH at which that functional group is 50 percent ionized or 50 percent protonated. Due to the relatively low pK_a (pH = 3.87) of the carboxylic acid group on lactate, there is complete ionization of lactate across the range of human physiologic pH values (~ 6.2 – 7.5) (Busa & Nuccitelli, 1984; R. A. Robergs, Ghiasvand, & Parker, 2004). Thus, healthy human cellular pH values can never reach the pK_a of the carboxylic acid group on lactate and thus, there is virtually no direct association between this functional group and the hydrogen ions produced during anaerobic glycolysis.

The rate of glycolysis is determined by the need to resynthesize ATP. Thus, a greater work output creates a higher demand for ATP, and thus increases flux through gylcolysis. In this way, the rates of ATP hydrolysis and lactate formation are coupled. Therefore it's not surprising that there is a high correlation between increased lactate formation and decreased pH values in blood and skeletal muscle samples taken at rest as well as during exercise due to the accumulation of metabolites (particularly hydrogen ions) resulting in metabolic acidosis, and the fact that the MCTs co-transport lactate and hydrogen ions (Busa & Nuccitelli, 1984)

FACTORS AFFECTING PHYSICAL PERFORMANCE

Altitude

Although millions of people live at elevations above 10,000 feet (3,050 m), very few permanent residents are found above 18,000 or 19,000 feet (4,488 – 5794 m), suggesting that above that elevation, humans are incapable of surviving long-term. Thousands of people have made it to the top of the Earth on Mount Everest (29,029 ft or 8,848 m); some even without supplemental oxygen, but climbers have coined the upper reaches of Everest as the "death zone" for a reason. As one ascends in elevation, the barometric pressure (P_{bar}) declines because the weight of the air column above it gets less. As the pressure decreases, less oxygen is available (due to its ability to bind to hemoglobin), affecting the ability to take in, transport, and use oxygen. Working at elevations below 5,000 feet (about 1,500 m) has little noticeable effect on gas transport and utilization. However, as one ascends above 1,500 meters, the reduced level of oxygen to the working muscles reduces their work capacity. Even highly fit workers are affected by altitude, but in general, they can still produce more than unfit workers. Over time, working at elevation leads to acclimatization by increasing air intake (ventilation), improving oxygen transport (more red blood cells), improving the use of oxygen in muscle, and increased capillaries. These physiological adjustments reduce, but never eliminate the effects of altitude on aerobic fitness (Armstrong, 2000).

Heat/Cold

Environmental temperature affects human performance. At body temperatures substantially higher than the optimal levels (36.8^{o} C = 98.2^{o} F), both physical and mental performance deteriorates because of the complicated interplay of physiological and pathophysiological processes that are heat-sensitive (Sund-Levander, Forsberg, & Wahren, 2002). Prolonged heat exposure leads to loss of body fluids, which in itself impairs performance, especially during sustained exercise. It is well known that heat stress places an additional load on the cardiovascular system. This is evident by the elevated heart rate seen in workers working at the same workload in a hot environment versus cooler environments (Kristal-Boneh, Harari, & Green, 1997). Hard work is demanding alone, but under conditions of heat, humidity and/or the sun, heat stress poses a serious threat to workers. Heat stress can be defined as a rise in core body temperature beyond safe limits (Sharkey & Davis, 2008). Evaporation of sweat is the major mechanism for heat transfer during exercise. As sweat evaporates, it cools the body. However, if fluids lost in sweat are not replaced, thermoregulatory control can become impaired, and core body temperature can climb dangerously high.

Since workers generate heat during work and clothing can be worn for protection, cold temperatures do not pose as large a threat as that of heat. However, exposure to low temperatures and wind can lead to frostbite, hypothermia, and even death. Working in the cold is primarily a matter of maintaining thermal balance, because both energy metabolism and neuromuscular functions are temperature dependent (Rodahl, 1991). Although protective clothing helps in reducing the effects of the cold, it can reduce dexterity and increases energy expenditure. In a study in Finland, Anttonen and Virokannas (1994) showed that in outdoor work during the winter, cold stress reduced working ability by up to 70 percent (Anttonen & Virokannas, 1994). The body vasoconstricts blood flow to the extremities during cold exposure as a way of protecting the vital organs of the body which can lead to a loss of fine motor movements.

Respiratory Hazards

Respiratory protection is required in some physically demanding occupations such as firefighting and other first responders. Work environments contain a number of health hazards ranging from wood smoke to life-threatening products. Some products, such as silica, coal dust, and asbestos cause disability or death years after exposure. In some cases, first responders may face unknown chemical, biological, or even radiologic or nuclear exposures. As a result, respirators are required in a number of occupations. The biological effects of respiratory hazards include: impaired pulmonary ciliary action, suppression of the immune system, reduced oxygen transport, chronic obstructive pulmonary disease (COPD), lung and other cancers, or heart disease (Sharkey & Davis, 2008). Although this is not an exclusive list, the point is that there are many adverse affects of occupational pollution, some of which are not seen until years later. Respiratory hazards are complex. The smoke from forest fires contains hundreds of products. Structural firefighters are exposed to thousands of hazards in smoke, many of which are toxic, all in a confined environment. Therefore, the use of a proper air-purifying respirator (APR) is necessary for work and survival in certain occupations. Although respirators prevent workers from inhaling the toxins of various work environments, they have also been shown to decrease work performance (Figure 4) as a result of breathing resistance, heat stress, increased dead space, and respirator weight (James, Dukes-Dobos, & Smith, 1984; Johnson et al., 1999; Johnson et al., 2000; Rothwell & Sharkey, 1996; Sharkey & Davis, 2008; Thompson & Sharkey, 1966). Additionally, APRs increase the sense of dyspnea (breathlessness) during strenuous effort and have been shown to cause claustrophobia in some subjects (James, Dukes-Dobos, & Smith, 1984; Thompson & Sharkey, 1966).

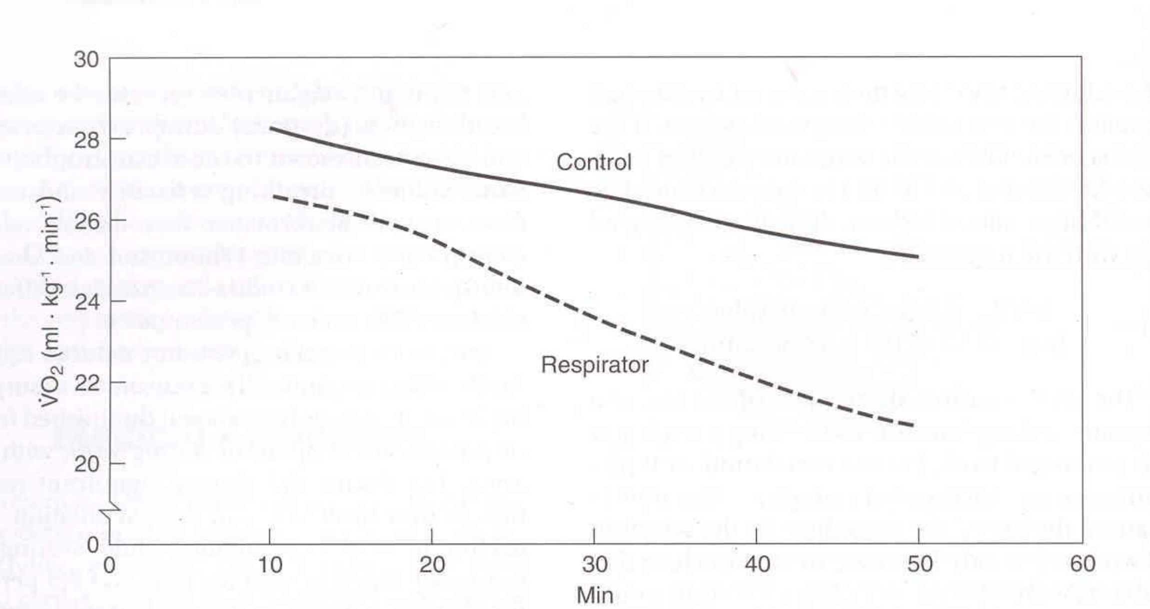

Figure 4: Effect of respiratory protection on work performance

Adapted from B.J. Sharkey, 1997, Respiratory protection. In *Health hazards of smoke: Recommendations of the consensus conference,* edited by B.J. Sharkey (Missoula, MT: USDA Forest Service) 65-74.

ASSESSING PHYSIOLOGIC STRAIN

Physiologic strain is an umbrella term that includes a multitude of variables; many of which will be discussed in the section below. Each variable can independently be defined by its physiological affect on the body, which is how the following section will be approached. However, in a general sense and for the purpose of this review physiologic strain is defined as a change in a person's normal physiologic homeostasis due to environmental stress.

Fire fighting involves relatively fit individuals performing high physical workloads in adverse conditions. While these work requirements may lead to decrements in performance or exhaustion, it is less well recognized by fire chiefs that even moderate levels of strain reduce physiological performance through detrimental effects on metabolism, digestion, hydration and cardiovascular functions.

The problem can be complicated by the combined requirements of firefighter operations in a variety of climates and by the added loads imposed from wearing protective fire fighting gear. Thus, the development of firefighter training must be informed by reliable data on the attendant physiological strain.

Physiological Strain Components Utilized in the Present Study

Borg Scale

This scale, based on the research of Gunnar Borg, is handy for quantifying the intensity of exercise or rate of perceived exertion (RPE) (G. Borg, 1970). The original scale is between 6-20, but the American College of Sports Medicine (ACSM) has also developed a similar scale between 1 and 10 (G Borg, 1998). The original RPE scale is made to correspond to the heart rate level (divided by 10) as well as the perceived exertion (G Borg, 1998). For example, when someone gives a rating of ‘somewhat hard’ (rating 13), you may also find that their heart rate is about 130 (13 x 10).

Heart Rate

As stated previously, heart rate (HR) correlates well with RPE and is therefore a good indicator of exercise or work intensity (G Borg, 1998). In a given person, there is generally a linear relationship between oxygen uptake and heart rate. Therefore, the heart rate, under standardized conditions can be used to estimate workload. In field testing standardized conditions are hard to come by; as a result, environmental conditions, working muscle groups, emotional stress levels, among other factors are all different and heart rate may vary accordingly. Heart rate can be determined by palpation, using an electrocardiogram (ECG) or by wearing a heart rate monitor that transmits a signal to a watch for display and/or storage. Today portable devices are available that not only record HR, but also environmental conditions and other physiological responses (Astrand, Rodahl, Dahl, & Stromme, 2003).

Blood Pressure

Blood pressure refers to the force exerted by circulating blood on the walls of the blood vessels. Blood pressure is often measured using a sphygmomanometer, which uses the height of a column of mercury to reflect the circulating pressure. Today, electronic devices are used to measure blood pressure and values are still reported in millimeters of mercury (mmHg), however these devices don’t actually use mercury. Blood pressures are variable from person to person and can be affected by changes in response to stress, nutritional factors, drugs, disease, exercise and temporarily from standing up (orthostatic hypotension) (Sharkey, 2002).

Blood Lactate

Lactate measurement is most often used by sport scientists, coaches and athletes to accurately determine training zones, recovery and pacing. Lactate is a metabolic product that can be measured by taking a drop of blood at a finger tip the same way diabetics monitor their blood sugar level. The blood lactate level increases with exercise intensity is a reflection of corresponding changes in blood pH. Since the Farrell et al. study in 1979, research has shown that lactate threshold is the best physiological predictor of distance running performance (Farrell, Wilmore, Coyle, Billing, & Costill, 1979), and it may be important in occupational settings involving intense physical work.

Maximal Aerobic Capacity (VO_2 max) / Aerobic Economy

Lactate measurement differs from, but is complimentary to VO_2 max testing. Aerobic capacity is the maximum capacity or volume an individual's body can transport and utilize oxygen during exercise which reflects the physical fitness of the individual. Accurately measuring VO_2 max involves a physical effort sufficient in duration and intensity to fully tax the aerobic energy system. During clinical and athletic testing, this usually involves a graded exercise test (either on a treadmill or on a cycle ergometer) in which exercise intensity is progressively increased while measuring ventilation (breathing) and oxygen and carbon dioxide concentration of the inhaled and exhaled air.

VO_2max is reached when oxygen consumption remains at steady state despite an increase in workload.

Aerobic economy is the volume of oxygen consumed at submaximal efforts. In 1930, David Dill was among the first physiologists to suggest that there are marked differences in the amount of oxygen different athletes use when running at the same speeds, and that these differences in "economy" of oxygen use are a major factor explaining the differences in running performance of athletes with similar VO_2max values (Dill, Edwards, & Talbott, 1932). If we translate this over to occupational athletes, economy may be the most important factor in predicting work performance (especially in firefighters who are dependent on supplemental oxygen) because it indicates how hard one is working in relation to the maximum ability to use oxygen. For example, if two firefighters have a VO_2max of 60 ml/kg/min and a lactate threshold of 7 minutes per mile, but firefighter A uses 40 and firefighter B uses 50 milliliters of oxygen at 7:30 pace, the pace feels easier for firefighter A because he is more economical. Therefore, firefighter A can work harder before using the same amount of oxygen and feeling the same amount of fatigue as firefighter B.

Minute Ventilation (V_E)

Respiratory minute volume (V_E) is the volume of air that one can inhale or exhale from a person's lungs in one minute. Minute volume is normally calculated by taking the tidal volume and multiplying the respiratory rate (breaths per minute). A slightly more sophisticated calculation can be done to estimate V_E from changes in respirator volume, which is more applicable to firefighters in the field. Using the ideal gas law ($PV = nRT$)

as well as initial and final pressures in their SCBA tank and maximum tank capacity, V_E can be calculated (more on this in the methods section). A normal resting V_E ranges from five to eight liters per minute (K. J. Donovan & McConnell, 1999). Higher V_E reflect greater workloads and thus higher energy expenditure. Additionally, as stated earlier, firefighters are dependent on supplemental air while fighting fire. As a result, the more air they consume (higher V_E) the quicker their air tank will become depleted and the less time they can spend attacking the fire. Additionally, firefighters work in teams or companies, when any team member runs out of air, the entire team must evacuate. Minute ventilation could have important implications for incident commanders not only estimating how long each of his or her companies can stay in a fire, but also for putting firefighters with similar V_E (and fitness levels) in the same company so there is no "weak-link" on each company.

Summary

Clearly, there is a need for simple and valid methods to quantify the physiological status of firefighters in the field and training. This would facilitate the identification of critical individual deficiencies which may impose an unsustainable physiological burden, and also provide the means by which firefighters can better train for future fire fighting operations. Both outcomes would benefit the firefighter's company, station, and department.

CHAPTER III

METHODS AND PROCEDURES

Prior to the beginning of this study, approval from the Colorado State University Human Research Committee was obtained (Appendix A). All subjects were informed of the testing procedures and the risks associated with involvement in the study. The subjects were also informed that they could withdraw from the study at any time. Informed consent was obtained from each subject prior to participation in the study (Appendix B). No monetary compensation was provided.

Subject Selection

A total of 14 healthy volunteer subjects participated in the study. All subjects completed the study. They were recruited through the Northern Colorado Fire Consortium Fire Academy. In collaboration with the Poudre Fire Authority the study was designed to examine the association between physiological fitness levels and exposure to controlled fires. The fires that these firefighters were fighting were a part of their normal training to graduate from the fire academy. The data collection was an addendum to a drill the cadets were already performing.

Determination of VO_2max

Subjects performed a progressive treadmill exercise test whereby the initial speed was set by subject choice, and grade increased by one percent every minute until exhaustion.

During the progressive exercise test, each subject was encouraged to give a maximal effort. VO_2max was recorded as the highest VO_2 value reached during the incremental test. VO_2max was confirmed when the respiratory exchange ratio (RER) was higher than 1.10.

Experimental Design

Each firefighting bout was preceded and followed by testing which included blood lactate level, weight with and without gear, blood pressure, heart rate, and self contained breathing apparatus (SCBA) air pressure levels.

Pre Fire Bout Measurements

The following measurements were taken by the same researchers throughout the duration of the study.

Blood Lactate Level

A fingertip capillary blood sample was collected to determine blood lactate concentration (Lactate Pro LT-1710, Arkray, Japan; Lactate Pro Exclusive Test Strips) on the left index finger. Lactate Pro Exclusive Calibration Test Strips (Arkray, Japan) were used to calibrate each monitor before and verified after each test according to the manufacturer's instructions. Blood was drawn using a lancet device (Softclix Pro Lancet device and Accu-chek Softclix Pro Lancets, Indianapolis, Indiana).

Mass

Mass of each subject with and without their firefighting gear on was measured to the nearest 0.5 kilograms on Detecto 439 (Webb City, Missouri).

Blood Pressure

Blood pressure was taken on the right arm of each subject prior to fire entry (Medline Standard Handheld Aneroid Sphygmomanometer, Boston, Massachusetts).

Heart Rate

Heart rate was recorded using the Polar T31 system, which was worn throughout the fire drill (Lake Success, New York). These units do not have a data recording mode, and as such, no data on heart rate during the live burn is available.

Air Pressure / Minute Volume (V_E)

SCBA air pressure was recorded to the nearest 50 pounds per square inch (PSI) five minutes after each subject had their bottles refilled. Respiratory minute volume was calculated later (see below).

Fire Bout

Timing

Prior to entry into the fire, each firefighter was followed by a timer. The timer's responsibility was to begin timing each firefighter upon entry and record the time of departure from the fire as well as the amount of time it took to get blood lactate, heart rate, blood pressure and SCBA air pressure levels after exiting.

Temperature

Temperatures of all rooms in the training building were recorded every two to three minutes during each firefighting bout from the building temperature monitor system located outside the burn building.

Post Fire Bout Measurements

The same measurements were taken as “pre fire bout” (see above). However, post fire measurements were timed after exit from the fire as to try to regulate measurements times as best as possible. Blood lactate levels were always measured first after exit. Blood pressure and heart rate were taken simultaneously either after blood lactate or during by various research assistants. SCBA air pressure levels were recorded as soon as possible, but were not first priority in taking measurements. Body mass, with and without protective gear, was recorded as well.

Calculation of minute ventilation (V_E) from SCBA air pressure

The ideal gas law is derived from the fact, that in the ideal state of any gas a given number of its particles occupy the same volume, and the fact that volume changes are inverse to pressure changes and linear to temperature changes. The state of an amount of gas is determined by its pressure, volume, and temperature according to the equation: $PV = nRT$ where P is the absolute pressure of the gas; V is the volume of the gas; n is the number of moles of gas; R is the universal gas constant; and T is the absolute temperature. Since we know that the volume, universal gas constant and temperature stay the same and because the delivered volume of gas (n) in the tank is proportional to the pressure (P) we can use this equation to calculate the amount of delivered air to the body:

$$V_{delivered} = ((P_{initial} - P_{final}) / P_{max}) \times (V_{delivered})_{max}$$

It should also be noted that because our measurements were taken in Fort Collins, Colorado at an approximate elevation of 5,000 feet, values in this study have been adjusted to take into account the changes in barometric pressure. This is important because air tanks are pressure rated at sea level and when they are brought up in elevation those ratings change. The tanks we used were rated at 40 cubic feet of air at sea level and were adjusted by multiplying 40 by (101/84) where 101 is the number of kilopascals of air (kPa) in Florida (sea level) and 84 is the number of kPa in Fort Collins, CO. This conversion equates to 48.095 cubic feet of air which is the value used to calculate the max volume of delivered air.

Statistical Analysis

Data was analyzed using SPSS 17.0 for Windows (SPSS Inc., Chicago, Illinois). Descriptive characteristics were assessed and presented as means and standard deviation or percents. Data from burn days one and two were analyzed using a 2 (day) x 2 (pre vs. post) repeated measures analysis of variance. When significant interactions were present, post-hoc analysis was conducted using the Sheffe procedure. For selected data, paired T-tests were performed to determine the differences in resting (lab visit), pre-burn and post-burn strain variables. Reliability estimates between burn 1 and 2 were determined using intraclass correlation coefficients. The intraclass correlation is a classic measure of inter-rater reliability, which is not a perfect fit for the data in question (the reliability in question is not for a “rater”, but for the strain induced by a live burn exercise). Moreover, the intraclass correlation relies on an assumption of normally distributed data. Not all of the strain data are normally distributed. Thus, Spearman’s rank-order (Rho) correlations were also calculated on burn 1 and 2 data. Spearman’s Rho is a non-parametric bivariate correlation which compares relative “ranks” for a given variable as opposed to the absolute value. In other words, if a given firefighter had the highest post-burn heart rate on day 1 and day 2, the Spearman’s Rho would be high (1.0 in this case), regardless of the absolute heart rate. Importantly, spearman’s Rho does not require normally distributed data.   In all cases, statistical significance was accepted at $P<0.05$.

CHAPTER IV

RESULTS

The final analysis consisted of 14 firefighters training to become professional firefighters in the states of Colorado and Wyoming. The firefighter cadets’ clinical characteristics were as follows (mean ± SD): age 28.8 ± 5.7 years; stature 1.8 ± 0.1 m, 70.1 ± 2.6 inches; mass 83.8 ± 12.9 kg, 184.8 ± 28.5; body mass index (BMI) 26.3 ± 3.0; maximal aerobic capacity 45.0 ± 4.4 ml/kg/min, 3.77 ± 0.6 L/min. Complete clinical characteristics of the study population are presented in Table 1.

Table 1: Characteristics of the study population

Subject #	Age	Height (in)	Height (m)	Weight (lbs)	Weight (kg)	BMI	VO2max (ml/kg/min)	VO2max (L/min)
2	28	70	1.78	190	86.2	27.3	43.4	3.74
9	23	68	1.73	175	79.4	26.6	54.5	4.34
6	29	70	1.78	187	84.8	26.8	49.3	4.19
17	24	74	1.88	180	81.6	23.1	51.1	4.18
4	27	70	1.78	228	103.4	32.7	47.2	4.89
18	33	70	1.78	178	80.7	25.5	40.9	3.31
8	38	72	1.83	184	83.5	25.0	43.1	3.6
11	26	70	1.78	205	93.0	29.4	44.1	4.11
7	31	73	1.85	220	99.8	29.0	41.6	4.16
14	26	68	1.73	145	65.8	22.0	43.6	2.87
3	24	72	1.83	175	79.4	23.7	45.4	3.61
12	22	68	1.73	150	68.0	22.8	44.1	3.01
5	29	66	1.68	151	68.5	24.4	42.7	2.93
15	44	65	1.65	154	69.9	25.6	43.7	3.06
Mean	28.8	70.1	1.8	184.8	83.8	26.3	45.0	3.77
Std. Error	1.4	0.6	0.0	6.9	3.1	0.7	1.1	0.1
Std. Deviation	5.7	2.6	0.1	28.5	12.9	3.0	4.4	0.6
Min	22.0	65.0	1.7	145.0	65.8	22.0	35.9	2.87
Max	44.0	74.0	1.9	250.0	113.4	32.7	54.5	4.89

Table 2 shows the intervention data from each trial. Table 3 shows reliability data as determined by both Intraclass Correlation and Spearman’s Rho.

Table 2: Descriptive Data with T-tests

		Day 1 (N = 14)		**Day 2 (N = 14)**	
	Rest	**Pre**	**Post**	**Pre**	**Post**
Air Tank (psi)	-	4250 ± 234.5 (3600 - 4500)	1535 ± 540.1 (900 - 2200)	4250 ± 235.8 (3800 -4500)	1822 ± 995.0 (0 -3600)
V_E (L/min)	-	83.4 ± 13.5 (62.9 - 107)		85.1 ± 23.5 (21.2 - 127.4)	
% VE max		90.0 ± 18.9 (49.1 - 123.9)		85.8 ± 25.6 (24.9 - 123.1)	
Blood Lactate (mmol/L)	-	3.3 ± 1.9 (1.1 - 7.0)	7.2 ± 3.3[¥] (2.1 - 13.6)	2.7 ± 1.0 (1.3 - 4.7)	5.3 ± 2.3[¥€] (2.2 - 11.2)
Systolic Blood Pressure (mmMg)	-	117 ± 18.7 (90 - 150)	139 ± 9.7[¥] (116 - 150)	122 ± 11.0 (106 - 142)	131 ± 17.7 (102 - 175)
Diastolic Blood Pressure (mmHg)	-	68 ± 9.1 (58 - 84)	61 ± 16.8 (40 - 96)	76 ± 8.9 (58 - 92)	68 ± 8.1[¥] (52 - 78)
Heart Rate (bpm)	67.4 ± 7.8 (55 - 81)	92.7 ± 18.0* (67 - 126)	156.8 ± 20.9* (95 - 186)	96.4 ± 13.8* (74 - 121)	156.2 ± 18.5* (123 - 187)
Fire time (min)	-	9.6 ± 1.5 (7.5 - 12.3)		9.3 ± 2.6 (5.6 - 13.8)	

* Significant ($p < 0.05$) vs. Rest

¥ Significant ($p < 0.05$) vs. Pre

€ Significant ($p < 0.05$) vs. Post

Table 3: Reliability Statistics

	ICC	Spearman's Rho
Pre Lactate (mmol/L) 1 vs. 2	0.348	0.253
	0.225	0.382
Post Lactate (mmol/L) 1 vs. 2	0.602	0.323
	0.055	0.259
Pre Systolic Blood Pressure (mmHg) 1 vs. 2	0.491	0.293
	0.118	0.309
Pre Diastolic Blood Pressure (mmHg) 1 vs. 2	0.274	0.165
	0.286	0.573
Post Systolic Blood Pressure (mmHg) 1 vs. 2	0.288	0.158
	0.274	0.590
Post Diastolic Blood Pressure (mmHg) 1 vs. 2	0.021	-0.064
	0.514	0.829
Pre Heart Rate (bpm) 1 vs. 2	0.233	0.101
	0.320	0.730
Post Heart Rate (bpm) 1 vs. 2	0.042	0.091
	0.47	0.758
Data are presented as Correlation with respective P value in the row below.		

Day 1 Burn Data

The mean (± SD) duration of fire exposures was 9.6 ± 1.5 minutes. Mean heart rate prior to entry into the fire exercise was 92.7 ± 18.0 bpm and post exercise was 156.8 ± 20.9 bpm. The firefighters had mean blood pressures of 117 ± 18.7 / 68 ± 9.1 prior to the fire exercise and 139 ± 9.7/ 61 ± 16.8 after. The mean pre-burn blood lactate recorded was 3.3 ± 1.9 mmol/L and post-burn was 7.2 ± 3.3 mmol/L. Mean minute ventilation achieved during the fire exercise was 83.4 ± 13.5 L/min, or 90.0± 18.9 % of the VE max achieved during the laboratory testing.

Day 2 Burn Data

The mean (± SD) duration of fire exposures was 9.32 ± 2.6 minutes. The mean heart rate prior to entry into the fire exercise was 96.4 ± 13.8 bpm and post exercise was 156.2 ± 18.5 bpm. The firefighters had mean blood pressures of 122 ± 11.0 / 76 ± 8.9 respectively prior to the fire exercise and 131 ± 8.9 / 68 ± 17.7 respectively after. The mean pre-burn blood lactate recorded was 2.7 ± 1.0 mmol/L and post-burn was 5.3 ± 2.3 mmol/L. Mean minute ventilation achieved during the fire exercise was 85.1 ± 23.5 L/min, or 85.8 ± 25.6 % of the VE max achieved during the laboratory testing. Figures 1 - 7 presented below represent individual changes in blood lactate, heart rate, blood pressure, and mean minute ventilation in both pre and post exercise measurements. The solid black bar on each the tables is the mean for the time point in question.

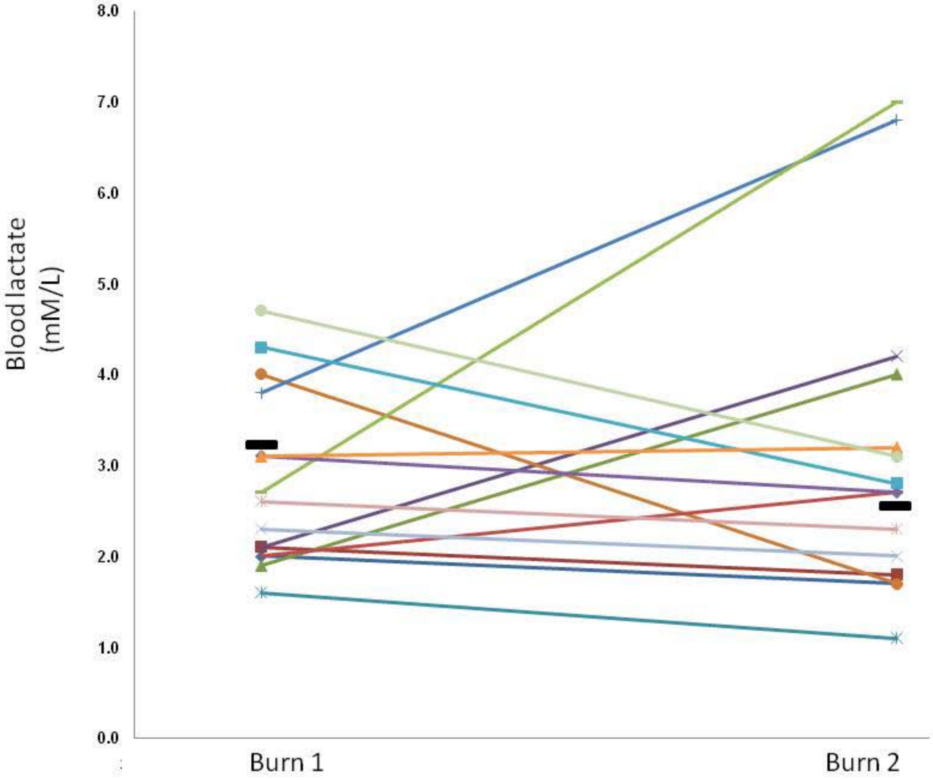

Figure 1: Individual pre-burn blood lactate data for burn 1 and burn 2.

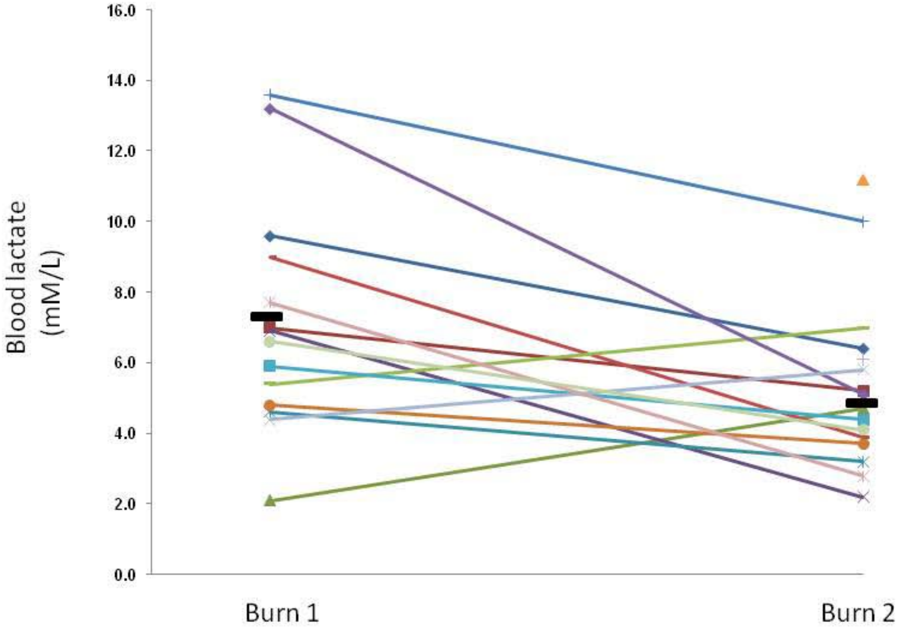

Figure 2: Individual post-burn blood lactate data for burn 1 and burn 2.

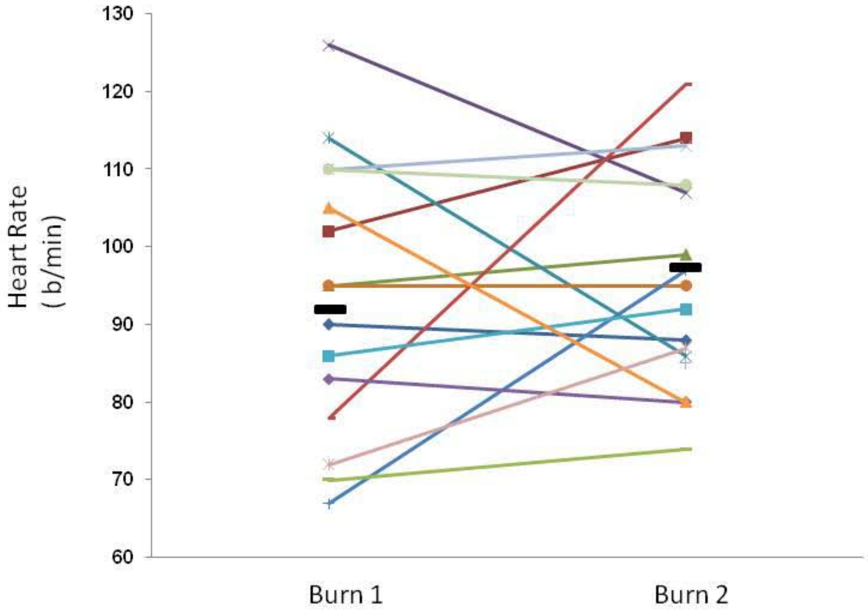

Figure 3: Individual pre-burn heart rate data for burn 1 and burn 2.

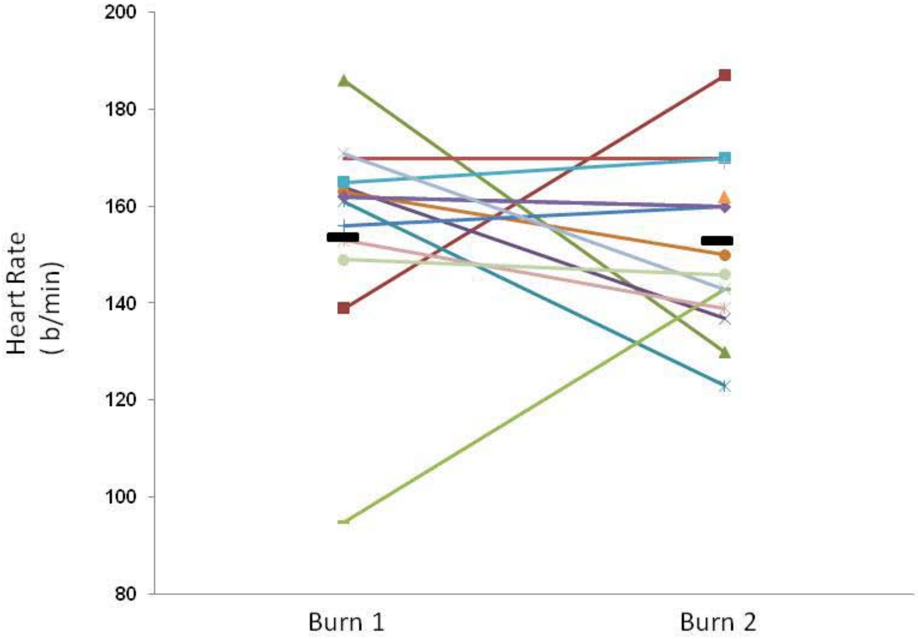

Figure 4: Individual post-burn heart rate data for burn 1 and burn 2.

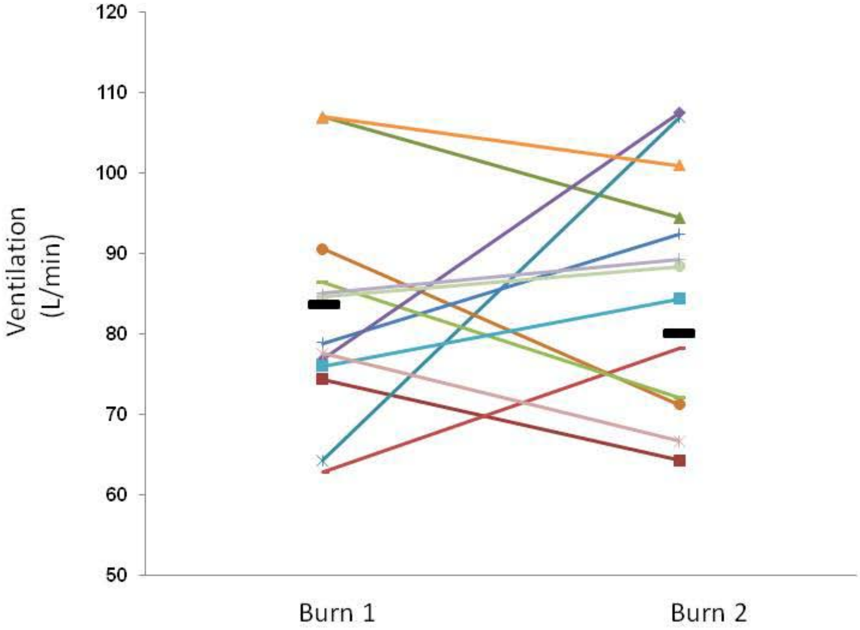

Figure 5: Individual minute ventilation data for burn 1 and burn 2.

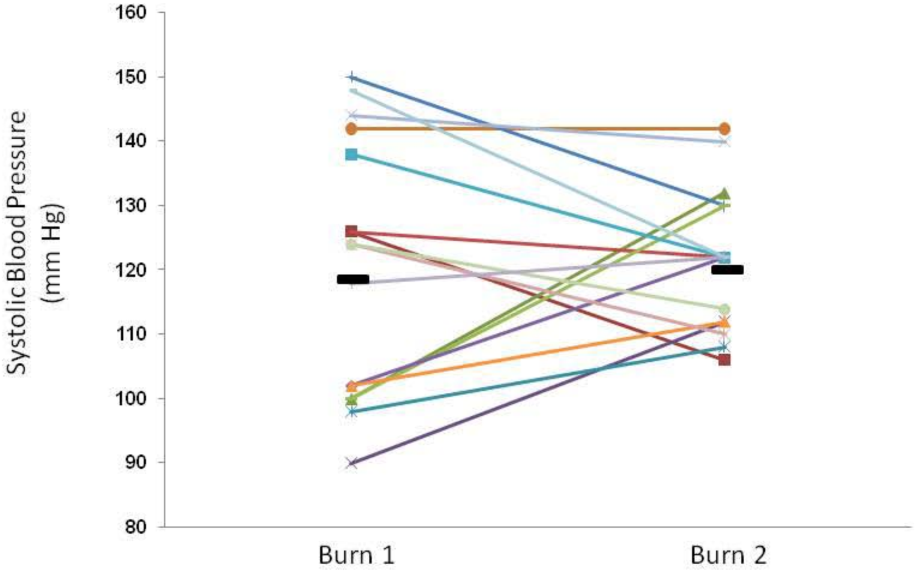

Figure 6: Individual pre-burn systolic blood pressure data for burn 1 and burn 2.

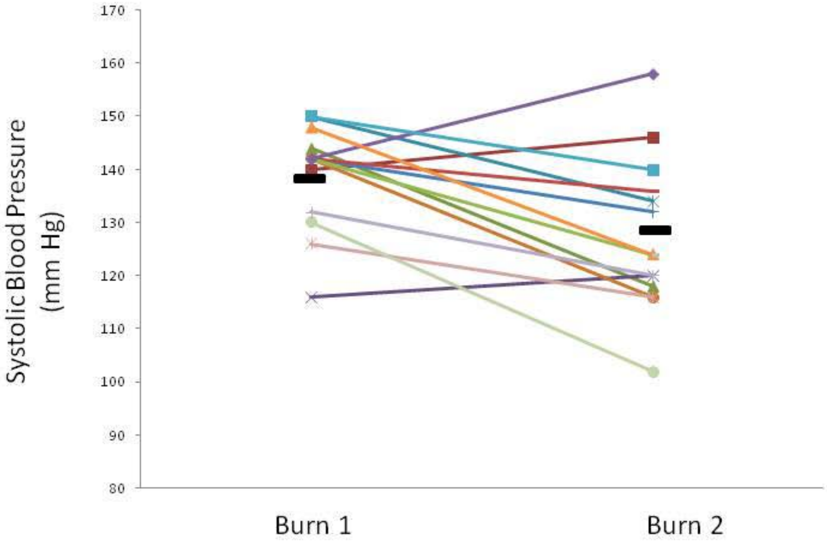

Figure 7: Individual post-burn systolic blood pressure data for burn 1 and burn 2.

CHAPTER V

DISCUSSION

The present study examined the physiological strain of firefighters during a live fire training exercise. To date, few published study has examined physiological responses to a live burn exercise in either cadets or experienced firefighters. Attempting to characterize the physiological response to a live burn exercise is comparatively novel. While several studies have described the physiologic responses to simulated fire fighting activities (without a fire) (Davis, Dotson, & Santa Maria, 1982; Gledhill & Jamnik, 1992; Romet & Frim, 1987), health risks to fire fighters (Davis, Biersner, Barnard, & Schamadan, 1982; Matticks, Westwater, Himel, Morgan, & Edlich, 1992), or specific responses to live firefighting activities such as ventilatory response (K. J. Donovan & McConnell, 1999), core body temperature (Selkirk & McLellan, 2004), or total energy expenditure (B. C. Ruby et al., 2002), few investigations have been conducted describing physiologic strain during a live burn. Although previous reports have documented the environmental, physiological and physical stresses of firefighting duties, there is an absence of literature as to whether or not these responses are the same in live fire scenarios. Therefore, the observations made in this study offer a unique insight into the possible physiological changes that occur during fire exposure in healthy fire academy cadets.

PRE-BURN DATA

Fourteen firefighter cadets were studied on two occasions during the Northern Colorado Fire Consortium Fire Academy. While the mean BMI was considered overweight {mean BMI of 26.3 (range 22 – 32.7)}; the cadets fell into three categories according to BMI: the normal range (BMI 18.5 – 24.9) (N = 6), overweight (BMI 25.0 – 29.9) (N = 9), obese (BMI > 30) (N = 2) (American College of Sports Medicine., Whaley, Brubaker, Otto, & Armstrong, 2006). Nevertheless, it must be made clear that BMI is not a precise measure of body composition; the absence of data on body fat precludes any judgment about the "fatness" of the cadet population being studied. In fact, published data clearly show that the percent body fat at a given BMI can vary by up to 8 fold (Ellis, 2001). Thus, it would be premature to conclude that these cadets were necessarily overweight/obese, or "at risk". The subjects mean maximal oxygen consumption stands in the 'good' category for their age group (45 ml/kg/min – 3.77 L/min) by the Cooper Institute for Aerobic Research Like the BMI data, there is some variability in the fitness categories: one subject was in the poor category (VO_2max 33.0 – 36.4 ml/kg/min), several others were in the fair category (VO_2max 36.5 – 42.4 ml/kg/min) (N = 4), while all others (N = 9) were in the good category and above (Heyward, 1998). Complete descriptive data for the characteristics of the study population are contained in Table 1 of Chapter 4 (above).

Day 1 Pre-Burn Data

Prior to performance of the fire search and rescue task, the firefighters' mean heart rate was 92.7 bpm (range 67 – 126 bpm). Normal resting heart rate averages 60 to

80 bpm. In middle-aged, unconditioned, sedentary individuals, the resting heart rate can exceed 100 bpm. In highly conditioned, endurance athletes, resting rates in the range of 28 to 40 bpm have been reported (Wilmore & Costill, 2004). It should be noted that these values are not “resting” values. resting heart rate data collected during the lab testing prior to the fire exercises provides a better perspective on “resting” heart rate. The mean heart rate of 67 bpm is well within normal ranges, and provides evidence of some degree of cardiovascular strain in the pre-burn data collection on both burn days, as the pre-burn heart rates were significantly elevated above rest. Mean pre-burn blood lactate values were 3.3 mmol/L (range 1.1 – 7.0 mmol/L). Resting blood lactate values are usually below 1.0 mmol/L (Robert A. Robergs & Roberts, 1997), although no such data is available in the present study. Again, it should be clear that these pre-burn blood lactate values are not resting lactate concentrations. Prior to the fire exercise, each firefighter completed different fire tasks leading up to our drill, however, other studies show that the duration of recovery each firefighter had on both burn days (20 or more minutes) is sufficient to allow blood lactate to return to resting levels (Crisafulli et al., 2006). Importantly, in a lab setting, recovery heart rate and lactate kinetics show that blood lactate can peak as late as the ninth minute of recovery then return back to baseline by 15 min post-exercise (Crisafulli et al., 2006). Thus, it is likely that the elevated pre-burn lactate represents an influence of an anticipatory rise in sympathetic neural drive, and less an issue of residual elevation for an activity that was completed 30 minutes prior to obtaining the pre-burn lactate. In the absence of data on plasma catecholamine concentrations or other indices of sympathetic activity, this is, of course, speculation. The term lactate threshold describes the highest oxygen consumption or exercise intensity

with less than a 1.0 mmol/L increase in blood lactate concentration above the pre-exercise or resting level (Weltman et al., 1990). The onset of blood lactate accumulation (OBLA) signifies when blood lactate concentration shows a systematic increase to a plasma concentration of 4.0 mmol/L (Seip, Snead, Pierce, Stein, & Weltman, 1991; Yoshida, Chida, Ichioka, & Suda, 1987). Some researchers believe that the 4.0 mmol/L value for OBLA implies the maximum exercise intensity that a person can sustain for a prolonged duration. In reality, however, the maximum stable lactate level varies considerably individuals, and can often be well above 4.0 mM/L (Coyle, 1995). Mean pre-burn lactate values for the study population approached the OBLA value of 4.0, with five subjects meeting or exceeding OBLA.

Day 2 Pre-Burn Data

Prior to performance of the fire search and rescue task on day two the firefighters' mean heart rate was 96.4 bpm (range 74 – 121 bpm). Mean blood lactate values were 2.7 mmol/L (range 1.1 – 7.0 mmol/L). Mean lactate levels were slightly lower in day two measurements (not statistically different), but still elevated above normal resting values. Three subjects exceeded OBLA. Blood pressure values ranged from 106/58 to 142/92 (mean 122/76). The mean pre-burn data obtained on day 2 did not differ significantly from the day 1 pre-burn data. Reliability estimates obtained from both intraclass correlations and Spearman's Rho suggest that while mean physiological strain responses pre and post-burn on days one and two did not differ, there was considerable individual variability in responses to the two live burn exercises. The conservative conclusion is that

The present study represents the physiological strain firefighters undergo when exposed to a live fire exercise. A similar study, which described only the most demanding situations encountered by the firefighter—a presumed worst-case scenario simulation—showed pre-test data more severe than seen in this study (heart rates of 150-190 beats per minute) (Barnard & Duncan, 1975). Specifically, in their study, Barnard and Duncan (1975) argued that the element of anxiety was present which contributed to the resting data being elevated (Barnard & Duncan, 1975). Since the firefighters in this study were being graded on their performances in a highly selective firefighter academy, the element of anxiety is likely to be present, albeit somewhat less and of a different quality than in a true emergency response situation. Further, the pre-burn data were obtained 30 minutes following other physical activity requirements for the cadets on a burn day, as noted above. As a result, the elevated pre-burn heart rate, and blood lactate likely represent a combination of the strain of the day’s physical activity and the anticipation that attends exposure to an upcoming live burn exercise.

BURN DATA

All firefighters perform physical work under rigorous environmental conditions (Gledhill & Jamnik, 1992; Romet & Frim, 1987). Data from this study was collected from the firefighter cadets during their academy drill sessions. In these sessions various companies are formed, each of which has different responsibilities during the fire, including two attack companies, one search company, and a support company, while other companies rested. Although this was a drill, it should be noted that these firefighters are attacking real fire in a structured burn building. The process of this drill is a simulation, but the risks and dangers are real as are the arduous environmental conditions, as evidenced by ceiling temperatures of 1,800 degrees Fahrenheit, and floor temperatures in excess of 500 degrees Fahrenheit during the live burn. The data reported herein were taken on the search company—the most demanding task according to training Chiefs and Captains—whose responsibilities included searching for and rescuing three victims in a three level 2,400 square foot building.

Day 1 Post-Burn Data

The mean time to complete the live fire exercise was 9.6 min (range 7.53 – 12.25 min). The firefighters' mean heart rate immediately following the completion of the task was 156.8 bpm (range 95 – 186 bpm). On average, it took the investigators less than 13 seconds to get a heart rate from the subject upon immediate completion of the task. This time includes transport from the exit point of the burn building to the research station as well as removal of protective fire gear for all measurements. Heart rate responses were comparable to that in other investigations of the physiological strain that attends firefighting. In a study by Barnard and Duncan (1975), heart rate responses to actual firefighting tasks were reported to range from 150-190 bpm for extended periods of time (Barnard & Duncan, 1975; Davis, Dotson, & Santa Maria, 1982). Mean post-burn blood lactate values were 7.2 mmol/L (range 2.1 – 13.6 mmol/L) immediately after completion of the task. The time it took for lactate to be measured was 1.76 minutes (range 0.33 – 2.97 min.). These blood lactate levels are similar to that of incremental exercise tests done at 75 to 90 percent of maximal exercise capacity in subjects with similar fitness levels (Osnes & Hermansen, 1972). Blood pressure values ranged from 116/40 to 150/96 (mean 139/61). Post-burn blood pressure measurements were obtained within 1.7 minutes. Subjects achieved mean respiratory minute ventilations (V_E) of 83.4 L/min (range 62.9 -107 L/min). A normal resting minute volume is five to eight L/min (Wilmore & Costill, 2004). In endurance athletes, who are well conditioned, minute ventilation during strenuous exercise can increase 27 times the resting value (Wasserman & Whipp, 1983). Generally, minute ventilations that exceed 50 L/min are considered moderate exercise, and those in excess of 100 L/min are considered vigorous exercise. Values upwards of 150 L/min and above is considered maximal exercise for most people (McArdle, Katch, & Katch, 2007; Robert A. Robergs & Roberts, 1997). Importantly, the calculated mean minute ventilation during the burn exercise on day 1 was 90.0 ± 18.9 percent of the minute ventilation max obtained during treadmill exercise in the lab. Clearly, the minute ventilation data suggest a considerable level of physiological strain. Taken together with the mean post-burn heart rate and blood lactate data, it is evident that this live burn exercise induces a physiological strain comparable to high intensity exercise.

Day 2 Post-Burn Data

The mean time to complete the live fire exercise was 9.32 min (range 5.58 – 13.8 min). The firefighters' mean heart rate immediately following the completion of the task was 156.2 bpm (range 123 – 187 bpm). The time to obtain heart rate was 21 seconds after completion of the task. The post-burn heart rate on day 2 was not significantly different than day 1. During simulated 'smoke dives' in the heat, near maximal heart rates have been recorded in young fit firefighters (Lusa, Louhevaara, Smolander, Kivimaki, & Korhonen, 1993). Similarly, Williams et al. (1996) monitored four instructors during live fire training exercises and found that their heart rates approached or exceeded their age-predicted maximum, and in some cases were higher than that recorded for the trainee firefighters (Eglin, Coles, & Tipton, 2004; Williams, Petersen, & Douglas, 1996). The mean blood lactate was 5.3 mmol/L (range 2.2 – 11.2 mmol/L) immediately after completion of the task. The time it took for lactates to be measured was 2.2 minutes (range 1.2 – 4.6 min.). Although blood lactate levels were significantly lower from day one measurements they are still reflective of high work intensities. Blood pressure values ranged from 102/52 to 175/978 (mean 131/68). Blood pressure time took on average 2.9 minutes. Subjects achieved mean respiratory minute ventilations of 85.1 L/min (range 21.2 - 127.4 L/min), or 85.8 ± 25.9 5 VE max. .

Firefighters can be exposed to severe metabolic and environmental thermal loads during their normal duties. The protective clothing worn by the firefighter is a necessary component to ensure their safety, but also increases energy expenditure for a given task and reduces heat dissipation from the body (Duncan, Gardner, & Barnard, 1979; Goldman, 1990). In addition, the strenuous nature of firefighting tasks, coupled with the effects of heat, can cause heat illness. Several studies have recorded very high physiological strain measures similar to this study *without* the additional exposure to the fire (Bennett, Hagan, Banta, & Williams, 1995). Although, hydration status was not measured in this investigation, it is possible that it could affect strain measures in the study as the firefighters were exposed to high levels of heat throughout the duration of the study. Other studies have reported dehydration by three percent body mass over greater exposure time than seen in this study. Nonetheless, it is known that dehydration increases heart rate and core body temperature during exercise and may lead to a reduction in physical performance and heat tolerance (Sawka et al., 1992). In the present study, the maximal weight loss recorded was 1.75% of body mass, and the majority of weight loss was less than 0.5% of body mass. Even when compared to the baseline body mass obtained on the lab visit, no cadet reached a 2% loss in body mass (the clinical definition of dehydration). It should also be noted that the work tasks used in this study did not reflect a full working day for structural firefighters. It is likely that physiological strain measures would be magnified as task length and work shifts were extended.

WORKING IN THE HEAT

Environmental temperature affects human performance (see Figure 3 in Chapter II). At body temperatures substantially higher than the optimal levels, both physical and mental performance deteriorates because of the complicated interplay of adaptive responses to thermal stress. The effects of heat stress can be seen in an individual's physiological response to arduous exercise even over short durations such as seen in this study. However, there are wide individual variations in the tolerance of different climatic stresses; these include environmental stressors, the nature and type of work, and clothing and other measures of protection. A number of studies have examined the effects of heat stress on physiological responses and exercise performance in various populations. One such study examined elite cyclist; subjects performed 30-minute time-trials at 32°C, (HT) and 23°C (NT). They found power output was 6.5 percent lower during HT compared with NT. Mean skin temperature and sweat rate were higher ($P<0.05$) in HT compared with NT, and blood lactate was higher (Tatterson, Hahn, Martin, & Febbraio, 2000). A similar study in sedentary individuals found comparable results. Eight subjects cycled to exhaustion at 70 percent of their maximal work load in cold room temperature (3 degrees C), neutral temperature (20 degrees C) and hot temperature (40 degrees C). Intramuscular lactate concentration was not different at rest when the three trials were compared but higher ($p < 0.05$) at fatigue in the hot temperature compared to the ambient room temperature (Parkin, Carey, Zhao, & Febbraio, 1999). Other studies have found similar results where lactate, heart rate, along with other physiological strain measures were not significantly different at neutral or ambient temperatures, but significantly different at high temperatures (Marino et al., 2001; Morris, Nevill, Boobis, Macdonald, & Williams, 2005; Smith, Petruzzello, Kramer, & Misner, 1997). The relationship between heat and ventilatory response during exercise has been examined as well. During a 60 minute cycle ergometer test at 50 percent of maximal oxygen update, subjects were found to have significantly higher minute ventilations from minutes 45 to 60 in both 35 and 45 degree Celsius as compared 10 degrees Celsius. The authors concluded that during prolonged submaximal exercise in the heat, minute ventilation increase with core temperature (Hayashi, Honda, Ogawa, Kondo, & Nishiyasu, 2006). It is quite clear that the thermal stress of a live burn exercise adds to the overall physiological strain. It was not the purpose of the present study to compare physiological responses to simulated firefighting at different ambient temperature, but to characterize the strain that attends a live burn. The integrated physiological response to such an exercise includes, as noted in the literature review, the physical work capacity of the cadet, the training state of the cadet, the strain that attends any exercise with the excess load of gear, clothing, and SCBA, the requisite component of physical work in an extraordinary environment (note once more the ceiling and floor temperatures exceed 1,800 and 500 degrees Fahrenheit, respectively). As noted above, when one adds to the foregoing objective factors that directly influence physiological strain, the subjective component of psychological stress and anticipation, it is clear that live-burn exercises (and actual firefighting) represents an extraordinary physiological strain.

ISSUES IN OCCUPATIONAL PHYSIOLOGY

In many occupational settings where physical arduous work is required the relationship between varying levels of fitness and performance of tasks within that specific discipline have a linear relationship; that is as tasks get more difficult, the required level of fitness to complete the task needs to be higher (Davis, Dotson, & Santa Maria, 1982). By law an employer cannot accommodate or give special treatment based on age, race, sex, or country of origin as proscribed in the Civil Rights Act of 1991, as a consequence, you also can not have separate standards based on ones identity for the same job (United States. Congress. House. Committee on the Judiciary., 1991). The job requirements are independent of the person who is performing the job. Therefore, in occupations where much is demanded in terms of physical work capacity, much should be expected not only initially, but also throughout the duration of a career.

Fort some occupations, such as law enforcement, firefighting, and the military, the tasks can vary considerably on a given day, ranging from quasi-sedentary “desk job” type activities to both intermittent and sustained bursts of highly demanding physical activity. It is not unreasonable to expect that any public safety responder, responding to an emergency will have the requisite health and physical work capacity that the job demands. However, this is clearly not always the case, and in some cases where emergency personnel lack the capacity for the task, their safety, the safety of other emergency personnel, and the safety of the public is at risk. Therefore, establishing job-related fitness standards should be based on the worst-case scenarios of that profession. Employers (and job related fitness standards) must also take into account the environmental element of some occupations; firefighting chiefs among these. The current practice in establishing physical performance standards is to use incumbent employees as the normative reference point. This approach however fails to appreciate the obvious fact that in law enforcement, police officers are not chasing and arresting each other and firefighters are not fighting amongst themselves, they are battling an environment (the fire). The data obtained from the present study, and the review of the literature would support the thesis that officers should have fitness goals/standards that meet or exceed the fitness levels of those they are seeking to apprehend. The same holds true in firefighting; they are battling environmental and physical elements that need to be overcome in order to put out the fire, rescue victims, or prevent the fire from damaging other persons or property. Thus, in setting fitness standards, employees should be able to meet not only the demands of the task, but also the physical demands of the environment.

Few people would deny that those who are more physically fit can run faster and farther and lift more than their less fit counterparts. In the 1998 *Lanning v. SEPTA* federal court case, defendants set out to support that a physically fit officer has a greater probability of success than his or her less fit counterpart. Arrest data for a year was collected and correlated with the specific arresting police officers, and because all of the incumbents has fitness data on record, a discriminate function analysis was conducted, demonstrating the clear superiority of the more fit officers in performing job-related tasks ("Lanning v. SEPTA", 2000).

Unfortunately, physical fitness is an attribute that, if not maintained, degrades over time. When setting up hiring standards for emergency services (law enforcement, firefighting, military), employment is usually based on the ‘minimalist’ model which attempts to determine what the minimum requirements are to perform the job. Those persons that meet the minimal requirements are eligible for hire. Although this model works in some applications, this is not the case in emergency services. Figure 1, where on-entry starting points for KSA’s (knowledge, skills, and abilities) and fitness levels are presented, reveals an obvious dichotomy. At the time of hire an employee lacks most job related KSA’s. As expected, over time there is an upward trend as the employee gains experience and on-the-job training. However, the opposite is often the case with fitness. Without an ongoing intervention to prevent such a trend, physical fitness is almost always going to decline with age. One such study documented that within one year of appointment and training, a group of emergency service professionals was markedly less fit than on appointment to fire academy (Stamford, Weltman, Moffatt, & Fulco, 1978).

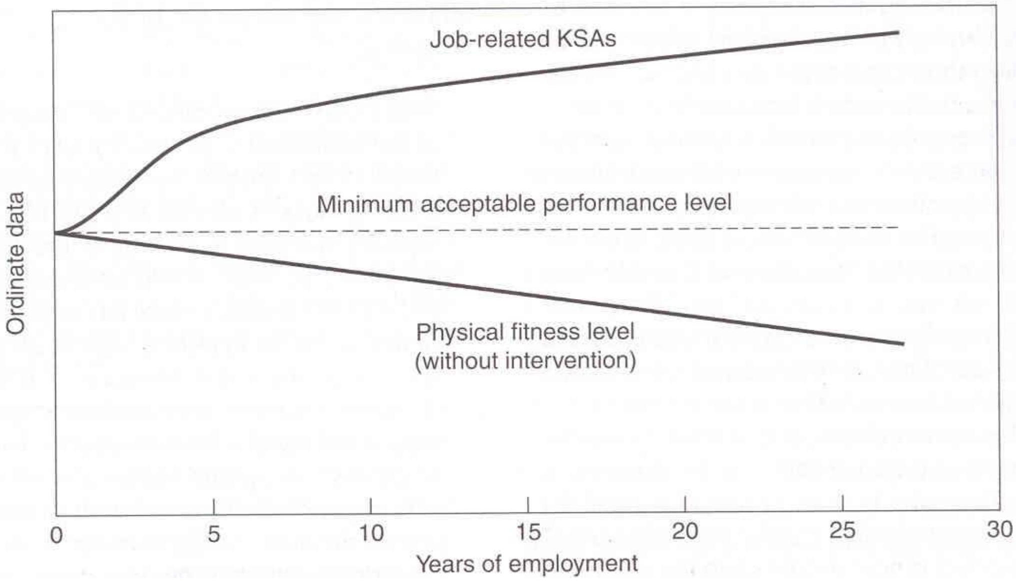

Figure 2: Minimalist model – contrasts in KSA's and fitness over employment history (BJ Sharkey, Davis, PO 2008, *Hard Work* (Champaign, IL: Human Kinetics).

The expected rate of loss of aerobic capacity in the general population is one percent per year (F. Kasch, Boyer, Van Camp, Verity, & Wallace, 1990; F. W. Kasch et al., 1995). It is not unusual to see public safety employees add more than 50 pounds (22.6 kg) to their frames before reaching retirement (Sharkey & Davis, 2008). Not surprisingly fitness degradation and weight gain places a significant toll on joint loading and interferes with ambulatory activities, in addition to being major risk factors for obesity, diabetes, and cardiovascular disease, to name a few.

Knowing that most physical training regimens are short lived and once people that graduate from fire academy, the normal course of action is to return to their previous sedentary state as evident in Figure 1. Another hiring model that should be considered is the 'buffer' model. As shown in Figure 2, the buffer model shows a person with a physical fitness level that starts above the minimal accepted performance level. As fitness level degrades over time (as expected) the person's buffer above the minimal acceptable level is steadily lost over time, but still allows him or her to perform the necessary tasks of the job. This phenomenon has been reported in several longitudinal studies in several occupational settings (F. Kasch, Boyer, Van Camp, Verity, & Wallace, 1990; F. Kasch, Wallace, Van Camp, & Verity, 1988; F. W. Kasch et al., 1995). An alternative to the minimalist or buffer models is some combination of the two which requires continued training standards throughout the professional career (thus attenuating the negative impact of the minimalist approach). By combining this with a buffer model (hire at above target fitness), the likelihood of sustained functional capacity improves considerably.

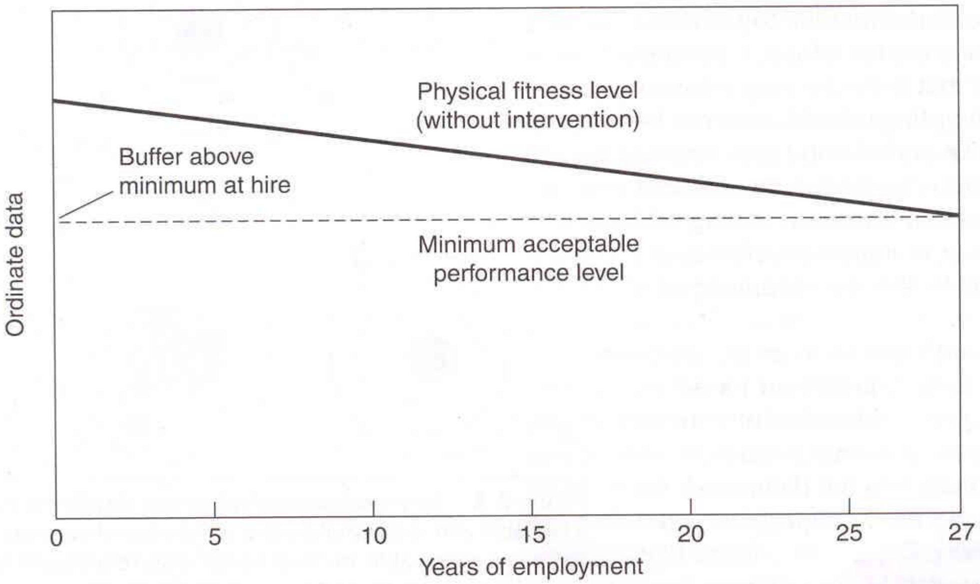

Figure 2: Buffer model – fitness level starts well above minimum acceptable performance level and degrades with time (BJ Sharkey, Davis, PO 2008, *Hard Work* (Champaign, IL: Human Kinetics).

Implication for Firefighting

Firefighters and others with physically demanding occupations are no exceptions to the general rule that aging and/or inadequate physical activity can lead to a deterioration in physical fitness. Currently cardiovascular disease and back injuries are the leading cause of premature retirement in the United States (Sharkey & Davis, 2008). Lack of training and physical fitness exacerbates the injuries suffered and costs resulting from injuries on the job. According to the FBI's *Law Enforcement Officers Killed and Assaulted* report from 2004, over 56,000 officers were injured (or worse: killed) on average over the past 10 years (Federal Bureau of Investigation, 2005). Lack of physical activity has overtaken smoking as a major risk factor for heart disease (U.S. Department of Health and Human Services, 2004). Millions of Americans fail fitness tests every year (Sharkey & Davis, 2008). If there is one profession in which fitness standards cannot be compromised, it is our public safety personnel.

It is clear that the physiological strain described in this study is considerable. Therefore, a reconsideration of how fitness standards are derived both at the time of hire and for the duration of employment is essential. The data from this study, while admittedly limited in scope, suggest that even in young and apparently healthy fire academy cadets (presumably at or near their peak fitness), the strain that attends a live burn exercise results in cardiovascular and pulmonary responses that require >80% of maximal capacity in some individuals.

Specific operational consideration based on both the data from the present study and extant published data include:

1. The current requirements necessitate firefighters to exercise for one hour while on duty. There needs to be both more accountability for such continued training and more information provided to firefighters on the proper balance of strength/resistance and endurance exercise. Accountability can be achieved by incorporating rigorous fitness standards into annual evaluation for fire safety personnel. Allowing unfit or inadequately fit fire safety personnel to remain on duty presents a risk to them, their colleagues, and the public.
2. Research should be conducted on the most effective means to create companies (or teams) for firefighting. The data from this study shows considerable inter-individual variability in physiological strain during a live burn exercise. As each company attacks the fire as a team, they are arguably limited by the 'weakest-link' of that company. That is, once one member of the company runs out of air from their SCBA tank, the entire team must escape to safety. It would make sense to pair or group individuals with similar VO_2 and V_E values together as to maximize their time attacking the fire, saving victims, or whatever that particular company's responsibility is. This will allow for more productive and efficient work as a company while fighting fire as well as lead to less injuries and deaths. The overall goal is to keep the firefighters safe and not create additional emergency situations. The suggestion of team building on the basis of common physiology (in this example, centered on respiratory responses to the burn) is not meant to ignore

other factors (experience, muscle strength and endurance, personality factors) which undoubtedly contribute to successful team dynamics. Nonetheless, little attention appears to have been given to the construction of successful (and safe) firefighting teams.

The intent of such tentative recommendations is simple: better safety and success in the challenging profession of firefighting.

Recommendations for Future Studies

1. Due to the limited funding for this study, a number of important and potentially useful strain markers were not measured in this study; most notably core body temperature and skin temperature, and real time measures of heart rate. Future studies should utilize as many tools as possible to capture the full breadth of strain undergone on as many bodily systems as possible in order to characterize the strain that attends a live burn.
2. Similar studies should be done on experienced firefighters to test what is assumed to be an anticipatory response of the firefighter cadets prior to the live fire exercise. It should not be assumed that the strain data obtained here would be the same for experienced safety personnel. Comparing the physiological response between novice and veteran firefighters could provide useful data and inform decisions on training, safety and help frame fitness standards for both prospective as well as incumbent employees.

3. It would be interesting to obtain annual longitudinal data on firefighters through the duration of their career.

Limitations

There are several limitations that attend this study which should be noted:

1. The data are limited by the specific strain measures chosen. With more funding a more comprehensive battery of strain markers could have been chosen. These could include skin temperature, core body temperature, and heart rate monitors that record heart over the duration of the fire exposure.
2. Resting and maximal data was obtained on selected variables on the day of the lab visit, but additional data (resting blood pressure and resting blood lactate) could have been obtained on the day of the lab visit. Such data could more accurately frame the relative strain on the days of the live burn exercise.
3. BMI is a gross measure of body composition. While it is suitable for large scale epidemiological studies, it lacks the precision of body composition measurements. Body fat could have been obtained during the initial lab visit.
4. All field studies have the inherent challenge of obtaining data in a relatively uncontrolled environment. Nonetheless, the aim of this study was to characterize physiological stain during a live burn exercise. This aim necessitates field data collection.

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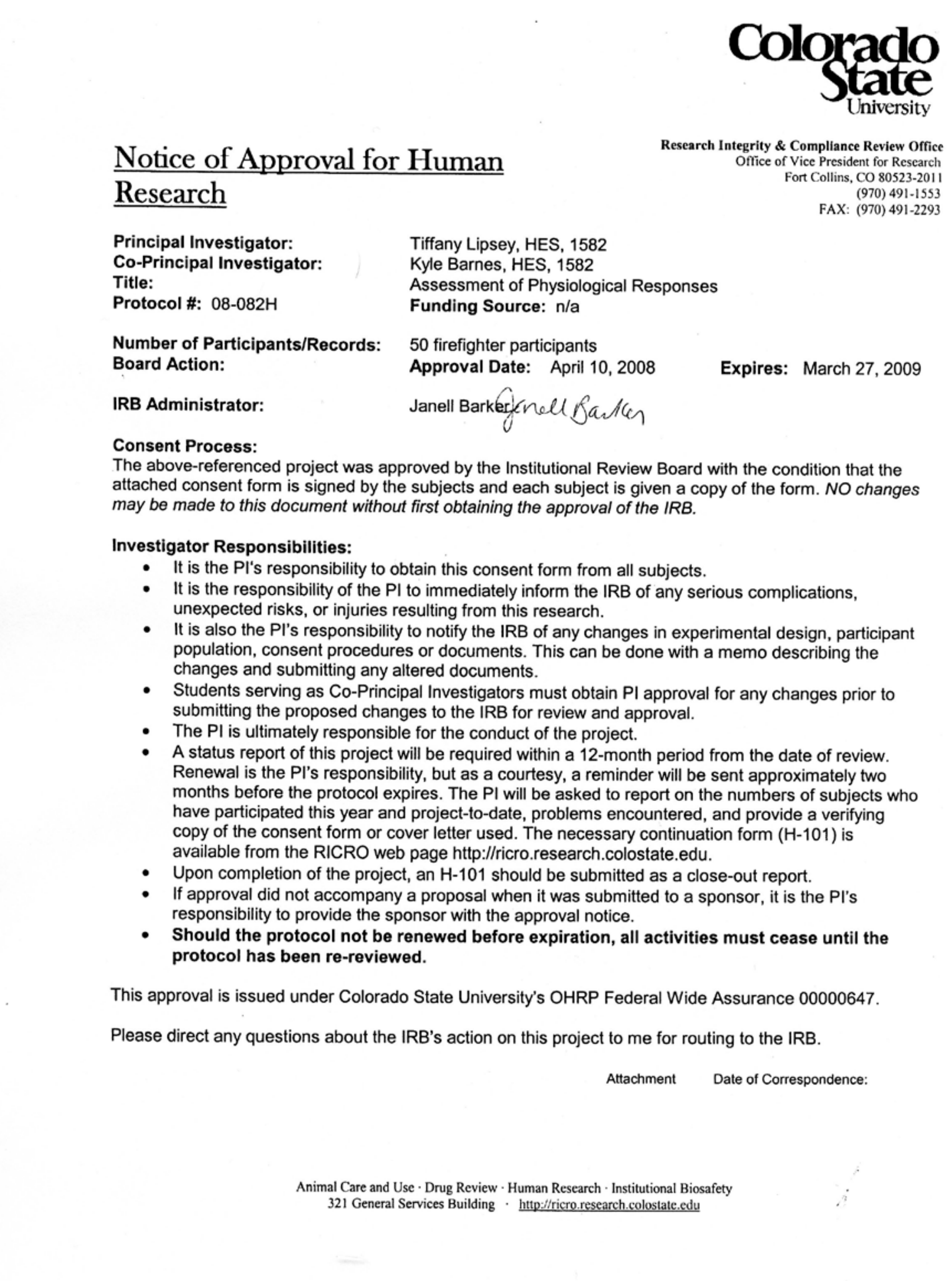
APPENDIX A

PROJECT APPROVAL FORM



Colorado
State
University

Research Integrity & Compliance Review Office
Office of Vice President for Research
Fort Collins, CO 80523-2011
(970) 491-1553
FAX: (970) 491-2293

Notice of Approval for Human Research

Principal Investigator:	Tiffany Lipsey, HES, 1582
Co-Principal Investigator:	Kyle Barnes, HES, 1582
Title:	Assessment of Physiological Responses
Protocol #: 08-082H	**Funding Source:** n/a
Number of Participants/Records:	50 firefighter participants
Board Action:	**Approval Date:** April 10, 2008 **Expires:** March 27, 2009
IRB Administrator:	Janell Barker Janell Barker

Consent Process:
The above-referenced project was approved by the Institutional Review Board with the condition that the attached consent form is signed by the subjects and each subject is given a copy of the form. *NO changes may be made to this document without first obtaining the approval of the IRB.*

Investigator Responsibilities:

- It is the PI's responsibility to obtain this consent form from all subjects.
- It is the responsibility of the PI to immediately inform the IRB of any serious complications, unexpected risks, or injuries resulting from this research.
- It is also the PI's responsibility to notify the IRB of any changes in experimental design, participant population, consent procedures or documents. This can be done with a memo describing the changes and submitting any altered documents.
- Students serving as Co-Principal Investigators must obtain PI approval for any changes prior to submitting the proposed changes to the IRB for review and approval.
- The PI is ultimately responsible for the conduct of the project.
- A status report of this project will be required within a 12-month period from the date of review. Renewal is the PI's responsibility, but as a courtesy, a reminder will be sent approximately two months before the protocol expires. The PI will be asked to report on the numbers of subjects who have participated this year and project-to-date, problems encountered, and provide a verifying copy of the consent form or cover letter used. The necessary continuation form (H-101) is available from the RICRO web page http://ricro.research.colostate.edu.
- Upon completion of the project, an H-101 should be submitted as a close-out report.
- If approval did not accompany a proposal when it was submitted to a sponsor, it is the PI's responsibility to provide the sponsor with the approval notice.
- **Should the protocol not be renewed before expiration, all activities must cease until the protocol has been re-reviewed.**

This approval is issued under Colorado State University's OHRP Federal Wide Assurance 00000647.

Please direct any questions about the IRB's action on this project to me for routing to the IRB.

Attachment Date of Correspondence:

Animal Care and Use · Drug Review · Human Research · Institutional Biosafety
321 General Services Building · http://ricro.research.colostate.edu

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APPENDIX B

INFORMED CONSENT TO PARTICIPATE IN RESEARCH PROJECT

COLORADO STATE UNIVERSITY
INFORMED CONSENT TO PARTICIPATE IN A RESEARCH PROJECT

TITLE OF STUDY: Assessment of Heart Rate and Blood Lactate Responses in Firefighters During a Live Fire Training Exercise

PRINCIPAL INVESTIGATOR: Tiffany Lipsey, M. Ed. 970-491-7035
CO-INVESTIGATOR: Kyle Barnes, 616-566-7613

Contact person and phone number for questions/problems:
Tiffany Lipsey, M. Ed., 970-491-7035

WHY AM I BEING INVITED TO TAKE PART IN THIS RESEARCH?

We are examining physiological performance levels in firefighters over the age of 18. Currently there is no research examining performance levels in firefighters. It is our hope through this study to begin looking at and possibly estimating performance in firefighters based on physiologic parameters. Often professional athletes can estimate their performances based on known physiologic measures such as heart rate, maximal VO_2, and blood lactate. If you think about your job as being an “occupational athlete,” we are interested in determining what physiologic measures could be used best to estimate performance in firefighters.

WHO IS DOING THIS STUDY? Department of Health and Exercise Science at Colorado State University

WHAT IS THE PURPOSE OF THE STUDY?

The proposed study will exmine the association between physiological performance levels and exposure to controlled fires (as measrued by blood lactate levels, consumed O_2, heart rate, and accelerometry data) among firefighters. It should be noted that we are in no way forcing these individuals to go into a real house fire simply to collect data. The fires that these firefighters will be fighting are a part of their normal training to graduate from fire academy. Our data collection will be an adendum to a drill they are already performing. Essentially you can think of firefighting as being an “occupational athlete.” As is the case with sports, we want to determine what physiological parameters are best for predicting performance in firefighters.

With your consent, the data obtained from your testing at the local controlled burned sites in addition to your visit to the Human Performance Clinical/Research Laboratory (HPCRL) will be coded (for confidentiality) and entered into a computer database. Your data will be coded and kept in a locked file cabinet on the CSU campus. The data will also be coded and entered into a computer database. Your name will not appear in the computer database. Additionally, you will not be identified in relation to your data for research purposes at any point. However, you should be advised that any time a researcher wishes to study the HPCRL databases to address a new research question; we will seek approval from Colorado State University to access the database to address that specific research question.

Page 1 of 5 Participant's initials _________ Date __________

I agree to allow the use of my research test data in the large research database. YES ☐
NO ☐

I agree to allow the HPCRL research team to contact me in the future if I qualify for other research projects. By agreeing to allow the research team to contact me, I am NOT obligated to participate in any research study.
YES ☐ NO ☐

WHERE IS THIS STUDY GOING TO TAKE PLACE AND HOW LONG WILL IT LAST?

This study will take place during the controlled burns you are fighting as part of the requirements for completion of fire academy. Testing will take place at the various controlled burn sites before, during, and after the burn. Additional VO_2 testing will take place at the Human Performance Clinical/Research Laboratory at Colorado State University in Fort Collins, CO.

WHAT WILL I BE ASKED TO DO?

Your participation in this research project will allow the researchers to use your collected data to examine the physiological characteristics related to firefighting in a live fire training exercise.

This study lasts no longer than the live fire training exercises you are required to do prior to completion of fire academy. For the duration of the study, we ask that you need to:

- Avoid ________?

The study only requires that you attend the live firefighting training exercises for fire academy. Our data collection will take place before, during and after the live training exercise. Additionally, one visit to the Human Performance Clinical/Research Laboratory (HPCRL) at Colorado State University (CSU) will be required after the completion of all live training exercises for a VO_2max testing exercise and blood lactate correlation. This visit requires approximately one hour in duration.

ARE THERE REASONS WHY I SHOULD NOT TAKE PART IN THE STUDY?

You may not participate in this study if:

- You are not currently eligible for wildland fire deployment. Those employed as seasonal firefighters may participate.
- You do not have active/online duty status such as pregnant women or those with injuries that make them unable to perform the duties of a wildland firefighter.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

1) **Acquisition of blood sample for lactate analysis**: There are risks of developing a bruise (hematoma), slight risk of infection, local soreness, and slight pain upon insertion of lancet into skin (ear or fingertip).

There are no known research risks for: respiratory symptom and demographics questionnaire, weight and height on beam scale, pulmonary function tests, and amount and degree of smoke exposure questionnaire. Other procedures used for testing include methods common in healthcare such as blood work and pulmonary function testing common in the fire service, which are also outlined in National Fire Protection Association (NFPA) 1582 Standard on Comprehensive Occupational Medical Program for Fire Departments 2006 Edition.

It is not possible to identify all potential risks in research procedures, but the researcher(s) have taken reasonable safeguards to minimize any known and potential, but unknown, risks.

Page 3 of 5 Participant's initials _________ Date __________

WILL I BENEFIT FROM TAKING PART IN THIS STUDY?

There are several benefits of participating in this project. You will receive testing valued at over $165 free of charge. You will receive detailed health information directly related to your cardiopulmonary function and health risk status. Results of all the tests will be provided to you and may be forwarded to your healthcare provider upon request.

DO I HAVE TO TAKE PART IN THE STUDY?

Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.

WHO WILL SEE THE INFORMATION THAT I GIVE?

In order to keep your test results confidential you will be assigned a code number. These codes will include a subject number, month and year. For example, if subject 4 starts in April of 2004, the code will be 0040404. No part of the code will include identifiable information such as your initials or portions of your social security number. You will not be identified in relation to the data collected for any research purpose or manuscript. Your data will be coded and kept in a locked file cabinet on the CSU campus. The data will also be coded and entered into a computer database. The computer database will be stored on a password-protected network accessible only to study investigators. Your name will not appear in the computer database. A copy of the uncoded data may be sent to your personal physician only upon your written request. However, you will not be identified in relation to your data for research purposes at any point. In addition, you should be advised that any time a researcher wishes to study this data to address a new research question, we will seek approval of the Colorado State University Human Research Committee to access the database to address that specific research question.

We will make every effort to prevent anyone who is not on the research team from knowing that you gave us information, or what that information is. For example, your name will be kept separate from your research records and these two things will be stored in different places under lock and key. You should know, however, that there are some circumstances in which we may have to show your information to other people. For example, the law may require us to show your information to a court.

CAN MY TAKING PART IN THE STUDY END EARLY?

Failure to complete testing at all live fire training exercises and post training VO_2max testing may result in your removal from the study.

WILL I RECEIVE COMPENSATION FOR TAKING PART IN THIS STUDY?

You will not receive any financial reimbursement; however, the testing you will receive for free is of an 85 dollar value.

WHAT HAPPENS IF I AM INJURED BECAUSE OF THIS RESEARCH?

The Colorado Governmental Immunity Act determines and may limit Colorado State University's legal responsibility if an injury happens because of this study. Claims against the University must be filed within 180 days after the date of the injury.

WHAT IF I HAVE QUESTIONS?

Before you decide whether to accept this invitation to take part in the study, you can contact the investigator, Kyle Barnes at 616-566-7613 or the primary-investigator, Tiffany Lipsey at 970-491-7035. If you have any questions about your rights as a volunteer in this research, contact Janell Meldrum, Human Research Administrator at (970) 491-1655. We will give you a copy of this consent form to take with you.

WHAT ELSE DO I NEED TO KNOW?

You are in no way required to participate in this study, however, this information could be helpful in learning how to further prevent injuries in firefighters as well as further optimize performance in firefighters during live fires.

Your signature acknowledges that you have read the information stated and willingly sign this consent form. Your signature also acknowledges that you have received, on the date signed, a copy of this document containing 5 pages.

____ ________________

Signature of person agreeing to take part in the study **Date**

____

Printed name of person agreeing to take part in the study

____ ________________

Name of person providing information to participant **Date**

____

Signature of Research Staff