THE EFFECTS OF OXYGEN-ENRICHED AIR ON FIREFIGHTER JOB PERFORMANCE

EXECUTIVE LEADERSHIP

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ABSTRACT

When using SCBA, firefighters are able to get to the seed of a fire more quickly, and are able to perform rescue, ventilation, suppression, and salvage and overhaul functions without breathing in toxic smoke and gases. A problem associated with the use of SCBA is that under heavy work loads, such as rescue maneuvers, stair climbing with equipment, and forcible entry, the rate of air flow from the regulator has the potential to limit the physical performance of firefighters.

The purpose of this research was to examine the potential for improving the operating efficiency of SCBA. Specifically, this research examined the use of oxygen- enriched (hyperoxic) air as a method of increasing the ability of firefighters to perform physically demanding tasks while using SCBA.

This research adopted an experimental research design in order to test the following hypotheses:

H1. The heart rate responses under the hyperoxia conditions will be lower than heart rates under the normox conditions.
H2. The blood lactate levels under the hyperoxia conditions will be lower than the blood lactate levels under the normox conditions.
H3. The perceived physical exertion under the hyperoxia conditions will be lower than perceived physical exertion under the normox conditions.
H4. The times on each individual event under the hyperoxia conditions will be lower than the event times under the normox conditions.
H5. The total elapsed times under hyperoxia conditions will be lower than the total elapsed times under normox conditions.

The procedures used to test these hypotheses involved a double-blind within-subjects design. During different trials in the study, 17 subjects completed a number of evolutions involving a series of simulated firefighting tasks. Subjects were randomly assigned SCBA that contained either normal breathing air (normoxic) or oxygen-enriched air (hyperoxic). Performance measures and physiological data were collected under the two different experimental conditions and the data were analyzed in order to test the hypotheses.

The results of the study provided support for H3, H4, and H5, however H1 and H2 were rejected. In rejecting H1 and H2, the researchers noted that although heart rate and blood lactate levels were similar under the two conditions (normoxic and hyperoxic) the reduction in times to complete the tasks indicated a higher level of work output at similar heart rates and lactate levels.

The results of the study provide strong support for the positive effects of hyperoxia on the performance of firefighters, and suggest the need for further research. Four recommendations for further research were proposed, including a recommendation to seek corporate and/or government funding to support further research.

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In addition to this report written by a single author, the results of this study have been submitted for publication in *Ergonomics,* and *Fire Engineering,* as research papers collaboratively authored by the research team.

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INTRODUCTION

One of the most essential pieces of equipment used by firefighters is the Self-Contained Breathing Apparatus (SCBA). The SCBA provides a supply of breathing air that allows firefighters to enter burning buildings that are charged with smoke and super-heated gases. When using SCBA, firefighters are able to get to the seed of a fire more quickly, and are able to perform rescue, ventilation, suppression, and salvage and overhaul functions without breathing in toxic smoke and gases.

While most would agree that the use of SCBA aids significantly in the effective performance of firefighting duties, the SCBA is not without its drawbacks and limitations. One problem associated with SCBA usage is the limited duration of the air supply. This can be a major concern when fighting fires in large industrial complexes and in highrise buildings. There is often the potential for the air supply to become depleted prior to the firefighters' retreating to smoke-free areas where the SCBA can be removed and the air bottle changed. A second problem is the limited air flow through the regulator. Under heavy work loads, such as rescue maneuvers, stair climbing with equipment, and forcible entry, the rate of air flow from the regulator has the potential to limit the physical performance of firefighters.

The purpose of this research was to examine the potential for improving the operating efficiency of SCBA. Specifically, this research examined the use of oxygen-enriched air as a potential method of increasing the ability of firefighters to perform physically demanding tasks while using SCBA. The research was based on the hypothesis that increasing the oxygen concentration in SCBA tanks would allow firefighters to perform at higher levels and work more efficiently than they could using normal breathing air that is typically found in SCBA tanks used for structural firefighting.

This study used an experimental research design, and compared the within-subject physiological responses of subjects performing simulated firefighting activities. The firefighting activities used were a series of tasks similar to those found in the Firefighters Combat Challenge. Following a number of training evolutions to familiarize the subjects with the tasks, subjects completed three different experimental evolutions. During the experimental evolutions subjects were randomly assigned SCBA tanks filled with either normal breathing air (NORMOX) or oxygen-enriched air (HYPEROX) using a double blind experimental procedure. During and following each of the experimental evolutions, key physiological data were collected including heart rate (HR), blood lactate level (BL), which is an indicator of physical fatigue, rating of perceived exertion (RPE), as well as elapsed time required to complete each event (ET) and the overall time to complete the evolution (OT). In each of the experimental evolutions the subjects were instructed to complete the various tasks as quickly as possible and to perform to their maximal potential.

The data collected under the two different experimental conditions were compared in order to test the following hypotheses:

H1. The heart rate responses under the hyperoxia conditions will be lower than heart rates under the normox conditions.
H2. The blood lactate levels under the hyperoxia conditions will be lower than the blood lactate levels under the normox conditions.
H3. The perceived physical exertion under the hyperoxia conditions will be lower than perceived physical exertion under the normox conditions.
H4. The times on each individual event under the hyperoxia conditions will be lower than the event times under the normox conditions.
H5. The total elapsed times under hyperoxia conditions will be lower than the total elapsed times under normox conditions.

BACKGROUND AND SIGNIFICANCE

The incidence of structural fires in North America continues to decline, causing many fire service managers to closely examine a variety of new and different public services. Yet despite the increasing emphasis on tasks such as public education, fire prevention, community service, and EMS, the defining moment for most fire departments continues to be their ability to effectively combat structural fires with aggressive interior attacks designed to rescue victims and minimize property loss. Technological advances in the type and quality of tools and equipment that firefighters use to perform their job have served to increase the level of performance and the level of safety associated with firefighting.

Changes in the design of turnout gear, and the evolution from the "slicker and boots" to "bunker gear" provide firefighters with a greater level of protection than has previously been possible. The use of human-made fire-resistant fibers such as nomex flash hoods have also increased the level of protection afforded to firefighters when conducting interior firefighting operations. New technology such as PASS devices increase the possibility that firefighters who experience difficulties will be found. And new fireground procedures such as the implementation of rapid intervention teams (RIT) help ensure that firefighters who experience difficulties will be rescued quickly.

While all of these equipment changes, safety devices, and fireground procedures are important, the most essential piece of personal protective equipment that firefighters use is the SCBA. The SCBA is the piece of equipment that allows firefighters to breathe clean air and to function in contaminated environments. Malfunctions of SCBA, improper usage of SCBA, and depletion of air supply are some of the most crucial and potentially lethal problems faced by firefighters. Without a supply of fresh breathing air survival is difficult within the hostile environments that firefighters operate.

As with other types of personal protective equipment, the SCBA has developed and improved in recent years. The use of lightweight steel, aluminum, and fiberglass wrap has resulted in decreased weight of SCBA tanks and increased air volume. Advances in design, such as the positive pressure mask, anti-fog lenses, vision correcting facepieces, low air warning devices, and others, have helped to make SCBA safer and more effective for firefighters to use.

As with any technology, however, there are still limitations in the use and effectiveness of SCBA. One of the limiting factors that has been identified is the ability of the SCBA to deliver a sufficient air flow under conditions of intense physiological demand. The physiological demands of structural firefighting are extreme. Firefighters dressed in turnout gear and wearing SCBA typically are carrying approximately 50 pounds of equipment. Add to that weight tools, highrise kits, hose packs, charged hoselines, and the need to move quickly up stairs, through confined spaces, and into dark unknown premises, and you can begin to appreciate the physical demands placed on firefighters. Add further to that extreme temperatures, turnout gear that does not "breathe" well, and the adrenaline rush that results from the fear, anxiety, and tension of the job, and one can develop a further understanding of the physiological demands placed on firefighters. These demands typically result in sharp increases in heart rate and ventilation rate and increase the demand for oxygen (Williams, Peteresen, & Douglas, 1996).

In firefighting, as in other physically demanding activities, a key component for effective performance is the body's ability to supply the muscles with sufficient amounts of oxygenated blood. A limiting factor to effective performance can be that firefighters working at high levels of intensity cannot get sufficient air and/or quickly deplete their air supply and are forced to exit the structure.

The total quality management principle of continuous improvement suggests that in order to deliver the best possible service to the customers, fire service managers should be constantly looking for ways to improve performance. The recognition of some of the limiting aspects of SCBA suggests the need to search for better or improved techniques and equipment in order to facilitate maximal performance.

The *Executive Leadership* course at the National Fire Academy includes a module dealing with "The Management Process." This module contains a discussion of the Kast and Rosenweig Systems Model. An essential component of the model is the **technical subsystem** which includes knowledge, techniques, equipment, and facilities. Consistent with that model, this research project seeks to develop aspects of the technical subsystem with a view to enhancing the overall job performance of firefighters.

LITERATURE REVIEW

The literature review for this project focused on three essential areas: (1) the physical demands and physiological responses involved in firefighting, and the importance of oxygen to physical performance; (2) the effects of oxygen-enriched air on human performance; and (3) concerns about taking oxygen into a fire. The first two topics were researched through literature searches conducted at the NETC Learning Resource Center and the University of Alberta Library. Information on the use of oxygen-enriched air in scuba diving in the second section was obtained by interviewing a scuba diving expert. The third topic was researched by conducting an interview with an expert in the field of chemistry and fire behavior.

The Physiological Demands of Firefighting

The physical demands of firefighting are well known and have been documented in a number of different research undertakings over the past two decades. One of the early articles on this subject was published by Lemon and Hermiston in 1977. This article established a physiological profile for professional firefighters and discusses the high physical demands faced by firefighters. A later article by Davis and Dotson (1987) discusses the physiological demands of firefighting and outlines the need for physical fitness programs. More recently Gledhill and Jamnik (1992a) conducted a series of tests intended to characterize the physical demands of firefighting and used this as the basis for developing fitness screening standards for firefighter candidates (Gledhill & Jamnik, 1992b).

The screening protocols developed by Gledhill and Jamnik (1992b) involve a series of firefighting task simulations as well as laboratory tests of physical fitness. The job-related performance tests were validated by 53 incumbent firefighters who were asked to complete Likert scale comparisons of the tests to actual firefighting. This method was used to establish the criterion validity of the job performance tests. The battery of job-related tests developed by Gledhill and Jamnik (1992b) are quite similar to the battery of tests included in the Firefighter Combat Challenge, and include the essential elements recommended in NFPA 1583.

The importance of maximal oxygen consumption was identified by Gledhill and Jamnik (1992b) in their testing procedures. They proposed that a laboratory test of oxygen uptake (V_{O2}) should be included as a standard test administered to firefighter applicants. The importance of oxygen consumption was also identified in research by Sothmann, Landry, and Saupe (1992) in their study of the influence of age on firefighting ability. These studies outline how the high intensity of the physical demands of the tasks performed by firefighters place significant demands on the respiratory system. These articles reinforce the idea that adequate oxygen supply is required for peak physical performance.

The potential for SCBA to limit oxygen uptake during exercise was examined by Louhevaara et al. (1985). These researchers noted that significant changes in ventilation patterns and rates occurred among subjects wearing SCBA. Specifically they observed shorter inspirations and expirations accompanied by an increase in breathing frequency. The authors in this study concluded that these changes in breathing pattern while wearing SCBA are likely the result of the weight of the SCBA and the shoulder harnesses which restrict the normal motion of the thorax. Research by Raven et al. (1977) supports the notion that the SCBA provides a restriction to normal air flow and limits the amount of physical work that can be performed while wearing SCBA. They found that the majority of the subjects in their research reported "lack of air" as the reason for stopping in a graded treadmill test designed to gradually increase the intensity of the workload. Based on this research on airflow through SCBA, it appears that increasing the oxygen concentration may be a viable method of overcoming some of the restrictions to breathing posed by the standard SCBA.

Other studies of the physiological demands of firefighting have noted additional physiological demands associated with firefighting, above and beyond the stresses of the physical nature of the work itself. For example, Bone et al. (1994) found that the insulative properties of NFPA 1500 compliant turnout gear caused a significant increase in the heart rate, temperature, and oxygen consumption of subjects due to the body's decreased ability to dissipate heat when encapsulated in bunkers pants and a nomex hood. They found that subjects experienced significantly higher physiological stress under similar work conditions when wearing bunker-style turnout gear as opposed to stationwear or hip-boots and jacket.

While the above noted research was based in a laboratory setting, it was theorized that the results would be more pronounced in a "hot and hostile environment" (Bone et al., 1994:54). This theory was extended to some degree through research conducted by Williams, Peteresen, and Douglas (1996). This research, while not examining actual firefighting, moved closer to the real thing by examining the physiological responses of subjects during live fire training. This study identified remarkably high heart rates during relatively low levels of exercise and attributed these high levels to the heat stress and psychological stress associated with the live fire training evolutions.

Overall, the literature reviewed in this area provided strong evidence of the physical demands of firefighting. These demands are related to not only the physical exercise associated with performing firefighting tasks, but also related to associated issues such as the body heat retention that is associated with wearing turnout gear, and the psychological aspects of fear and excitement. These findings suggest that research associated with the physiological responses of firefighters should attempt to simulate or replicate as many of these conditions as possible while at the same time controlling them in order to ensure that the different variables are held constant under the different experimental conditions.

Oxygen and Human Performance

For many years, exercise physiologists have been aware of the positive effects of breathing oxygen-enriched air during intense exercise. The use of oxygen-enriched air or "hyperoxia" has been found to produce effects such as reduced heart rate, higher levels of physical performance with less exertion, and decreased fatigue. All these effects have been generally viewed as beneficial to persons performing physically demanding activities (Welch, 1982; Plet et al., 1992).

The concept of hyperoxia generally involves providing breathing air that has a higher concentration of oxygen than the normal air naturally occurring at ground level in the earth's atmosphere. The concentration of oxygen that naturally occurs in atmospheric air at sea level is approximately 21 percent. The balance of the air is composed primarily of nitrogen. While different researchers have experimented with different concentrations of oxygen, the most widely used and generally accepted mixture for hyperoxic experiments is between 40 percent and 60 percent oxygen, and the balance nitrogen. This concentration is approximately two to three times that of normal breathing air and has been found to result in significant increases in human performance (Plet et al., 1992).

Experiments investigating the effects of hyperoxia have used athletes in sports such as rowing (Peltonen et al., 1995), cycling, and running (Hughson et al., 1995). While hyperoxia has been found to have positive effects on performance in these and other sports, it is not practical for athletes to use hyperoxic breathing apparatus while participating in these activities. Two physically demanding activities where it is practical to wear breathing apparatus, however, include scuba diving and firefighting.

While published research on the use of hyperoxic gases during scuba diving is not readily available for review, information was obtained through a local scuba diving expert. Through an interview with Mark Gunderson, a certified scuba diver, it was discovered that the use of "nitrox" (40 percent oxygen, 60 percent nitrogen) is a common practice among scuba divers. It is generally accepted that divers can stay down longer and feel better when using nitrox rather than the conventional normal air or "normox" which is 21 percent oxygen. Most jurisdictions require that divers take a prescribed course of study and obtain certification prior to scuba diving with nitrox (Gunderson, personal interview, September 1997).

In addition to scuba diving, the other logical place for using hyperoxic gases is in firefighting. In 1977, a group of Dutch researchers conducted an experiment which involved firefighters wearing SCBA and walking on a treadmill (van den Berg et al., 1977). Firefighters in this study were required to complete a number of treadmill runs of fixed duration and intensity, and were given the freedom to choose how long they rested between runs. The study showed that the rest time was decreased by 29 percent when hyperoxia was used, and the overall volume of air was reduced by 6 percent. This laboratory experiment established a positive effect for the use of hyperoxia, however, the results of the tests were not extended to further study in the field, or used as the basis for changes to practices in the profession of firefighting. The authors suggested that the potential advantages of using hyperoxia in firefighting include enhanced work capacity; reduced fatigue; and extended work time from a specific quantity of air. These suggestions reinforced the need for further research in this area in order to investigate the practical application of hyperoxia in professional firefighting.

Concerns Regarding Oxygen and Fire

One of the possible explanations for the lack of practical applications of hyperoxia research in firefighting could be the fear of introducing oxygen into a fire situation. This issue was raised by a number of firefighters who were approached by the researcher when seeking volunteers to be subjects in this study. The basic training in fire behavior and chemistry that most firefighters receive leads to concerns about introducing oxygen into a fire situation. It is well understood that in addition to fuel, heat, and chemical reactions, oxygen is an essential component of combustion. Thus, there may be a reluctance among some firefighters to enter an involved structure fire with a tank of oxygen-enriched air on their backs. There is a legitimate concern that exhaled air may be oxygen rich and may contribute to the intensity of the fire. A further concern that may be raised is the concern that if the valve on the tank were bumped or damaged the oxygen that would be released could escalate the intensity of the fire.

In reviewing these concerns, a personal interview was conducted with a chemistry expert, Dr. Ewe Terner, the Dangerous Goods Adviser for the Edmonton Emergency Response Department. Dr. Terner pointed out that the volume of air contained in the typical air tank is negligible when compared to the volume of air in the average room. He also pointed out that there is far less risk in using 40 percent oxygen than there would be using pure oxygen. Terner suggested that even in a damaged valve situation, the oxygen would dissipate quickly and would pose little if any threat of escalating the fire. It must be recognized, however, that as a practical matter, an attempt to introduce hyperoxia as a professional firefighting practice may result in opposition from firefighters based on these types of concerns.

PROCEDURES

In order to examine the potential benefits of hyperoxia on firefighters, a series of experiments were conducted involving simulated firefighting activities. The activities involved a circuit of simulated firefighting tasks similar to the Firefighters Combat Challenge. The research proceeded in two phases. Phase one was essentially a pilot phase which sought to establish an effect for hyperoxia. Following the completion of this phase the results were examined and the procedures modified for phase two. The two different phases are described below.

Phase One--This initial phase included five events in a circuit and were set up in the following sequence: Task 1: three-story stair climb carrying 40-pound highrise kit; Task 2: rope pull raising and lowering a 55-pound hose roll 50 feet vertically; Task 3: drag dummy 50 feet using a 200-pound rescue mannequin; Task 4: forcible entry simulation using an 8-pound sledge hammer; and Task 5: a 200-foot hose drag using 150 feet of 2-1/2-inch hose and nozzle. This circuit was set up in the athletics fieldhouse at the University of Alberta.

The study used a double blind research design in which the subjects completed a number of different trials wearing NFPA 1500 compliant turnout gear and Scott 4.5 SCBA using either 21-percent oxygenated normal breathing air (NORMOX) or 40-percent oxygen-enriched air (HYPEROX). The air tanks were coded and randomly assigned on different trials so that neither the subjects nor the researchers were aware of which subjects had which type of air on the various trials.

The subjects in the study were professional firefighters and university graduate students who received training in the use of firefighting equipment and SCBA. A total of 17 subjects participated (15 males and 2 females). All volunteers completed a graded exercise test and their blood lactate was measured prior to them being accepted as subjects. This testing ensured that the subjects had the fitness levels necessary to safely participate in the study. This initial testing also provided baseline data on the subjects' maximal heart rates and ventilatory threshold, which allowed the researchers to examine the extent to which subjects were working at full capacity during the simulated firefighting activities.

Following this initial fitness testing, all the subjects completed at least three practice sessions using normox in order to become familiar with the simulated firefighting circuit. This was intended to reduce the possibility of differences due to learning effects. Following initial familiarization sessions, the subjects completed three different trials on different days. The possibility of learning effects occurring was measured by conducting a reliability test on the data from the last practice test using normox and the first experimental circuit using normox. In all trials the subjects were instructed to complete the circuit as quickly as possible using a maximal effort.

The research procedures were designed to compare the effects of hyperoxia to normoxia using five different measures: (1) the overall time to complete the circuit; (2) the task specific times; (3) the level of exertion as measured by the level of lactate in the venous blood following the activity; (4) the comparative heart rates of subjects; and (5) the perceived level of exertion reported by the subjects during the simulated firefighting tasks.

The times for each event, the time accumulated in between events, and the total cumulative times were measured using stopwatches. The blood lactate levels were measured using laboratory tests comparing venous blood samples taken 5 minutes after each completion of the circuit by each subject. Heart rates were continuously monitored using Polar model PE 3000 heart monitors. Perceived level of exertion was measured in between tasks 2 and 3, and 4 and 5, using a standardized 9-point scale for Rating of Perceived Exertion (RPE) developed by Borg (1982).

Statistical analysis was conducted using a standard personal computer and a statistics software package. A repeated measures analysis of variance (ANOVA) was used to test for within-subject differences between the performance variables under the normox and hyperoxic conditions. A probability value of $P<0.05$ was considered significant.

Phase Two--Following the review of the preliminary results from phase one, it was generally agreed by the researchers that lengthening the overall firefighting simulation circuit would likely yield stronger and more meaningful results for the use of hyperoxia. The average time to complete the training circuit in phase one was approximately 5 minutes, and the effects of the hyperoxia began to appear in the final event in the circuit. The simulation was adjusted and lengthened in order to increase the overall time and tap into the aerobic energy pathways. The circuit was expanded significantly by adding walking distance between tasks and lengthening the requirements within the events. Once again the subjects were asked to complete the circuit as quickly as possible using their maximal effort. The subject pool for this second phase of the research was reduced to 6.

There are several limitations that may be noted in the design of this experimental research. The challenge of this type of research is to make the experiment as similar to the real job as possible while at the same time controlling variables other than those being researched. A number of different control measures were put in place in this study. For example, a number of training evolutions were undertaken in an attempt to minimize the extent to which performance would be influenced by a learning effect. Other variables such as temperature and weather conditions were controlled by conducting the experiment indoors in a climate-controlled fieldhouse. The resistance in each of the various tasks was also controlled by using standardized tools and props and having researchers ensure that standardized methods were used in tasks such as the rope pull and the forcible entry simulation.

A major limitation of the study was the fact that it was a simulation that was meant to represent the physical demands of firefighting. The use of NFPA 1500 compliant turnout gear and SCBA made the tests realistic in some respects. In other respects, however, such as the absence of heat, smoke, and reduced visibility, the test did not realistically represent actual firefighting. It was recognized, however, that as an initial experiment to test for the potential positive effects of hyperoxia, the research design was similar enough to real firefighting to be a valid test of the effects.

Other concerns or limitations included the sample size and the duration of the simulation circuit. There were several significant costs associated with this study including the cost of having the hyperoxic mixture custom blended and transferred to SCBA bottles, and the cost of conducting the blood lactate analysis. There was also a significant time commitment required by the research team to set up the simulation course, supervise the subjects as they went through, and collect and analyze the data for each subject. Because of these concerns, it was determined that 15 subjects was the maximum that could be accommodated. Following standard statistical techniques it was established that such a sample size would yield reliable and valid results given the within-subject design of the study.

The time commitment required by subjects and the rigorous nature of the testing procedures in this study made it difficult to recruit subjects. These factors resulted in a high attrition rate between phase one and phase two of the study. The researcher himself served as a subject and can attest to the fact that the study was time consuming, physically demanding, and somewhat uncomfortable both when working at peak performance and when providing blood samples after each evolution.

RESULTS

The initial results of this study demonstrated some positive effects for the use of hyperoxia. Specifically, the results indicated a reduction in overall time and in perceived fatigue following task 4. There were not, however, any significant differences in the heart rates or the lactate levels when comparing the hyperoxic and normoxic trials. When comparing times on specific events, there were not significant differences on the initial 4 tasks, but there were significant differences on the final task, the hose drag. A comparison of the within-subject means on the various measures is presented in Appendix A.

A comparison of the data from the last practice circuit using normox and the first experimental circuit using normox indicated a high reliability of .99. This indicated that any improvements observed in the experiment could be attributed to the effects of the hyperoxia rather than the effects of learning through repeated trials.

In examining these initial results it became clear to the researchers that the effects of the hyperoxia do not become fully used until the body reaches a level of aerobic exertion. It was observed that the nature of the circuit of simulated firefighting tasks required muscular strength fueled primarily by the anaerobic energy pathways, and as such, the benefits of hyperoxia did not begin to take effect until the aerobic energy pathways became fully engaged.

It was also noted by the researchers that in order to test the specific benefits of hyperoxia in actual firefighting situations, it would be necessary to modify the simulation tasks in order to more closely represent the physical demands of firefighting. It was generally agreed by the researchers that the specific tasks were valid simulations of individual tasks performed by firefighters. It was further acknowledged, however, that a circuit that could be completed in less than 4 minutes was not representative of the complete bundle of tasks typically performed by firefighters under actual work conditions. Based on this reasoning, the test circuit was extended and modified in order to lengthen the overall time of the simulation.

The results from phase two of the study showed a more marked positive effect for the use of hyperoxic air. The results are provided in Appendix B. The data related to the hypotheses in the following ways:

H1. The heart rate responses under the hyperoxia conditions will be lower than heart rates under the normox conditions.

This hypothesis was rejected. There were not significant differences in heart rate when breathing normal SCBA air or the hyperoxic mixture. The researchers observed that in all trials the subjects were working at maximum performance and therefore the recorded heart rates were relatively consistent in all trials. It should be noted, however, that although the heart rates were similar, tasks were completed in less time using hyperoxic air suggesting that there was a greater output achieved at a similar heart rate.

H2. The blood lactate levels under the hyperoxia conditions will be lower than the blood lactate levels under the normox conditions.

This hypothesis was also rejected. There were not significant differences in the blood lactate levels of the subjects when breathing normal SCBA air and the hyperoxic mixture. As above, the researchers attributed this lack of difference to the fact that subjects were working at maximal levels in all trials.

H3. The perceived physical exertion under the hyperoxia conditions will be lower than perceived physical exertion under the normox conditions.

This hypothesis was supported in both phase one and phase two of the study. The support was found to be less pronounced, in terms of statistical significance, in phase two of the study. This was attributed to the smaller sample size in phase two which lowered the degrees of freedom substantially, and made it more difficult to achieve statistical significance.

H4. The times on each individual event under the hyperoxia conditions will be lower than the event times under the normox conditions.

This hypothesis was rejected in all but one of the events in phase one, and was accepted in all of the events in phase two of the study. The increase in event duration in phase two demonstrated that the positive effects of hyperoxia increase over time.

H5. The total elapsed times under hyperoxia conditions will be lower than the total elapsed times under normox conditions.

This hypothesis was supported in both phase one and phase two of the study, indicating a positive effect of hyperoxia on the performance of simulated firefighting tasks. The overall increase in performance using hyperoxic air was approximately 6-percent.

DISCUSSION

This research was a preliminary attempt to extend previous research and to examine the benefits of hyperoxia in simulated firefighting situations. In both of the firefighting simulations undertaken, the use of a hyperoxic mixture in the SCBA bottles was found to have a significant effect on task performance. The effects of hyperoxia were much more pronounced in the second research scenario which involved an extended overall time period and a longer duration for each task. While the second research design was more closely representative of the actual demands of firefighting, neither design was representative of the fact that a typical working fire will require firefighters to work until their air tank becomes totally depleted or at least until the low-air warning device is activated. Thus, although this study established a preliminary basis to support the use of hyperoxic air in SCBA tanks, further research is required.

The fact that subjects performed better and reported feeling less tired when using hyperoxia suggests that there may be some positive reasons for conducting further research and possibly some trials under actual firefighting conditions. This study demonstrated that the use of hyperoxic air does have the potential to assist firefighters in performing at higher levels and feeling less fatigued afterwards. This could be of particular benefit in older urban centers where firefighters face the possibility of responding to several working fires within the time parameters of a single shift.

This study suggests that hyperoxic air may also sustain a firefighter for a longer duration than does a regular SCBA air mixture. While this study was not designed to systematically measure the amount of air consumed in the different trials, the researchers did monitor air consumption and generally concluded that subjects tended to use less hyperoxic air than normal air. There are many variables that are difficult to control, including the seal on the face and the calibration and accuracy of the tank pressure indicators. Further research will require more accurate measurement devices and more controlled laboratory conditions in order to accurately measure the actual air consumption when using hyperoxic air rather than normal air.

A secondary issue that arose in this research relates to the extent to which firefighting simulations such as the Combat Challenge are fair representations of the actual physical demands of firefighting. Exercise physiologist, Dr. Loren Myhre, has previously observed that the Combat Challenge and similar test are not a fair representation of the physical demands of firefighting, in that people may "tough it out" and get through the test while not being aerobically fit to perform the more sustained physical activities that actual firefighting requires (personal communication, August 1996). The lack of a significant effect for hyperoxia in phase one of the this study, and the more marked effects found in phase two suggest that this observation is accurate, and highlights the need for firefighter fitness tests to be extended in duration in order to more accurately represent the physical demands of firefighting, and evaluate the subjects' aerobic and well anaerobic performance capabilities. This observation also supports the recommendations of Gledhill and Jamnik (1992b), that fitness screening for firefighters should include job-related tests **and** laboratory tests of aerobic fitness.

The 6-percent improvement in performance found in the results of this study may be seen as highly significant in emergency situations where every second counts. These effects may be even more pronounced when studied over longer durations.

RECOMMENDATIONS

Previous research in Holland (van den Berg et al., 1977) established that the use of hyperoxic air had a positive effect on firefighters in a laboratory. The researchers in that study theorized some of the potential positive effects that could be realized by firefighters under actual working conditions. The current study extended that initial research by investigating the effects of hyperoxic under field research conditions using a series of simulated firefighting tasks. The present study has confirmed the positive effects of hyperoxic air in SCBA tanks and suggests the need to carry out further research in a number of areas. The research findings lead to the following recommendations:

1. Further research should be conducted using moderate to heavy workloads and measuring the duration of the air supply. In other words, subjects should be required to work until the tank is completely empty in order to establish whether hyperoxic air actually sustains a firefighter for a longer duration than normal air under identical work conditions. This type of research will require careful calibration of tank volume, and careful control of workloads.

2. Further research is required to measure the effects of hyperoxia over a longer duration of time. This study looked at average durations of 5 minutes and 9 minutes in phases one and two respectively. Realistically, firefighters typically work for periods of 30 to 60 minutes when using SCBA in actual working conditions. Further research should explore the effects of hyperoxia when used over longer durations.

3. One of the limitations of the more widespread study and use of hyperoxia is the cost factors. Researchers and fire service personnel who are interested in exploring this technology should work with air supply companies and SCBA manufacturers to investigate ways to reduce the costs of producing and packaging hyperoxic air.

4. Finally, in order to support the further investigation of the potential of hyperoxic air to improve the job performance of firefighters, researchers and fire service professionals should seek corporate and/or governmental sponsorships to support further and ongoing research.

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APPENDIX A

Phase One Data Analysis

Table 1
Physical and performance characteristics during graded exercise testing (n=17).

Variable	Mean	S.D.	Range Low-High
Age (yr)	27.7	8.09	20-45
Height (cm)	179.1	7.03	l65-1.91
Mass (kg)	78.7	10.8	63.1-100.0
VO_2 @ Tvent ($ml•kg^{-1}•min^{-1}$)	38.7	6.1	32.2-51.5
HR @ Tvent ($beats•min^{-1)}$	168	10.1	155-184
VO_{2max} ($ml•kg^{-1}•min^{-1}$)	51.8	6.1	44.3-65.4
Blood lactate* (mM)	11.48	2.22	7.4-16.2
HRmax ($beats•min^{-1}$)	192	8.1	179-203

*the blood sample was drawn exactly 5 min post exercise.

Table 2
Mean (± S.D.) performance times during the work task circuit under normoxic (NOX) and hyperoxic (HOX) conditions (n=17).

Time (s)	NOX	S.D.	HOX	S.D.
Stair climb	78.5	16.1	78.7	14.3
Rope pull	39.4	13.0	38.9	13.5
Victim drag	18.9	7.3	17.6	6.4
Forcible entry	31.2	22.8	28.3	19.5
Hose drag	29.4	9.6	25.9*	8.3
Total 'event'	197.2	58.9	189.4*	51.8
Total 'between'	128.6	22.4	124.4*	17.4
Total overall	325.8	78.3	313.8*	66.0

*$p<0.05$

Table 3
Mean (±S.D.) heart rate, perceived exertion (RPE), and blood lactate responses to the work task circuit under normoxic (NOX) and hyperoxic (HOX) conditions n=17).

Variable	NOX	S.D.	HOX	S.D.
Heart rate (beats•min$^{-1)}$	173	9.6	174	9.5
RPE-1	12.9	2.3	12.5	2.0
RPE-2	15.7	1.9	15.0*	1.7
Blood lactate (mM)	15.57	2.25	15.74	2.01

Note: RPE-1 and RPE-2 obtained after the second and fourth events respectively.

* $p<0.05$

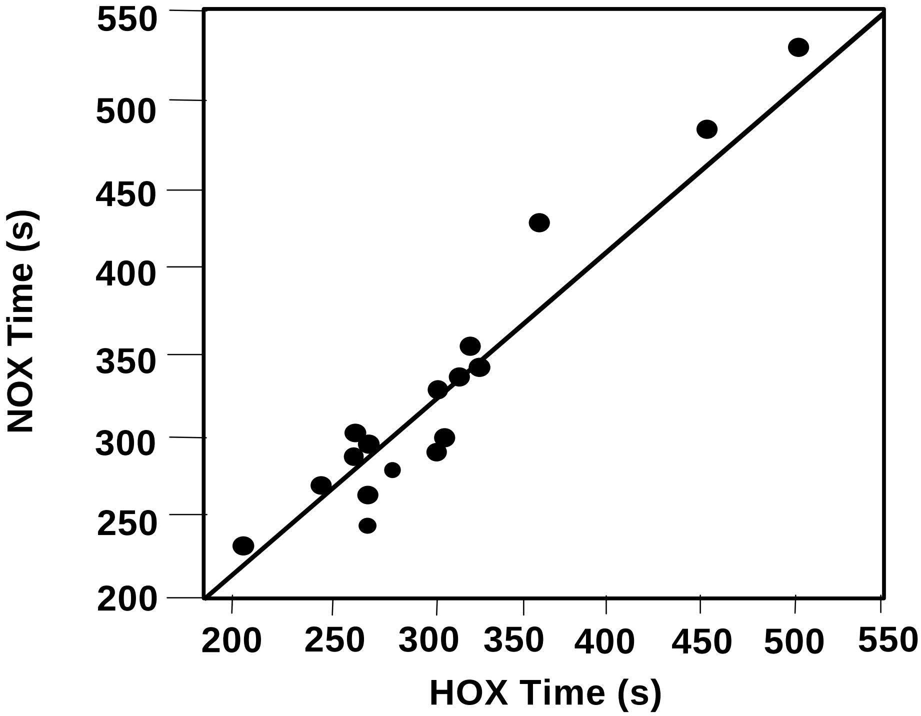

Figure 1. Scatterplot of performance time to complete the work task circuit under normoxic (NOX) and hyperoxic (HOX) conditions (n=17).

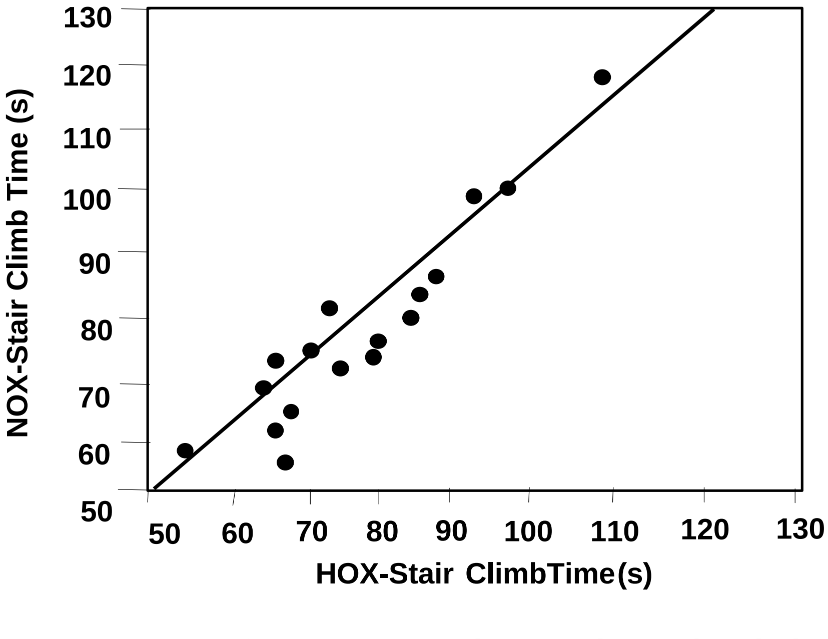

Figure 2. Scatterplot of performance time on the Stair Climb event under normoxic (NOX) and hyperoxic (HOX) conditions (n=17).

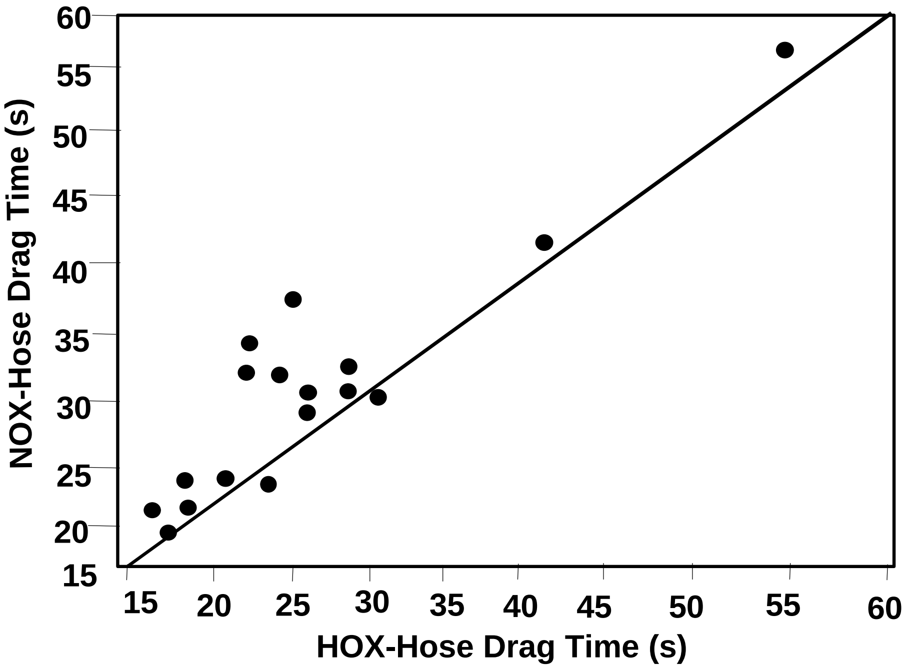

Figure 3. Scatterplot of performance times for the Hose Drag event under normoxic (NOX) and hyperoxic (HOX) conditions (n=17).

H VS N RPE 1

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	16	137.941	8.621	12.745	.0001
Within subjects	17	11.5	.676		
treatments	1	1.441	1.441	2.292	.1495
residual	16	10.059	.629		
Total	33	149.441			

Reliability Estimates for- All Treatments: .922 Single Treatment: .854

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
RPE1-H	17	12.471	2.004	.486
RPE1-N	17	12.882	2.288	.555

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
RPE1-H vs. RPE1-N	-.412	.577	2.292	1.514

H VS N RPE 2

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	16	94.765	5.923	6.712	.0002
Within subjects	17	15	.882		
treatments	1	4.235	4.235	6.295	.0232
residual	16	10.765	.673		
Total	33	109.765			

Reliability Estimates for- All Treatments: .851 Single Treatment: .741

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
RPE2-H	17	15	1.696	.411
RPE2-N	17	15.706	1.929	.468

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
RPE2-H vs. RPE2-N	-.706	.596*	6.295*	2.509

*Significant at 95 percent.

H VS N HOSE DRAG TIME

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	16	2447.881	152.993	11.33	.0001
Within subjects	17	229.56	13.504		
treatments	1	105.178	105.178	13.53	.002
residual	16	124.382	7.774		
Total	33	2677.441			

Reliability Estimates for- All Treatments: .912 Single Treatment: .838

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
HD-H	17	25.865	8.284	2.009
HD-N	17	29.382	9.599	2.328

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
HD-H vs. HD-N	-3.518	2.028*	13.53*	3.678

*Significant at 95 percent.

H VS N TOTAL TIME REPEATED MEASURES ANOVA

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Source:	**df:**	**Sum of Squares:**	**Mean Square:**	**F-test:**	**P value:**
Between subjects	16	164689.56	10293.098	40.141	.0001
Within subjects	17	4359.24	256.426		
treatments	1	1224	1224	6.246	.0237
residual	16	3135.24	195.952		
Total	33	169048.8			

Reliability Estimates for- All Treatments: .975 Single Treatment: .951

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Group:	**Count:**	**Mean:**	**Std. Dev.:**	**Std. Error:**
H-TOT	17	313.8	66.01	16.01
N-TOT	17	325.8	78.305	18.992

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Comparison:	**Mean Diff.:**	**Fisher PLSD:**	**Scheffe F-test:**	**Dunnett t:**
H-TOT vs. N-TOT	-12	10.18	6.246	2.499

*Significant at 95 percent.

APPENDIX B

Phase Two Data Analysis

This figure shows the performance times for the six subjects to complete the extended work circuit in the second pilot study. We extended the simulated firefighting work circuit so that it involved almost twice as much work as the circuit in the first study. Note that all six subjects improved their performance while on the HOX gas mixture. It is important to remember that the test-retest reliability for total time on NOX trials was 0.99 **before** we conducted the experimental trials that you see below. The means (±SE) values for total time are as follows:

NOX	9.11 (0.34) min
HOX	8.60 (0.33) min

As you can see, the HOX condition was faster by 0.51 min or 30.6 s ($p<0.05$). This represents a relative improvement of about 6 percent.

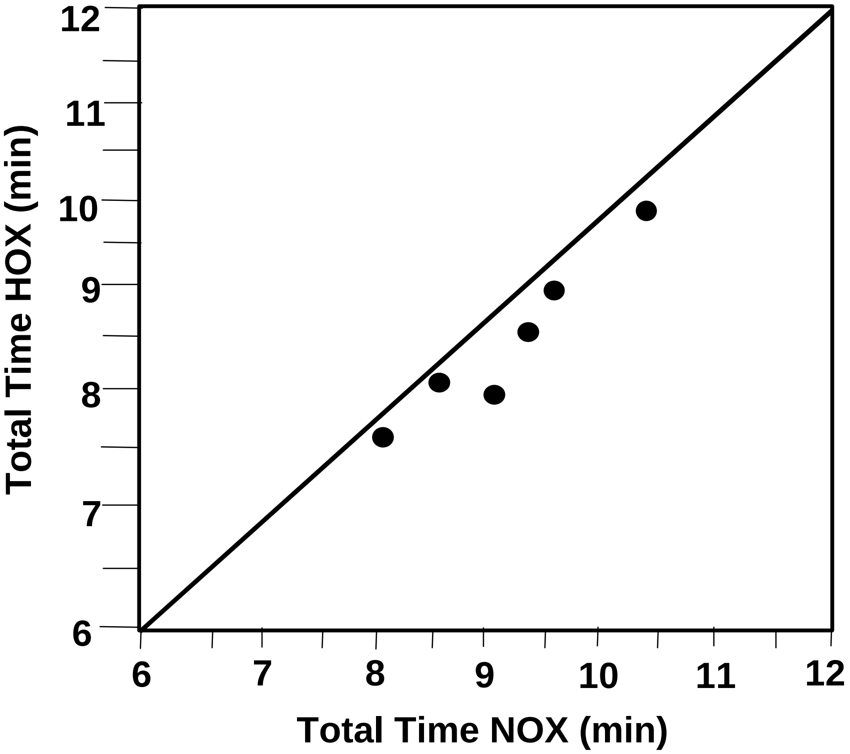

Figure 1. Scatterplot of performance times to complete the extended work task circuit under normoxic (NOX) and hyperoxic (HOX) conditions (n=6.)

This figure shows the performance times for the six subjects during the first portion of the extended work circuit. This evolution consisted of stair climbing while carrying a highrise hose pack. It should be noted that all subjects improved their performance while on the HOX gas mixture. The mean (±SE) performance times for the two conditions are as follows:

NOX	147.7 (8.0) s
HOX	137.3 (7.5) s

This represents an absolute improvement of 10.4 s ($p<0.05$) or in relative terms, a 7-percent decrease in the time required to complete this task.

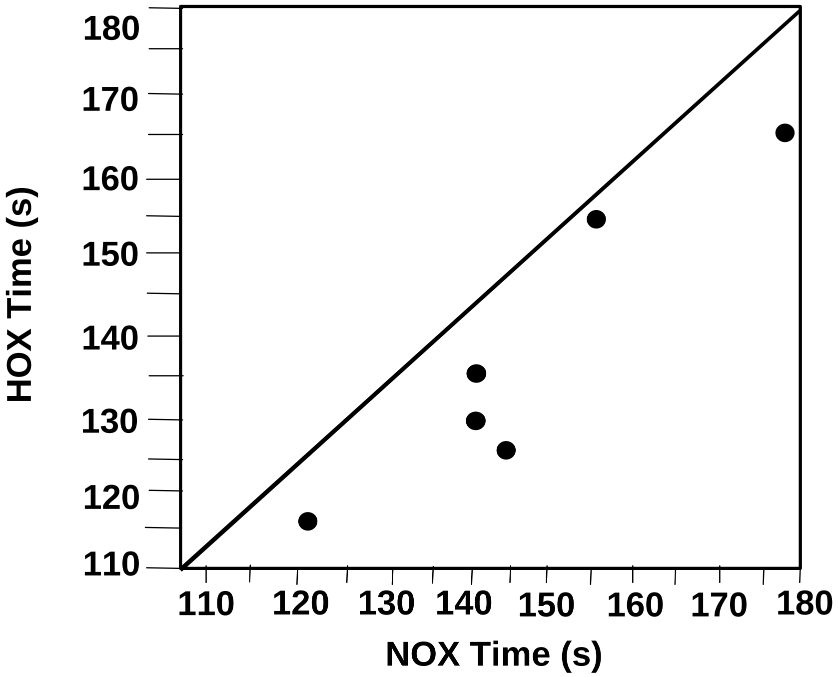

Figure 2. Scatterplot of performance time for the stairclimb event (from start to beginning of rope pull) under normoxic (NOX) and hyperoxic (HOX) conditions (n=6).

This figure shows the performance times for the six subjects in the second pilot study during the final evolution of the extended work circuit. This evolution consists of dragging 3 lengths of 65-mm hose and nozzle a distance of 100 m. This is the last component of the circuit and it is important to remember that the subjects are very fatigued by the time they begin this task. The mean (±SE) performance times for the two conditions are as follows:

NOX	40.4 (1.8) s
HOX	37.2 (1.6) s

This represents an absolute improvement of 3.2 s ($p<0.05$), or in relative terms, an 8-percent reduction in the time required to complete the task.

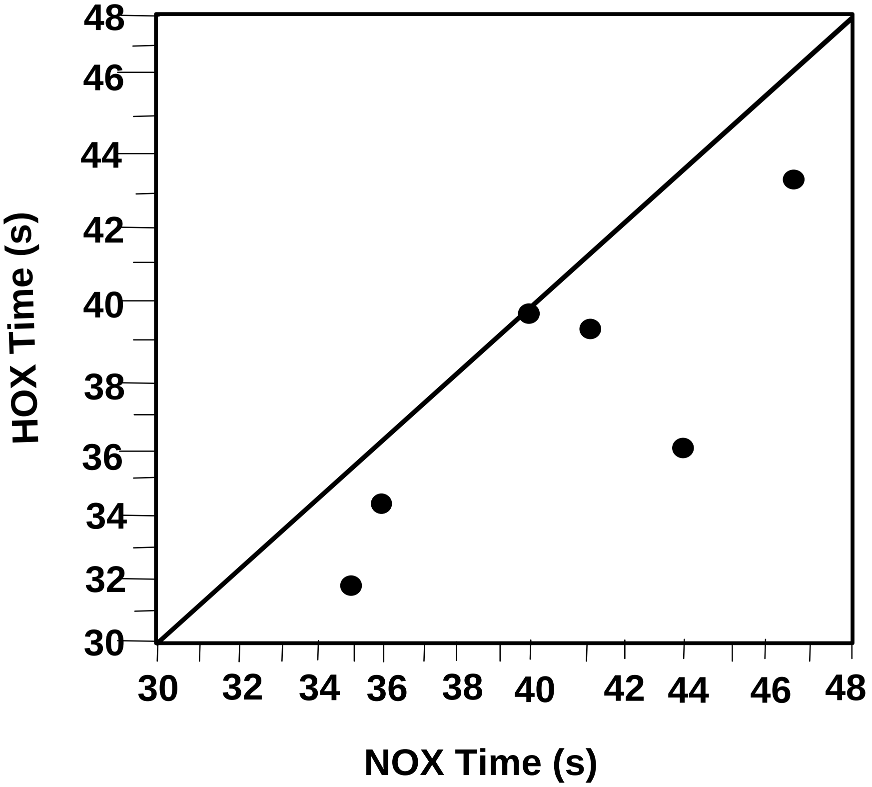

Figure 3. Scatterplot of performance time to complete the hose drag evolution on the extended work circuit under normoxic (NOX) and hyperoxic (HOX) conditions (n=6).

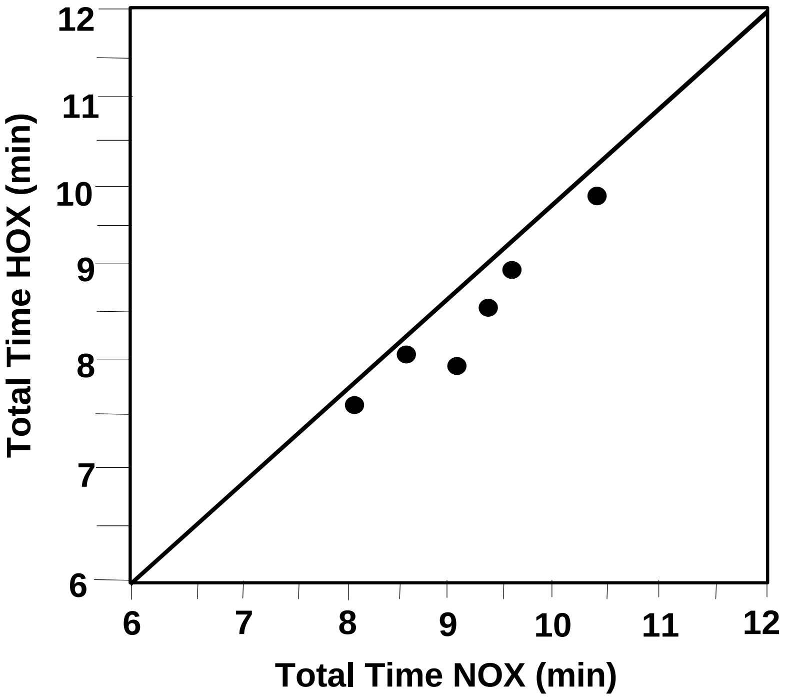

Figure 1. Scatterplot of performance times to complete the extended work task circuit under normoxic (NOX) and hyperoxic (HOX) conditions (n=6)

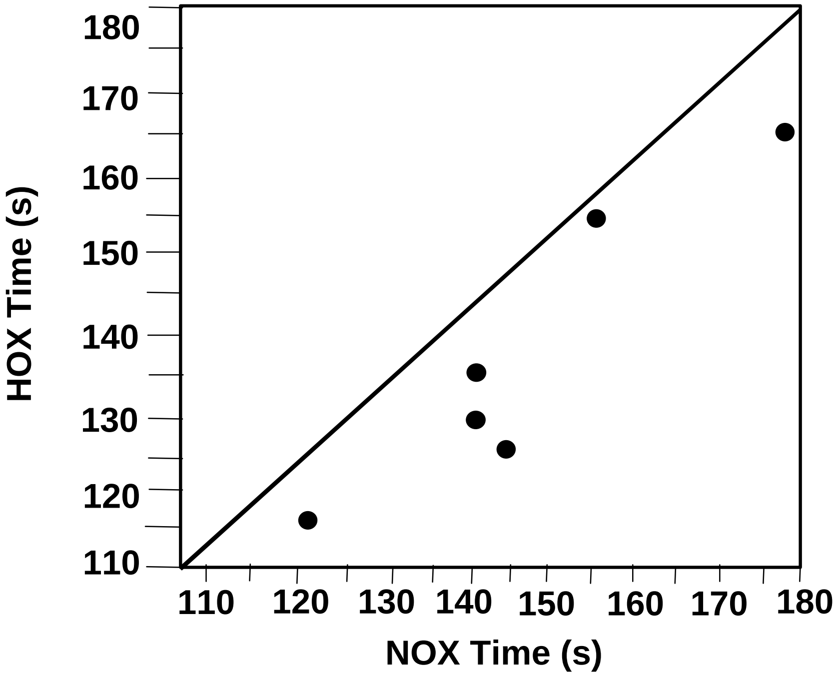

Figure 2. Scatterplot of performance time for the stairclimb event (from start to beginning of rope pull) under normoxic (NOX) and hyperoxic (HOX) conditions (n=6).

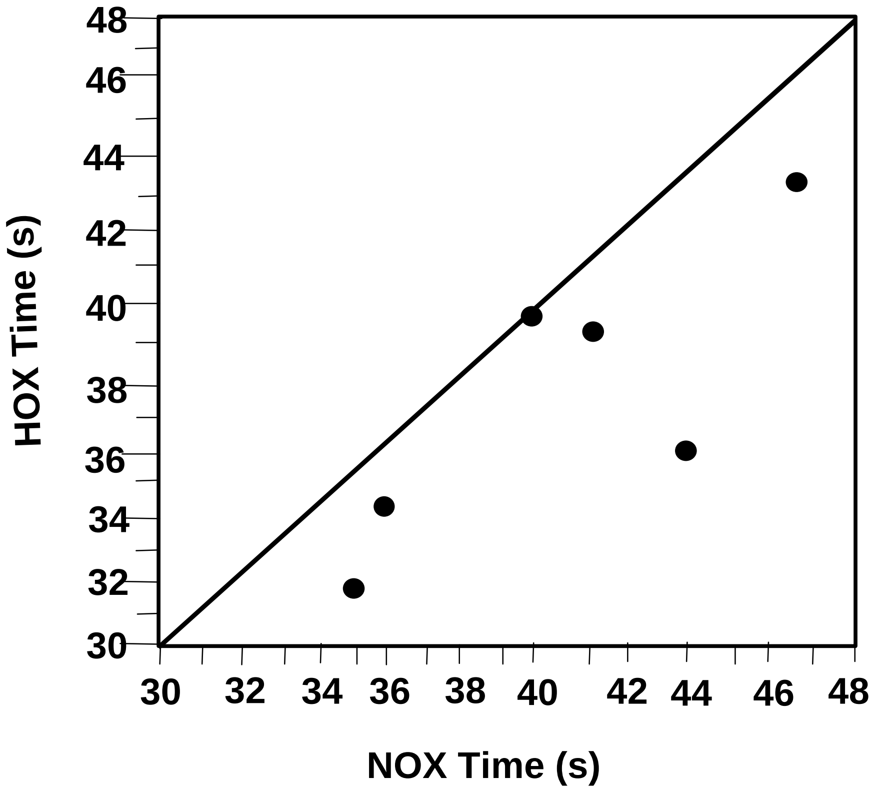

Figure 3. Scatterplot of performance time to complete the hose drag evolution on the extended work circuit under normoxic (NOX) and hyperoxic (HOX) conditions (n=6).

STAIRCLIMB/HIGHRISE PACK ANOVA

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Source:	**df:**	**Sum of Squares:**	**Mean Square:**	**F-test:**	**P value:**
Between subjects	5	3437.957	687.591	8.842	.0097
Within subjects	6	466.565	77.761		
treatments	1	327.608	327.608	11.788	.0186
residual	5	138.957	27.791		
Total	11	3904.523			

Reliability Estimates for- All Treatments: .887 Single Treatment: .797

Note: 1 case deleted with missing values.

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Group:	**Count:**	**Mean:**	**Std. Dev.:**	**Std. Error:**
T2R NOX	6	147.7	19.485	7.955
T2R HOX	6	137.25	18.323	7.48

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Comparison:	**Mean Diff.:**	**Fisher PLSD:**	**Scheffe F-test:**	**Dunnett t:**
T2R NOX vs T2R HOX	10.45	7.825*	11.788*	3.433

*Significant at 95 percent.

HOSE DRAG ANOVA

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Source:	**df:**	**Sum of Squares:**	**Mean Square:**	**F-test:**	**P value:**
Between subjects	5	158.049	31.61	4.149	.0563
Within subjects	6	45.711	7.619		
treatments	1	28.213	28.213	8.062	.0363
residual	5	17.498	3.5		
Total	11	203.76			

Reliability Estimates for- All Treatments: .759 Single Treatment: .612

Note: 1 case deleted with missing values.

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Group:	**Count:**	**Mean:**	**Std. Dev.:**	**Std. Error:**
HOSE NOX	6	40.358	4.387	1.791
HOSE HOX	6	37.292	3.983	1.626

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Comparison:	**Mean Diff.:**	**Fisher PLSD:**	**Scheffe F-test:**	**Dunnett t:**
HOSE NOX vs HOSE HOX	3.067	2.777*	8.062*	2.839

*Significant at 95 percent.

TOTAL TIME ANOVA

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Source:	df:	Sum of Squares:	Mean Square:	F-test:	P value:
Between subjects	5	6.415	1.283	8.046	.0123
Within subjects	6	.957	.159		
treatments	1	.77	.77	20.64	.0062
residual	5	.187	.037		
Total	11	7.371			

Reliability Estimates for- All Treatments: .876 Single Treatment: .779

Note: 1 case deleted with missing values.

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Group:	Count:	Mean:	Std. Dev.:	Std. Error:
TOT NOX	6	9.107	.824	.336
TOT HOX	6	8.6	.801	.327

One Factor ANOVA-Repeated Measures for $X_1 \ldots X_2$

Comparison:	Mean Diff.:	Fisher PLSD:	Scheffe F-test:	Dunnett t:
TOT NOX vs TOT HOX	.507	.287*	20.64*	4.543

*Significant at 95 percent.