ANALYSIS OF FATIGUE IN FIREFIGHTERS: FOOT CLEARANCES OVER STAIR EDGES AND VALIDATION OF A NOVEL MEANS FOR METABOLIC DATA COLLECTION

BY

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THESIS

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ABSTRACT

Firefighting is a physically challenging occupation which demands high levels of energy exertion and can result in high levels of fatigue. The combination of slip, trip, and fall injuries with those caused by overexertion comprise a significant number of total firefighter injuries each year.

To better assess the energy expenditure and exertion of firefighters during simulated firefighting activities, a standard firefighter facepiece was modified to interface with a portable metabolic monitoring device (Cosmed $K4b^2$). This design allowed for the collection of metabolic data while the firefighter utilizes a standard self-contained breathing apparatus (SCBA) as the air supply. This modified facepiece was then validated in a stationary bicycling variable-workload assessment with two metabolic measurement devices (the portable Cosmed $K4b^2$ unit and a limited portability metabolic cart unit). These conditions were: (1) the standard mask with the Cosmed $K4b^2$, (2) modified SCBA facepiece with the Cosmed $K4b^2$, (3) standard headpiece with the metabolic cart, and (4) modified SCBA facepiece with the metabolic cart. These results showed the modified facepiece was an accurate and reliable tool for the collection of metabolic data, and is suitable for use in future studies which demand the collection of metabolic data while utilizing a SCBA system.

Previous studies have attempted to simulate firefighting in safe, controlled environments, but a standard has yet to be developed. This study examined three protocols, each designed to simulate the environment and workload associated with firefighting. To assess the biomechanical differences between conditions, firefighters ascended and descended stairs before and immediately after activity. For half of the trials firefighters carried an asymmetrical hose load, as is commonly done on the fireground. Clearances of the heels and toes were examined over each stair edge. Some significant changes occurred due to condition, pre/post activity, and load carriage. These results can lead to the development of a standard for the simulation of firefighting and lead to reduced injuries on the fireground by allowing for a better understanding of how fatigue and load carriage affect firefighters.

DEDICATION

I dedicate this work to Britni. Without her support and that of my parents, Rick and Donna, and my brother, Scott, this would not have been possible.

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CHAPTER 1: INTRODUCTION

Firefighting by its very nature is inherently dangerous. Every year there are approximately 40,000 fireground injuries to firefighters in the United States. A vast number of injuries are the result of either overexertion or slips, trips, and falls (STF). Nearly 17,000 of the 38,600 annual injuries from 2005-2009 can be attributed to one of these two causes. STF and overexertion injuries each account for approximately 20-25% of fireground injuries [1]. When injuries are divided into minor (no lost work time) and moderate/severe (lost work time), the significance of STF and overexertion injuries is even more apparent. On average, 28% of moderate/severe injuries were due to STF events, while 23% of moderate/severe injuries were the result of overexertion. Further, in 2009, 60% of all fatal injuries were the result of overexertion and nearly 10% were from a fall or jump [2]. While there has been significant study of exertion related to cardiac response (e.g. [3, 4]), further research is necessary to develop better methods for quantifying energy expenditure and exertion of firefighters and examine the biomechanical effects of firefighting and their impacts on STF injuries.

Firefighting demands high levels of exertion to complete necessary tasks on the fireground. Examination of the heart rate, oxygen consumption and other metabolic demands of firefighting may help to understand the causal mechanisms for overexertion injuries; however, current methods of collecting metabolic data from firefighters are limited both by the data acquisition equipment and personal protective equipment (PPE) traditionally worn by firefighters. Typically research is limited to collecting heart rate data to quantify the physiological demands of firefighting. However, this procedure has limited utility due to the vast differences in fitness in firefighters. The traditional firefighter's PPE consists of pants, coat, hood, gloves, boots, helmet and a self-contained breathing apparatus (SCBA). The SCBA consists of a compressed air cylinder, facepiece, and a harness worn around the shoulders which supports the air cylinder. This gear, especially the design of the SCBA, limits the ability to collect metabolic data while the firefighter is "on-air" (breathing through the SCBA and consuming air from the compressed air supply). It is, however, essential that we quantify the physiological demands associated with firefighting as accurately as possible to better understand the metabolic costs needed to fulfill these demands; therefore it is necessary to develop new methods to capture these data.

Determining the effects that fatigue and load carriage have on firefighters can improve firefighter safety leading to decreased STF injuries. Previous research has shown that muscle fatigue has an effect on limb position and movement [5] and that wearing firefighting PPE can impact gait and balance [6-10], yet there has been little research connecting the significant number of slip, trip, and fall injuries with the high levels of fatigue experienced during firefighting. Falls on stairs has been identified as the fifth most prevalent fireground injury [11]. It is, however, unknown how fatigue and load carriage can affect STF injury while traversing stairs.

Previous research has used a wide variety of methods to simulate the activity experienced by a firefighter on the fireground, however no standard exists. Methods include performing a single task related to work on the fireground in a live-fire environment [12], climbing stairs in a temperature controlled environment [13], and walking on a treadmill in a temperature controlled environment [14-17]. To better understand how fatigue affects firefighters while wearing their PPE, it is preferable to develop standardized protocols for the safe, controlled simulation of firefighting.

Fireground injuries due to overexertion

Overexertion on the fireground is the leading cause of injury for firefighters. Exhaustion or fatigue resulted in 2,150 annual injuries to firefighters between 2005 and 2009, of which 25% were moderate or severe. Cardiac symptoms resulted in 500 annual injuries, with 60% being moderate or severe. An annual average of 6,135 firefighter injuries (22% of all injuries) were the result of overexertion or strain. Close to half (44%) of overexertion injuries were moderate or severe, resulting in lost work time [1]. The high occurrence and high severity of overexertion injuries on the fireground demand further insight into the metabolic costs associated with firefighting.

Collection of Metabolic Data

Metabolic data, or the quantification of energy expenditure and exertion, can be measured with a variety of devices, but is best explained by several parameters including volume of oxygen consumption (VO_2), volume of carbon dioxide production (VCO_2), breathing volume per minute (V_E), breathing rate (R_f), and heart rate (HR).

Metabolic cart

The current gold-standard for the collection of metabolic data is the metabolic cart (e.g., Truemax 2400, ParvoMedics Inc.; Sandy, Utah) (Figure 1). This specific system consists of a mouthpiece that is tethered to a large base station via a set-length of hose. The metabolic cart's base station consists of exhaled breath flow and gas content analyzers and computerized algorithms to calculate VO_2, VCO_2, and other metabolic parameters. The mouthpiece contains two one-way valves to control inhalation and exhalation air pathways. Air is inhaled from atmosphere through the mouthpiece and all exhaled air is sent out the mouthpiece and into the base station. A nose clip ensures that all air passes through the mouthpiece. The large size and immobility of the metabolic cart limit its use to specific laboratory settings that offer limited portability and limited mobility for the test subject, e.g., treadmill or stationary bicycle use.

Figure 1. Standard mouthpiece and nose clip for use with the metabolic cart.

Cosmed K4b^2

The Cosmed K4b^2 (Cosmed S.r.l.; Rome, Italy) is one example of a portable system used in the breath-by-breath analysis of metabolic data (Figure 2). The portability of this system allows for metabolic analysis in a wide variety of applications. The data collection unit is worn on the subject’s chest and can transmit data wirelessly to a base computer. Traditionally, the system is worn with a silicone mask that encapsulates the subject’s nose and mouth and directs air through a small turbine and gas sampling line. The Cosmed system typically uses both inhaled and exhaled air to determine the beginning and end of each breath; however the system also has a secondary mode (aqua trainer/Exhalation Only mode) which allows the device to determine breaths based solely on expired air.

Figure 2. Cosmed K4b^2 with standard silicone mask.

The Cosmed K4b^2 uses a turbine to measure the velocity-time characteristics of expired air. The Truemax 2400 metabolic cart uses a pneumotachometer to determine pressure differences across a screen from which flow characteristics are derived. Both devices have sensors that directly measure O_2 and CO_2 content. From this information both systems calculate the volume and gas content of exhaled air.

Benchmarking of the Cosmed K4b^2

The Cosmed K4b^2 has previously been validated against the standards in the metabolic data collection industry. One previous study compared the Cosmed K4b^2 system to Douglas bags (large bags that collect exhaled gas for later volume and gas concentration analysis) and have shown that it is an acceptable tool to measure metabolic data [18]. Mclaughlin et al. [18] used a cycle ergometer with power outputs of 50, 100, 150, 200 and 250 Watts as the exercise protocol. At 50, 100, 150, and 200W, the K4b^2 reported significantly higher oxygen consumption (VO_2) values than measured via Douglas bags. At rest and 250W, no significant differences in VO_2 were observed. At 200 and 250W, carbon dioxide production (VCO_2) values were significantly lower than values measured via Douglas bags. Since the magnitude of these differences was small (about 0.09 L/min) and within the 3-4% day-to-day variation normal during cycle ergometry [19, 20], McLaughlin et al. concluded that the Cosmed K4b^2 is acceptable for measuring oxygen uptake over a wide range of exercise intensities. Pinnington et al. found small but significant differences between the Cosmed and Tissot tank analysis (another standard for metabolic data collection) for oxygen and carbon dioxide fractions (F_EO_2 and F_ECO_2), as well as V_E during treadmill running but developed a linear regression model to improve the accuracy of the Cosmed K4b^2 [21].

Keskinen et al. modified a swimming snorkel device, initially developed by Toussaint et al. [22], to collect expired air while swimming for analysis by the Cosmed K4b^2 [23]. Keskinen et al. used a cycle ergometer protocol with five four-minute long periods (warm-up, 100, 150, 200 W, and cool-down) on separate days to compare results with the modified and standard masks. Significantly higher values for V_E, VO_2 and VCO_2 were found with the standard mask, though relative magnitudes were considered moderate and absolute differences were constant across all periods [23]. To account for this offset, Keskinen et al. developed a set of linear regression models to help improve the accuracy of the measurements. The authors conclude that with these regression models the Cosmed K4b^2 can be considered a valid device for metabolic analysis when the snorkel mask is used [23].

Metabolic Cost of Firefighting

Numerous studies have examined the metabolic costs associated with firefighting. It is common and practical to collect heart rate data during either simulated drills [3, 24] or live-fire operations [25, 26] because equipment used to collect this measurement is relatively simple, portable, and unobtrusive. Using estimation relationships, it is possible to extrapolate VO_2 from the collected heart rate data [25]. The vast variability in firefighter fitness, however, limits the general applicability of this method since each individual's HR-VO_2 relationship must be known and may vary significantly (e.g., [27]).

Direct measurement of VO_2 can eliminate these concerns, but is limited by the design of firefighters' SCBA equipment. Previous studies have generally collected metabolic data from subjects performing simulated firefighting activities or treadmill testing while wearing SCBA without actually breathing "on-air" or using the firefighting facepiece [27-31], with weighted vests to simulate gear and SCBA [27, 32, 33] and without any gear or SCBA [34].

Metabolic data collection tools have previously been integrated with firefighting SCBA equipment; however, no archival publications have integrated and validated a portable metabolic measuring device with SCBA while allowing the firefighter to remain on air. Smith et al. used a mouthpiece with two one-way valves in the traditional SCBA facepiece to allow for the collection of expired air for later analysis, but this setup was limited to stationary use on a treadmill and prevented the firefighter from being on-air [35]. Eves et al. and Dreger et al. have modified SCBA equipment to allow data collection via a metabolic cart by placing a Plexiglass cone over the exhalation ports on a Scott SCBA facepiece, though the use of a metabolic cart limits the applicability of this method to stationary testing [36, 37].

Williams-Bell and co-workers integrated a Cosmed $K4b^2$ portable metabolic data collection unit with a commercial SCBA facepiece for use in room-temperature simulated firefighting activities [38, 39]. The integrated setup was benchmarked with a custom mechanical calibrator that simulated breathing; however, the system was never validated with human testing, and no published journal papers exist regarding the mechanical validation of this design.

Facepiece Issues

The traditional SCBA facepiece allows inhalation of air from a compressed air tank through a regulator containing a one-way valve. The regulator locks into place at the front of the traditional facepiece and exhaled air is vented to the atmosphere through another one-way valve. The combination of one-way valves minimizes the mixing of inhaled and exhaled air, allows the SCBA to maintain positive pressure, and preserves the seal between the environment and the firefighter (Figure 3). Metabolic monitoring devices require collection of exhaled air which is not well controlled with the design of the traditional firefighter facepiece.

Figure 3. Modified facepiece (left) in comparison to the standard configuration (right).

Slips, Trips and Falls on Fireground

Slip, trip, and fall (STF) injuries are the leading cause of firefighters' moderate to severe injuries and the second leading cause of minor injuries on the fireground. From 2005 to

2009, 28% of injuries resulting in lost work time and 20% of less severe injuries were STF related. Icy, slippery, and uneven surfaces account for the greatest numbers of severe and moderate STF injuries at nearly 44% (over 12% of all moderate and severe injuries). Further, STF injuries are the only causes of injury which have a higher percentage of moderate to severe injuries than minor injuries [1]. Results from a 2008 survey of 148 firefighters indicated stairs as the fifth most prevalent cause of fireground injury [11]. This high prevalence of stair injuries and the inherent risks associated with ascending and descending stairs calls for an increased need to examine stair climbing in high-risk populations.

Behavior on Stairs

Ascending and descending stairs is generally regarded as a common everyday activity; however the U.S. Consumer Product Safety Commission estimated that there were approximately one million stair related accidents in 1990, and according to Grossman there were 819,000 falls suffered on stairs requiring a visit to the emergency room in 1989 [40]. The risks of trips and falls on stairs have been studied in high-risk populations including subjects with progressive supranuclear palsy [41] and knee osteoarthritis [42, 43]. Hamel et al. [44] examined stair climbing in the elderly and showed that after a reduction in ambient lighting young adults increased their foot clearance over stair edges while older adults maintained the same clearance as before the reduction in lighting. By not increasing their foot clearances with decreased ambient light, older adults put themselves at a higher risk of STF injuries [44]. The effect of fatigue [45] and compromised visual feedback [46] on stair climbing performance has also been studied.

Bergmann et al. used a body sensor network to examine the effects of fatigue on stair performance and found that while force production decreased post-fatigue, overall stair performance was not influenced [45]. Beschorner et al. noted increased toe clearances during ascent and increased normal force during descent when subjects were fit with unfamiliar multifocal lens glasses [46].

Firefighters who routinely traverse stairs are already at a high risk of STF injury due to the restrictions to movement and normal physiological function from wearing personal protective equipment (PPE). For example, firefighters have increased heat stress [35] and increased risk of trips [6] while wearing PPE when compared to standard station blues. Firefighters may be at an even greater risk of STF injuries following significant amounts of work and fatigue and while carrying heavy loads.

Fatigue Effects

Fatigue is common during firefighting tasks, and can be associated with increased risks on the fireground. Heat stress from firefighting has been shown to negatively impact firefighters by altering cognitive function, decreasing hydration levels, increasing strain felt by the cardiovascular system and decreasing the delay before muscular fatigue sets in [47, 48]. The early onset of fatigue can negatively affect how the firefighter responds to a situation and put the firefighter at an increased risk of STF injuries.

The effects of fatigue on the general population have been well documented and show increases in postural instability following fatigue. These studies have induced fatigue in assorted ways. Treadmill and cycle ergometer protocols have been used to fatigue the entire body [49, 50] or isolated muscle groups [5, 51-53]. Other studies have shown that fatigue can impact the sense of limb position and movement. For instance, in position and movement matching tasks without visual feedback, subjects were unable to match the movement of a fatigued arm with the targeted positions of the non-fatigued arm [5].

The effects of fatigue on balance are dependent on the intensity of the fatiguing protocol. As an example, Dickin and Doan had subjects perform repeated squat jumps until a vertical jump of 80% of maximal could not be attained. Subjects showed increased postural sway in the anterior-posterior direction which remained significant more than 10 minutes after the fatiguing protocol had ended [53]. Nardone et al. reported that as long as young healthy subjects exercised below an estimated anaerobic threshold, fatigue had little impact on body sway. When the individual performed above the anaerobic threshold, overall body sway increased and then returned to baseline after 15 minutes [49]. Fox et al. reported similar balance recovery times of 13 minutes following the conclusion of exercise [54]. Increased sway and lack of postural control immediately following intense bouts of firefighting could lead to increased risk of STF injuries on the fireground.

Load Carriage Effects

The extent to which load carriage impacts gait is largely influenced by the weight of the load carried [7, 55, 56]. Oxygen consumption [57, 58] and EMG activity [58] also increase as weight is increased. Loads of 15-20 percent of body-weight carried in a backpack affected gait in children (mean mass 31.8±7kg) [55, 56]. Changing the vertical location of the load showed no significant differences in ground reaction forces [55], but did alter spatiotemporal gait parameters [56]. In adults, 40 kilograms is required before erector spinae EMG activity increases above unloaded levels [58]. High erector spinae EMG activity would indicate more muscle motor units are needed to support the torso and load. Park et al. found that lighter firefighter SCBA loads carried on the back increased obstacle clearance and lowered firefighters chances of contacting an obstacle, but that lowering the center of mass (COM) of the load had little impact on gait parameters [7]. However, Knapik et al. noted that moving the load's COM closer to the body's COM reduced energy costs [58].

Asymmetrical load carriage has been shown to impact kinematic parameters on both the loaded and unloaded sides of the body [59-61]. Ozgul et al. [59] found changes in knee biomechanics which could contribute to joint degradation when subjects carried a backpack on one shoulder. Zhang et al. [60] documented increased trunk bend and greater asymmetry with increased dumbbell carriage in either hand. DeVita et al. [61] examined the effects of asymmetrical load carriage during walking and found that load carriage of 20% bodyweight carried in a sidepack disrupted the symmetric kinetics between the left and right limb. The impacts of load carriage on gait and oxygen consumption, specifically the effects of firefighters' asymmetrical hose load carriage, could lead to compromised performance on the fireground and increased injury risk.

Testing Environment Effects

A major limiting factor in analyzing fatigue after firefighting activity is the extreme conditions in which firefighting takes place and the difficulty in replicating such conditions in a controlled environment. The National Institute for Occupational Safety and Health (NIOSH) has described this limitation due to the wide variety of protocols currently used to safely simulate firefighting activities and has called for the establishment of a standard protocol [62]. Previous researchers have developed different approaches to simulate firefighting in a safe, controlled manner, but a standard has yet to be adopted. Studies have shown that temperature within the testing environment can significantly affect physiological (heart rate and tympanic membrane temperature) and psychological (perceived exertion and perception of respiratory distress) parameters furthering the need for a standard [12]. Attempts to simulate firefighting include performing a single task comparable to a task that may be faced on the fireground. Examples include stair climbing in a controlled environmental chamber at 40°C and 70% relative humidity [13] and performing a simulated ceiling overhaul task in a 90°C live-fire environment [12]. Several studies have utilized a walking protocol on a treadmill in a heated room [14-17]. Sothmann et al. [25] tracked the heart rate of on-duty firefighters during actual fire-suppression responses, although the variability in type of responses and timing make this type of data collection difficult. Romet and Frim [63] documented the large variability seen both across tasks and across positions within the same task. Live-fire testing has high costs and high risks. Further, the additional weight, bulk, and risk of damage to sensitive equipment limit data collection opportunities in live-fire situations. Temperature controlled environmental chambers allow for safe, controlled data collection but can be limited in their ability to replicate the thermal and visibility conditions of the fireground. There is limited research validating these environments and protocols as a means of replicating fireground conditions and workloads.

THESIS OVERVIEW

Given the above motivation, two studies were conducted for this thesis. The overall objectives of this Master's thesis were:

Objectives:

(Study 1) Research, design, build and validate a novel facepiece interface allowing for the collection of metabolic data while using a traditional positive-pressure open circuit self-contained breathing apparatus.

(Study 2) Quantify the impact of simulated firefighting protocol, fatigue, and asymmetrical load carriage on firefighter foot clearance during stair ascent and descent.

From these objectives, the following general hypotheses were drawn:

Hypotheses:

(Study 1) The novel facepiece design will not alter the metabolic data collected from a portable breath-by-breath metabolic monitoring system, and these results will be equivalent to those collected with a standard metabolic cart.

(Study 2a) Testing conditions that include simulated firefighting activities will result in decreased foot clearances relative to the condition involving walking on a treadmill because the simulated firefighting activities will require more exertion and result in higher levels of fatigue.

(Study 2b) After activity simulating workloads encountered on the fireground, fatigued firefighters will have significantly decreased foot clearances relative to pre-activity.

(Study 2c) Carriage of an asymmetrical hose load over the right shoulder will decrease foot clearance both before and after activity. This difference will be more drastic following activity.

Study 1:

The impacts of wearing a firefighting self-contained breathing apparatus (SCBA) have been previously reported to negatively impact balance [7, 9] and physiological measurements [35]. Current validated metabolic data collection techniques are typically used for the collection of data during stationary exercises such as treadmill running or cycling on an ergometer. However, they do not allow for the collection of data during simulated firefighting while breathing from an open-circuit SCBA (“on-air”).

Future studies being done in a collaborative effort between the University of Illinois and the Illinois Fire Service Institute require the concurrent use of SCBA and metabolic data collection. It is necessary for the firefighters to breathe air through the traditional SCBA system to accurately replicate live-fire conditions. Doing so provides air at controlled temperature and humidity conditions and consumes air contained in the compressed air cylinder worn on the back. It is essential to replicate fireground conditions as accurately as possible while collecting metabolic data. With this understanding we can begin to reach the ultimate goal of reducing injury rates on the fireground.

Therefore, the objective of this study was to develop and validate a reliable means of collecting metabolic data while the firefighter is breathing air from an open-circuit, positive pressure SCBA system. To allow for the collection of these data while firefighters are using SCBA, the traditional firefighting facepiece was modified for use with a portable metabolic monitoring system. First, the modified SCBA facepiece was tested to ensure that the modifications did not alter the seal or back pressure characteristics using standard NFPA 1981 tests [64]. Then the modified facepiece with Cosmed $K4b^2$ was validated against a traditional silicon mask worn with the Cosmed system, against a mouthpiece and nose-clip worn with the metabolic cart, and against the modified facepiece with metabolic cart during five different workloads.

Study 2:

This study aims to examine the effects of simulated firefighting testing environment, fatigue, and asymmetrical load carriage on the foot clearance of firefighters while ascending and descending stairs. Three different protocols were used to simulate the environment and workload experienced on the fireground: in a burn building with live fire (BBFF), simulated firefighting activities in a temperature-controlled heated room (ECFF) and walking on a treadmill in a temperature-controlled heated room (ECTM). Before and after the protocol firefighters ascended and descended a three-step staircase both with and without the carriage of an asymmetrical hose load. Vertical clearances of the toes during ascent and the heels during descent were examined.

CHAPTER 2: VALIDATION OF A MODIFIED FACEPIECE FOR METABOLIC DATA COLLECTION

ABSTRACT

To better assess the energy expenditure and exertion of firefighters during simulated firefighting activities, a standard firefighter facepiece was modified to interface with a portable metabolic monitoring device (Cosmed K4b^2). This design allowed for the collection of metabolic data while the firefighter utilizes a standard self-contained breathing apparatus (SCBA) as the air supply. This modified facepiece was then validated in a stationary bicycling variable-workload assessment with two metabolic measurement devices (the portable Cosmed K4b^2 unit and a limited portability metabolic cart unit). These conditions were: (1) the standard mask with the Cosmed K4b^2, (2) modified SCBA facepiece with the Cosmed K4b^2, (3) standard headpiece with the metabolic cart, and (4) modified SCBA facepiece with the metabolic cart. These results showed the modified facepiece was an accurate and reliable tool for the collection of metabolic data, and is suitable for use in future studies which demand the collection metabolic data while utilizing a SCBA system.

INTRODUCTION

Firefighting demands high levels of exertion to complete necessary tasks on the fireground. Overexertion on the fireground is the leading cause of injury for firefighters. Exhaustion or fatigue resulted in 2,150 annual injuries to firefighters between 2005 and 2009, of which 25% were moderate or severe [1]. The high occurrence and high severity of overexertion injuries on the fireground demand further insight into the metabolic costs associated with firefighting.

Metabolic data, or the quantification of energy expenditure and exertion, can be measured with a variety of devices, but is best explained by several parameters including volume of oxygen consumption (VO_2), volume of carbon dioxide production (VCO_2), breathing volume per minute (V_E), breathing rate (R_f), and heart rate (HR). It is essential that we quantify the physiological demands associated with firefighting as accurately as possible to better understand the metabolic costs needed to fulfill these demands.

Current validated metabolic data collection techniques are typically used for the collection of data during stationary exercises such as treadmill running or cycling on an ergometer. However, they do not allow for the collection of data during simulated firefighting while breathing from an open-circuit SCBA ("on-air"). It is necessary for the firefighter to breathe air through the traditional SCBA system to accurately replicate live-fire conditions. Doing so provides air at controlled temperature and humidity conditions and consumes air contained in the compressed air cylinder worn on the back. Consumption of the air lessens the weight on the back, which has been shown to significantly impact oxygen consumption and heart rate [7, 65]. Modification of the traditional firefighting facepiece to allow for the collection of these data with a portable metabolic monitoring system while firefighters are using SCBA would provide the most accurate data regarding energy expenditure and exertion during firefighting.

The current gold-standard for the collection of metabolic data is the metabolic cart (e.g., Truemax 2400, ParvoMedics Inc.; Sandy, Utah). The metabolic cart's base station consists of exhaled breath flow and gas content analyzers and computerized algorithms to calculate VO_2, VCO_2 and other metabolic parameters. The large size and immobility of the metabolic cart limit its use to specific laboratory settings that offer limited mobility and portability for the test subject, e.g., treadmill or stationary bicycle use.

Portable systems are also available for use in the breath-by-breath analysis of metabolic data (e.g., Cosmed $K4b^2$, Cosmed S.r.l.; Rome, Italy). The portability of this system allows for metabolic analysis in a wide variety of applications. The data collection unit is worn on the subject's chest and can transmit data wirelessly to a base computer. Traditionally, the system is worn with a silicone mask that encapsulates the subject's nose and mouth and directs air through a small turbine and gas sampling line. The Cosmed system typically uses both inhaled and exhaled air to determine the beginning and end of each breath; however the system also has a secondary mode (aqua trainer/Exhalation Only mode) which allows the device to determine breaths based solely on expired air.

Metabolic Cost of Firefighting

Numerous studies have examined the metabolic costs associated with firefighting. It is common and practical to collect heart rate monitor data during either simulated drills [3, 24] or live-fire operations [25, 26] because this measurement does not require advanced equipment. Previous studies collecting volumetric breath data have generally collected metabolic data from subjects performing simulated firefighting activities wearing SCBA without actually breathing "on-air" or using the firefighting facepiece [27-31], with weighted vests to simulate gear and SCBA [27, 32, 33] and without any gear or SCBA [34].

Metabolic data collection tools have previously been integrated with firefighting SCBA equipment; however, no published journal papers have integrated and validated a portable metabolic measuring device with SCBA while allowing the firefighter to remain on air. Smith et al., Eves et al., and Dreger et al. have integrated SCBA with metabolic carts, though the use of a metabolic cart limits the applicability of this method to stationary testing [35-37]. A portable metabolic data unit ($K4b^2$, Cosmed S.r.l., Rome, Italy) was integrated with a commercial SCBA facepiece for use in room-temperature simulated firefighting activities [38, 39]; however, the facepiece was never validated with human testing, and no published journal papers exist regarding the mechanical validation of this design.

Keskinen et al. modified a device, initially developed by Toussaint et al. [22], to collect expired air while swimming for analysis by the Cosmed $K4b^2$ [23]. Significantly higher values for V_E, VO_2 and VCO_2 were found with the standard mask, though relative magnitudes were considered moderate and absolute differences were constant across all periods. Keskinen et al. developed a set of linear regression models and concluded that, with these regression models, the Cosmed $K4b^2$ can be considered a valid device for metabolic analysis when the snorkel mask is used [23].

Facepiece Issues

The traditional SCBA facepiece allows inhalation of air from a compressed air tank through a regulator containing a one-way valve. Exhaled air is vented to the atmosphere through another one-way valve. The combination of one-way valves prevents the mixing of inhaled and exhaled air, allows the SCBA to maintain positive pressure, and preserves the seal between the environment and the firefighter. Metabolic monitoring devices such as the metabolic cart and the Cosmed $K4b^2$ require collection of exhaled air, something not incorporated into the design of the traditional firefighter facepiece.

To accurately understand the metabolic costs of firefighting, we must collect data during simulated firefighting activities while firefighters are on-air and the data must be accurate for firefighters with a wide range of fitness levels. With this understanding we can begin to reach the ultimate goal of reducing injury rates on the fireground.

The objective of this study was to develop and validate a reliable means of collecting metabolic data while the firefighter is breathing air from an open-circuit, positive pressure SCBA system. First, the modified SCBA facepiece was tested to ensure that the modifications did not alter the seal or back pressure characteristics. Then the facepiece was then validated in a stationary bicycling variable-workload assessment with two metabolic measurement devices (the portable Cosmed $K4b^2$ unit and a limited portability metabolic cart unit). These conditions were: (1) the standard mask with the Cosmed $K4b^2$, (2) modified SCBA facepiece with the Cosmed $K4b^2$, (3) standard headpiece with the metabolic cart, and (4) modified SCBA facepiece with the metabolic cart during five different workloads.

METHODS

Facepiece Modifications

To allow for collection of metabolic data while breathing from an open-circuit SCBA, a traditional facepiece worn by firefighters (Firehawk M7 Ultra Elite Facepiece, MSA Co.; Cranberry Township, Pennsylvania) was modified to collect exhaled air and to interface with a metabolic breath-by-breath monitoring system ($K4b^2$, Cosmed S.r.l.; Rome, Italy) (Figure 4-Figure 6).The modified component housing was first designed from a computer model (Inventor Professional, Autodesk Inc.; San Rafael, California) to replace the stock component housing and was then fabricated on an Eden 350 3-dimensional printing system (Objet Geometries; Minneapolis, Minnesota) using Objet's VeroBlack photopolymer resin material (Figure 7).

The modified component housing was designed with a 90° turn so that exhaled gases were directed to the firefighter's right (Figure 4). This turn prevented interference between the facepiece and turnout gear and allowed the firefighter to retain full movement of the head. Cross-sectional area was constant through the turn and a large turn radius was used so that flow properties were not significantly altered (Figure 7). A standard Cosmed calibration adaptor was press-fit into the opening on the modified facepiece to interface with the Cosmed turbine and gas sampling line. Two rubber O-rings were used to ensure a tight seal between the housing and calibration adaptor and silicone rubber sealant was used to prevent leaks between the facepiece and modified housing.

Figure 4. Front and side views of the MSA Firehawk M7 SCBA facepiece with modified component housing that accommodated the Cosmed turbine and gas sampling assembly via the calibration adapter.

Figure 5. a) Complete modified SCBA facepiece assembly with Cosmed K4b^2 and SCBA regulator connected. b) Modified SCBA facepiece with Cosmed K4b^2 system.

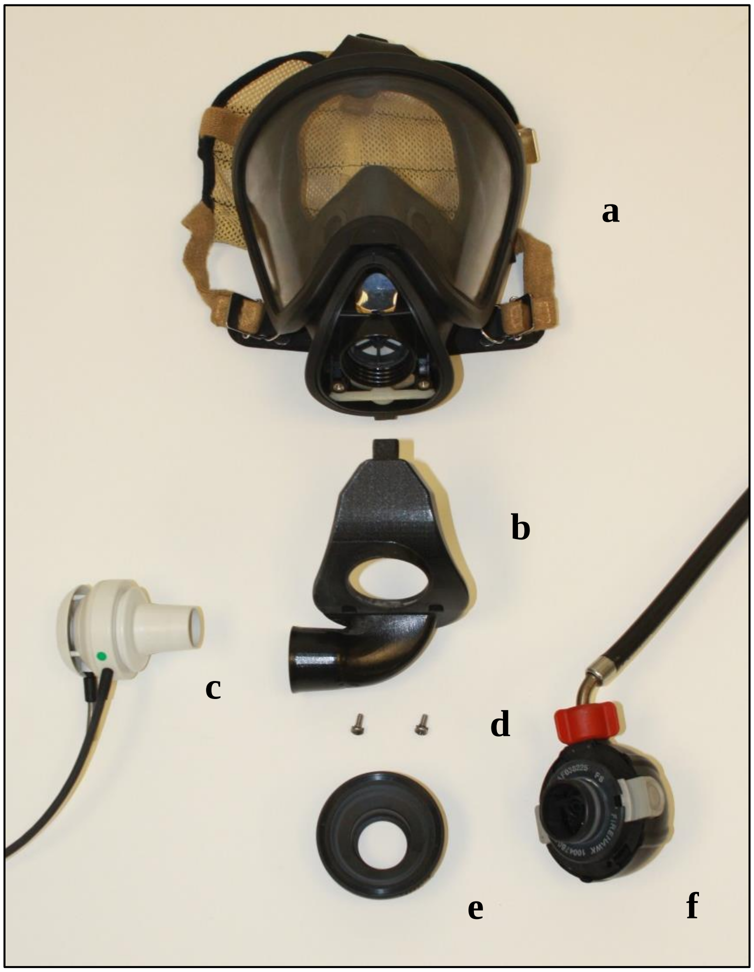

Figure 6. Exploded view of the facepiece. (a) Facepiece body. (b) Modified component housing. (c) Cosmed K4b^2 turbine and gas sampling line assembly with calibration adaptor. (d) Attachment screws. (e) Push-to-connect regulator adaptor. (f) SCBA regulator. Parts a,b,d and e were assembled with silicone rubber sealant to form an airtight seal, while rubber O-rings formed the seals between parts c and b and also parts e and f.

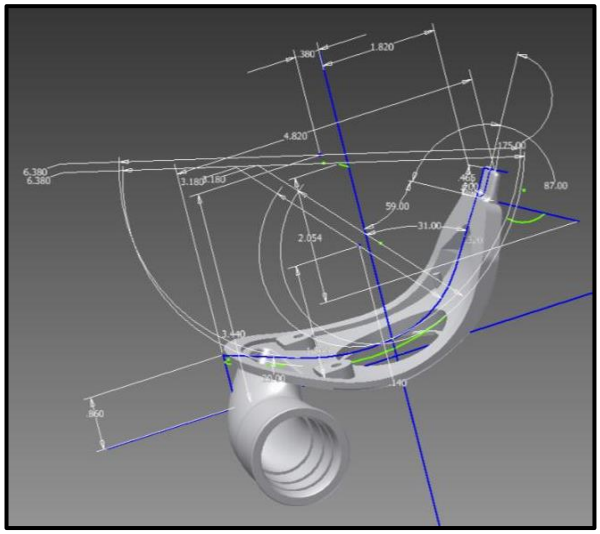

Figure 7. Solid model rendering of modified component housing used in 3-dimensional printing.

The SCBA facepiece is designed to protect the firefighter from potentially contaminated or elevated temperature air in immediately dangerous to life and health (IDLH) environments. This seal also prevents air from within the facepiece leaking to atmosphere, ensuring all expired air is directed through the modified SCBA component housing (Figure 8). The three one-way valves within the facepiece and standard nose cone separate inhaled and exhaled air to minimize mixing. The nose cone also helps to reduce deadspace within the facepiece. To ensure that the SCBA maintained its positive pressure function, expired air was collected after the existing exhalation valve within the SCBA facepiece (Figure 8).

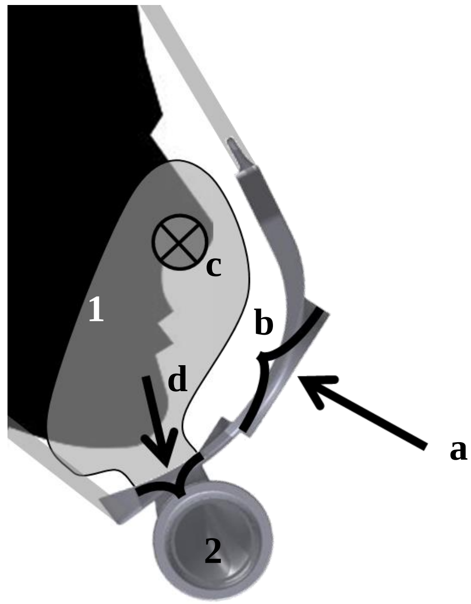

Figure 8. Schematic representation of airflow through the SCBA facepiece. Inspired air enters through a one-way valve in the front (a) and fills the facepiece void (b). Air enters the nose cone (part number 1) through a second one-way valve (c). Expired air then exits the nose cone through a one way valve (d) and is routed by the modified component housing (part number 2) to the K4b^2.

Testing protocols

Two tests were conducted to validate the modified component housing. First, the modified SCBA facepiece was benchtop tested to ensure that the modifications did not alter the seal or back pressure characteristics. Then the modified facepiece performance was validated with metabolic data tests against stock masks on the Cosmed K4b^2 and metabolic cart.

Positive pressure testing

To ensure that modification of the facepiece did not affect its performance during normal breathing, the facepiece was tested with a standard SCBA positive pressure testing rig (PosiChek, Honeywell Analytics; Lincolnshire, IL). First, the PosiChek starts an exhalation stroke and measures the pressure within the facepiece needed to open the exhalation valve. The facepiece passes the test if the pressure is within the manufacture's specifications (1.5 – 2.5 inches water column for the MSA Ultra Elite). Second, the pressure within the facepiece is measured when there is zero flow. The higher the static pressure, the greater the effort needed to exhale. The PosiChek tests the facepiece against the Code of Federal Regulations (42 CFR 84.91(d)) limit of 1.5 inches water column [66]. Two trials were conducted for each test.

Metabolic data testing

Participants

The subjects were 12 healthy males with no self-reported health issues (mean age 23.4±3.4 years, height 1.8±0.1 m, weight 85.2±14.0 kg and BMI 25.8±3.2 kg/m^2). Subjects completed a physical activity readiness questionnaire (PAR-Q) [67] prior to testing and all subjects were determined to be eligible for physical activity. All subjects were provided with the opportunity to ask questions and signed a written informed consent. Approval for this protocol was obtained from the University of Illinois Institutional Review Board.

Procedure

Subjects were tested in each of four conditions: 1) Cosmed $K4b^2$ with standard silicone mask (SC), 2) Cosmed $K4b^2$ with the modified firefighting facepiece (MC), 3) metabolic cart with standard mouthpiece (SU), and 4) metabolic cart with the modified firefighting facepiece (MU). To reduce the effect of fatigue impacting the results, subjects were required to have a minimum of 48 hours rest between sessions. Test conditions were performed in a counter-balanced order.

For each of the four test conditions, subjects rode on a stationary bicycle ergometer (Corival Cycle Ergometer, Lode BV; Groningen, Netherlands) repeating an identical stepwise 25 minute long exercise protocol, where power output in watts (W) was controlled by the research staff. The exercise protocol consisted of five defined steps each five minutes long: 1) rest period sitting on the ergometer, and then riding at 2) 50W, 3) 100W, 4) 150W, and 5) 200W. The ergometer automatically adjusted resistance based on the subject's cadence to maintain constant work output. The subject was instructed to maintain a cadence between 70 and 90 rotations per minute, with a target cadence of 80 rotations per minute. Variations of this protocol have been extensively used in the validation of metabolic monitoring devices [18-20, 23].

Data Collection Techniques

Data were collected continuously during the 25 minute trial. Metabolic data were recorded either on the Cosmed $K4b^2$ (Software Version 3.9, Cosmed S.r.l.; Rome, Italy) or with the metabolic cart (Truemax 2400, ParvoMedics Inc.; Sandy, Utah). For SC trials, the $K4b^2$ was operated in its Standard mode, where both inhalation and exhalation information from the turbine was used in computations of oxygen consumption. For MC trials, the device was used in its Exhalation-Only mode, since only expired air would be passing through the turbine and gas sensors. During SU and MU trials, the metabolic cart was used in its Standard mode because the metabolic cart only required exhaled gases to perform all calculations. Both systems were allowed standard warm-up time (e.g., 30 minutes) and gas sensors were calibrated to room air and standard gas concentrations, while the flow meter was calibrated with a 3 liter calibration syringe per the manufacturers' instructions.

Six metabolic parameters were analyzed, which were either directly measured or derived from measurements by each system. Data from the metabolic cart were automatically averaged in such a manner that a value was reported every 30 seconds, as per the manufacturer's software. The Cosmed $K4b^2$ sampled data on a breath-by-breath basis so that data were reported after each breath. After completion of each test, the $K4b^2$ data were averaged over 15 second epochs. A custom MATLAB script was written to average the last two minutes of each workload for analysis (i.e., during the following data collection time points: 3-5 min, 8-10 min, 13-15 min, 18-20 min, and 23-25 min) to ensure that the subjects reached steady-state for each workload and each metabolic test configuration. Data from this timeframe were used in the analysis of each variable: consumption of oxygen per minute (VO_2, ml/min), fractional expired oxygen concentration (F_eO_2, %), fractional expired carbon dioxide concentration (F_eCO_2, %) volume of air exhaled per minute (V_E, l/min), respiration frequency (R_f, breaths/min), and tidal volume (V_T, l/breath).

Oxygen consumption (VO_2) cannot be directly measured but is a calculated value. VO_2 is derived from the minute ventilation (V_E) and fractional concentration of expired oxygen

(F_eO_2). Inspired fractional oxygen concentration (F_iO_2) is known from the pre-test calibration.

$$VO_2 = V_E \times \left(F_{inspired}O_2 - F_{expired}O_2\right) \tag{1}$$

Minute ventilation is also a derived value and is the product of the tidal volume (V_T) and respiration frequency (R_f).

$$V_E = V_T \times R_f \tag{2}$$

Therefore, combining equations (1) and (2), VO_2 is fully defined as:

$$VO_2 = V_T \times R_f \times (F_iO_2 - F_eO_2) \tag{3}$$

A schematic breakdown of the calculation of VO_2 is shown in Figure 9.

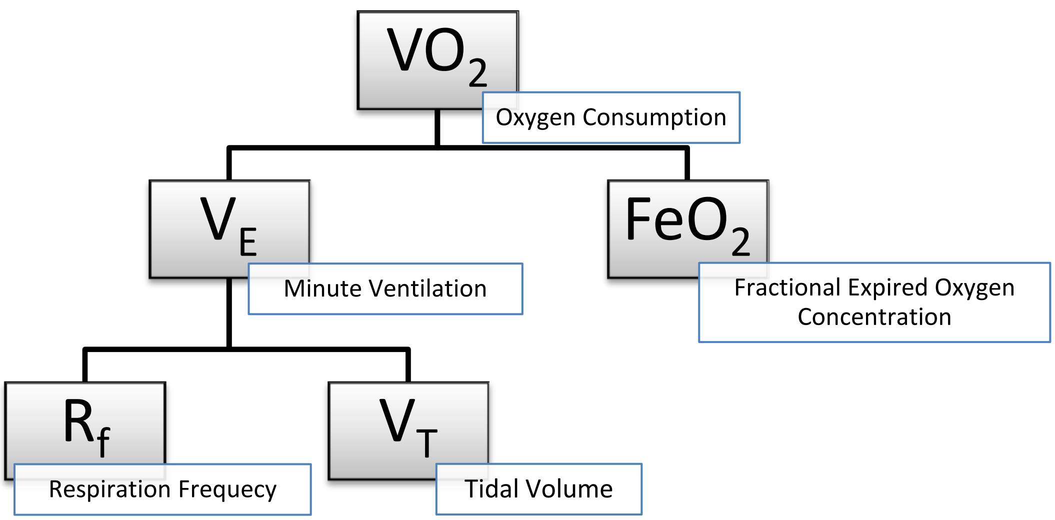

Figure 9. Schematic representation of the parameters involved in the computation of oxygen consumption.

Statistical Analysis

The data and statistical analysis were based only on nine test subjects. Two of the 12 subjects were unable to complete the entire protocol due to fatigue in each of the four sessions. A third subject completed three of the four sessions but was unable to complete the fourth, also due to fatigue. Subjects unable to complete sessions reported fatigue in the legs as the reason for stopping prior to completion, but no other medical conditions arose. The nine other subjects completed the entire protocol at each session.

Each parameter (VO_2, F_eO_2, F_eCO_2, V_E, R_f, and V_T) was analyzed using a 5 x 4 repeated measures ANOVA (SPSS Statistics 21, IBM; Armonk, New York). That is, there were five Workload conditions (Rest, 50W, 100W, 150W, 200W) and four Metabolic Data Collection Configurations (Stock Cosmed, Modified Cosmed, Stock Metabolic Unit, Modified Metabolic Unit) being assessed. Statistical significance was adjusted to $p<0.008$ for multiple ANOVAs of six parameters. A Tukey honestly significant difference (HSD) analysis was conducted to examine workload by configuration interactions.

RESULTS

Positive pressure testing

The modified component housing did not significantly impact the positive pressure attributes of the SCBA for use during normal breathing. The pressure needed to open the exhalation valve was 1.8 inches water column and 1.7 inches water column for the two trials. This was within the manufacturer's requirement of 1.5 – 2.5 inches water column.

For both trials in the static pressure test the modified facepiece was below the 42 CFR 84.91(d) threshold of 1.5 inches water column.

Metabolic data testing

The VO_2 data collected with all four metabolic test configurations across all workloads for a typical subject clearly show increasing oxygen consumption at each of the five workload stages (e.g., Figure 10). Further, a relatively steady plateu can be seen over the last 120 seconds of each 300 second stage as the subject reached steady-state. An analysis of each of these variables follows.

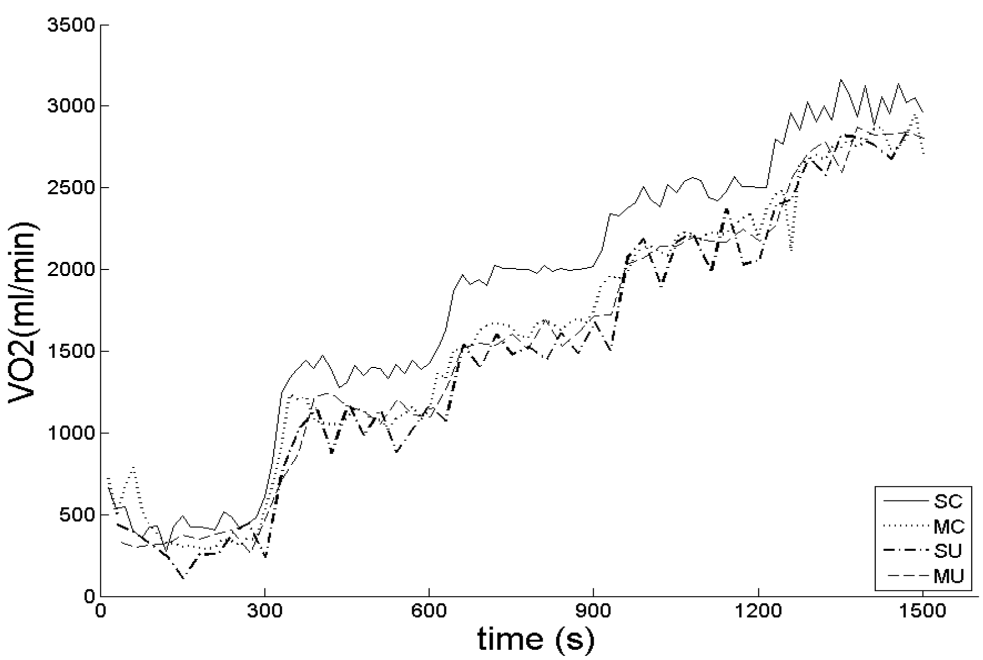

Figure 10. Oxygen consumption(VO_2) for a typical subject with four different metabolic test configurations (SC, MC, SU, and MU). Workload was increased every 300 seconds (from rest, to 50W, 100W, 150W, and 200W).

Oxygen Consumption - VO_2

For the main effect of workload, VO_2 was found to significantly increase with each successive workload ($p<0.001$), as expected with increasing exercise intensity (Figure 11 and Table 1). A significant main effect for mask configuration was found ($p <0.001$). The Cosmed $K4b^2$ and standard silicone mask (SC) configuration was found to have consistently larger estimations of VO_2 relative to the other mask conditions. No significant difference was detected between the other mask conditions. An interaction effect was also found such that SC was significantly greater than MC, SU, and MU, for all workloads except Rest. Further, deviations between SC and the other mask configurations increased in magnitude as the workload increased. MC, SU, and MU were not significantly different from each other at any workload.

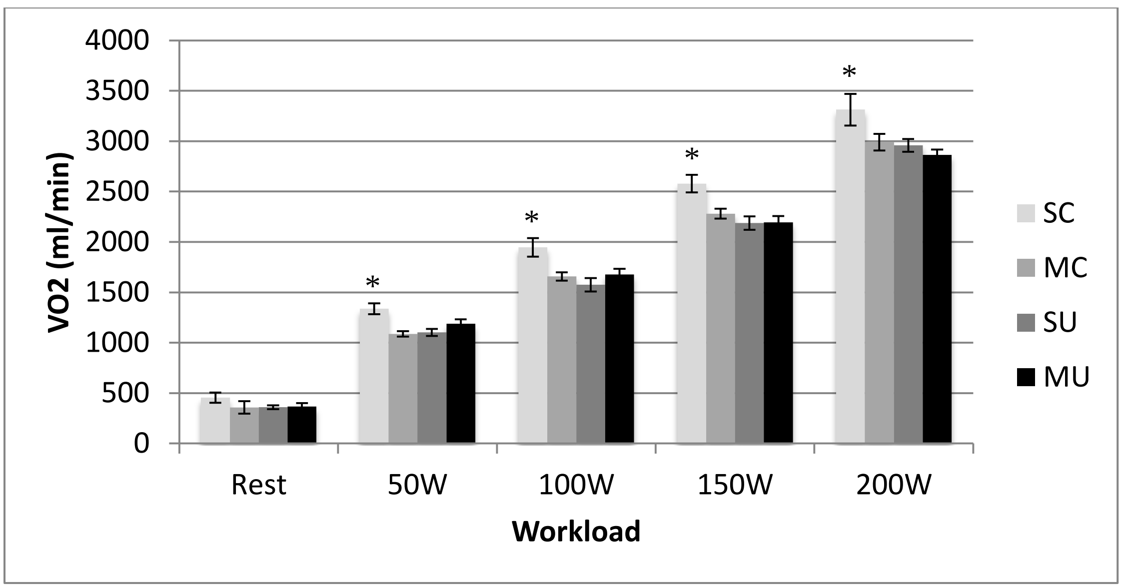

Figure 11. Oxygen consumption (VO_2) as a function of workload for each mask/unit configuration. Error bars indicate standard error. Significant differences within each workload are indicated with an asterisk (*).

Table 1. Average VO_2 (ml O_2/minute) at each workload for each mask configuration (Mean±SE)

VO_2	Stock Cosmed	Modified Cosmed	Stock Metabolic Unit	Modified Metabolic Unit
Rest	455±51	357±62	359±20	347±35
50W	1338±54	1087±27	1103±35	1134±44
100W	1947±92	1658±41	1575±67	1639±57
150W	2579±88	2280±49	2186±67	2146±63
200W	3312±156	2990±83	2958±65	2841±169

Fraction of Expired Oxygen and Carbon Dioxide - F_eO_2 and F_eCO_2

Investigation into the fractional expired concentrations of both oxygen (F_eO_2 – Figure 12) and carbon dioxide (F_eCO_2 – Figure 13) revealed no significant main effects for mask configurations. Significant main effects for workload were found for F_eO_2 ($p<0.001$) and F_eCO_2 ($p<0.001$). There was a significant difference between all workloads for F_eO_2, with the exception of 50W vs. 100W. For F_eCO_2, there was a significant difference between workloads, other than 50W vs. 150W, 50W vs. 200W, and 100W vs. 150W.

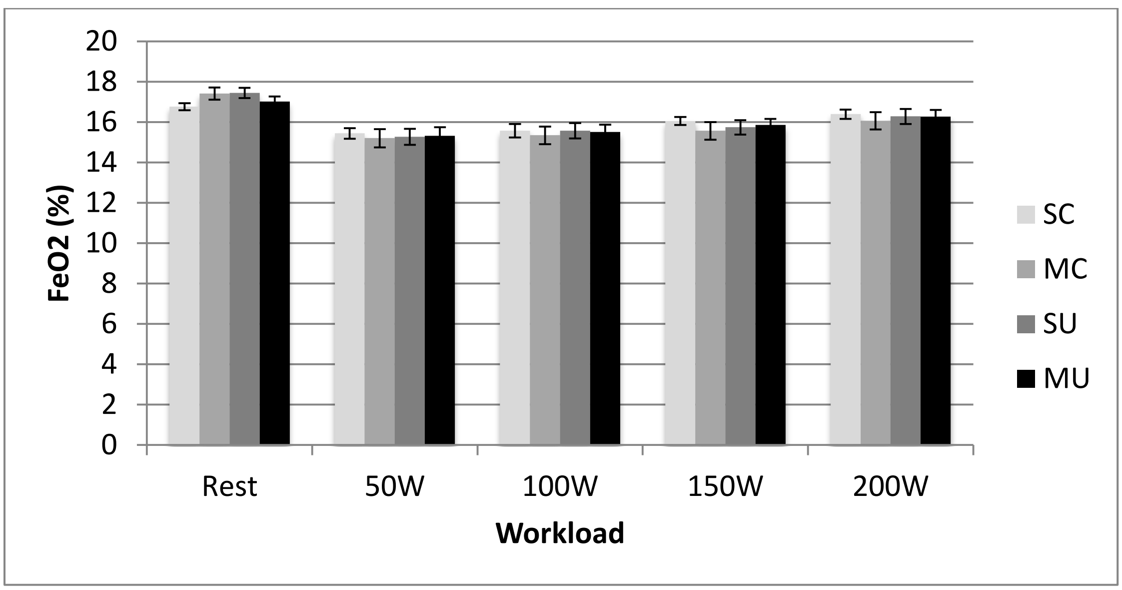

Figure 12. Fractional expired concentration of oxygen (F_eO_2) as a function of workload for each mask/unit configuration. Error bars indicate standard error.

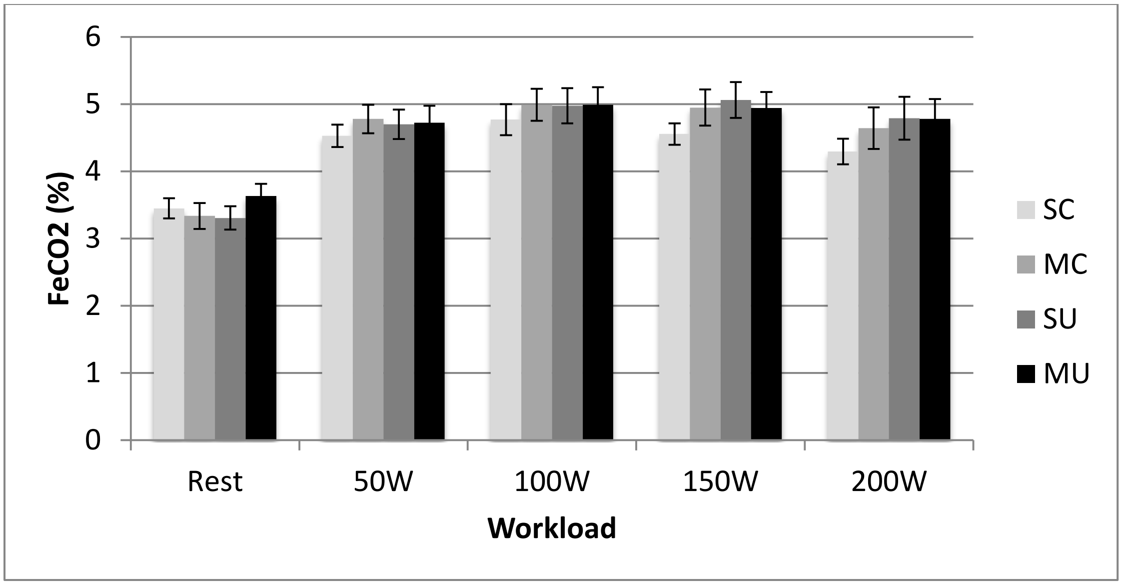

Figure 13. Fractional expired concentration of carbon dioxide (F_eCO_2)as a function of workload for each mask/unit configuration. Error bars indicate standard error.

Minute Ventilation - V_E

The minute ventilation (V_E) increased significantly between all workloads ($p<0.001$) as would be expected for the exercise protocol completed (Figure 14). For the main effect of mask configuration, V_E was found to be significantly different ($p = 0.002$). V_E was higher in the SC configuration than MC, SU, and MU. No differences were found between MC, SU, and MU. Absolute differences between SC and the other configurations range from 3.4 to 5.0 l/min at 50 W and increase to between 8.1 and 9.0 l/min at 200W, although average percent difference between SC and the other configurations decrease (14.6% at 50W, 9.0% at 200W). A post-hoc analysis of workload by mask interaction revealed the significant differences in SC occurred at 150W and 200W compared to other mask conditions.

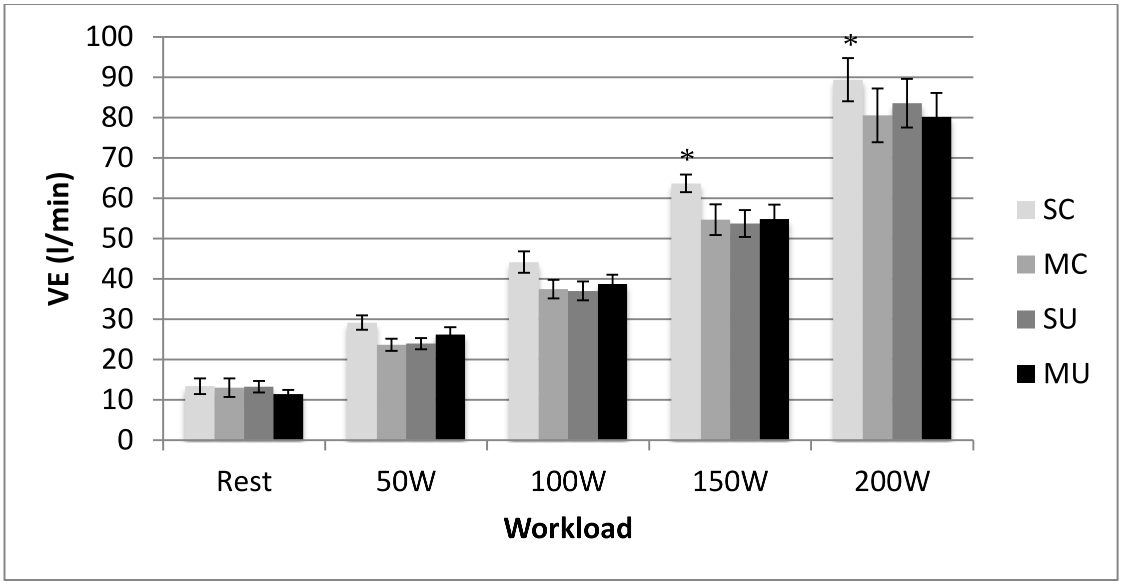

Figure 14. Minute ventilation (V_E) as a function of workload for each mask/unit configuration. Error bars indicate standard error. Significant differences within each group are represented with an asterisk (*).

Tidal Volume and Respiration Frequency - V_T and R_f

Measurements of tidal volume followed an increasing trend as workload was increased, with significant increases in V_T across all loads ($p<0.001$) (Figure 15). V_T was not significantly different between metabolic test configurations and no significant interactions were found.

There were significant differences in R_f between all workloads ($p<0.001$), with the exception of Rest vs. 50W (Figure 16). R_f had a mask configuration main effect, with the SC configuration significantly higher than MC, SU, and MC ($p<0.001$). No significant differences were measured between all other mask configurations (MC, SU, and MU). Further, an interaction between mask configuration and workload was found ($p=0.007$) for R_f with the Stock Cosmed significantly faster than other configurations at all workloads except Rest. The average absolute value of the differences remained consistent between the SC and other mask configurations (4.6 b/min at 50W, 3.8 b/min at 200W).

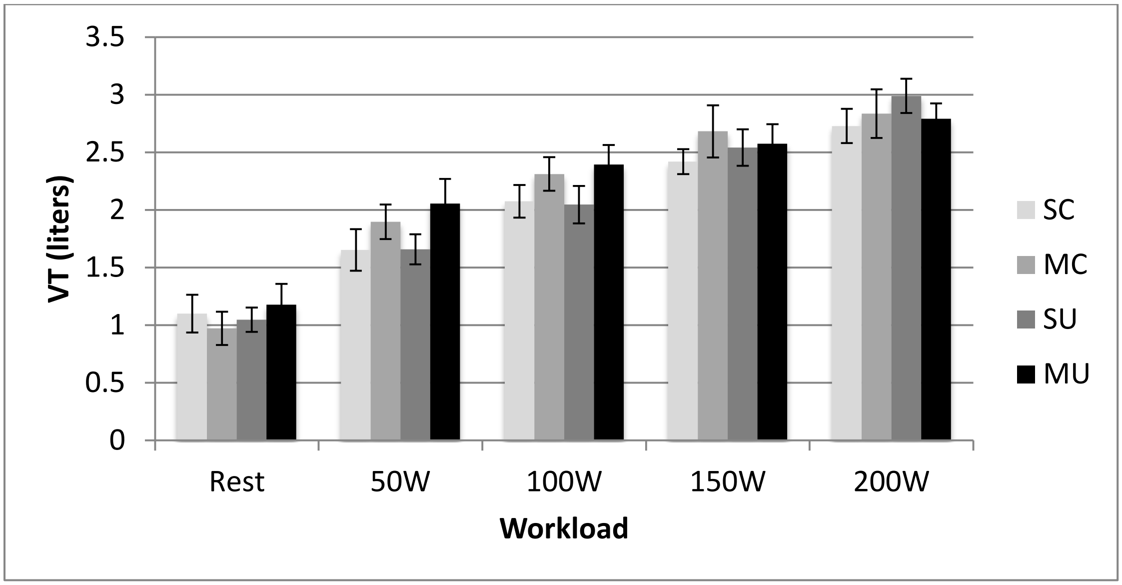

Figure 15. Tidal volume (V_T) as a function of workload for all mask/unit configurations. Error bars indicate standard error.

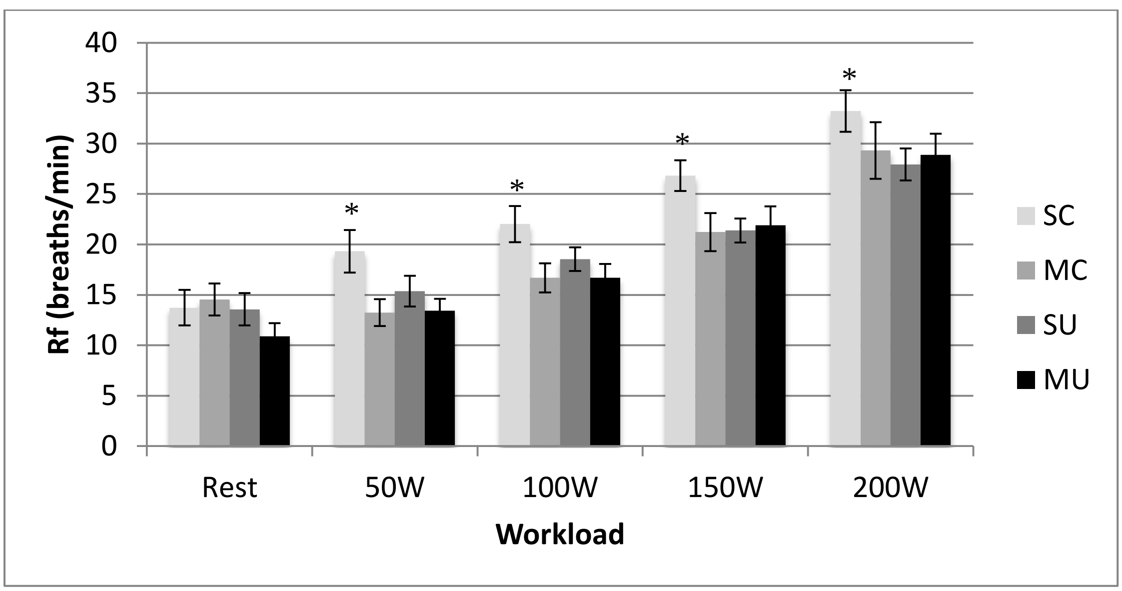

Figure 16. Respiratory frequency (R_f) as a function of workload for each mask/unit configuration. Error bars indicate standard error. Significant differences within each group are represented with an asterisk (*).

Analysis of 12 subjects

This study collected data on 12 subjects, three of whom were unable to complete all trials due to fatigue. Analysis of all 12 subjects across the first four workloads (rest, 50W, 100W, and 150W) revealed similar trends to those just described for nine subjects across all five workloads.

DISCUSSION

The goal of this study was to validate the modified facepiece against the gold-standard in the industry, the metabolic cart. The results from this analysis suggest that the modified facepiece, when used with the Cosmed $K4b^2$, is an accurate and reliable tool for the collection of metabolic data.

The overestimation of VO_2 with a stock Cosmed system has previously been reported in a comparison with Douglas bags [18]. The average differences McLaughlin et al. found were around 90 ml/min, while this study found average differences of 270 ml/min across all mask conditions (range 250 ml/min to 290 ml/min). The differences between mask configurations in this study were quite significant, given that average VO_2 across all mask configurations was around 3000 ml/min for the 200W workload. This variation of nearly 10% is outside of the 3-4% day-to-day variation found by both Armstrong et al. [19] and Stuart et al. [20].

To further understand why the SC configuration resulted in higher VO_2 values, we recall that VO_2 is not a measured variable, rather other measured variables are used in the calculation of VO_2. Therefore, measurements of the concentration of oxygen (F_eO_2) or volume of air exhaled per minute (V_E), which is determined by tidal volume (V_T) and respiration frequency (R_f), or some combination of these parameters contribute to potential variations in the calculation of VO_2 with the SC configuration.

Examinations of F_eO_2 and F_eCO_2 suggest that all metabolic test configurations resulted in consistent measurements of exhaled gas concentrations. All configurations recorded reduced oxygen and increased carbon dioxide concentrations in expired air following the rest phase. Hence, the overestimation of VO_2 in the SC configuration was not the result of varied gas content measurements, but rather the result of expired air flow differences between mask configurations, e.g., V_E, V_T and R_f.

V_E was found to be between 3.4 and 9.0 l/min higher with the SC configuration than all other mask conditions across the five workloads. This result, combined with the results of exhaled gas analysis, showed that V_E drove the overestimation of VO_2 with the SC configuration. V_E though is calculated through measured values of tidal volume (V_T) and respiratory frequency (R_f).

The significant differences in R_f and lack of differences in V_T indicate that the SC configuration estimated a higher number of breaths per minute (R_f) but similar volumes of exhaled air per breath (V_T) than the other mask configurations. This was an interesting finding as the SC configuration was the only metabolic test configuration which used both inhalation and exhalation to determine breath timing and hence respiration frequency. MC, SU, and MU configurations all operated solely on exhaled air for both breath timing and gas analysis.

By breaking down the parameters used to calculate VO_2, it was determined that increased estimation of R_f by the SC configuration was likely the driving force behind the higher estimation of VO_2. Concentrations of gas were estimated equally across all mask configurations, but the respiration frequency is overestimated by the SC configuration. This also explained the increased differences in VO_2 magnitude seen with increasing workload. R_f increased with workload, resulting in greater overestimation of VO_2 with the SC configuration.

CONCLUSIONS

Based on these results, the modified SCBA facepiece, when used with the Cosmed $K4b^2$ (MC configuration) is a reliable and accurate method for the collection of metabolic data. The MC configuration results in lower estimations of VO_2 than the SC configuration. However, the Cosmed $K4b^2$ in the standard configuration overestimated VO_2 relative to the industry gold-standard, the metabolic cart (SU), an observation which has previously been reported in comparison to another industry standard, the Douglas bag [18]. Further, the MC configuration showed no significant differences between the stock metabolic cart (SU) or modified metabolic cart (MU). The lack of any significant differences between the SU and MC configurations across all workloads allows for the assertion that the modified firefighting facepiece accurately estimates VO_2 across a wide range of workloads.

CHAPTER 3: ANALYSIS OF FOOT CLEARANCES IN FIREFIGHTERS DURING ASCENT AND DESCENT OF STAIRS

ABSTRACT

Previous studies have attempted to simulate firefighting in safe, controlled environments, but a standard has yet to be developed. This study examined three protocols, each designed to simulate the environment and workload associated with firefighting. To assess the biomechanical differences between conditions, firefighters ascended and descended stairs before and immediately after activity. For half of the trials firefighters carried an asymmetrical hose load, as is commonly done on the fireground. Clearances of the heels and toes were examined over each stair edge. Some significant changes occurred due to condition, pre/post activity, and load carriage. These results can lead to the development of a standard for the simulation of firefighting and lead to reduced injuries on the fireground by allowing for a better understanding of how fatigue and load carriage affect firefighters.

INTRODUCTION

Slip, trip, and fall (STF) injuries are the leading cause of firefighters' moderate to severe injuries and the second leading cause of minor injuries on the fireground. From 2005 to 2009, 28% of injuries resulting in lost work time and 20% of less severe injuries were STF related [1]. Results from a 2008 survey of 148 firefighters indicated stairs as the fifth most prevalent cause of fireground injury [11]. This high prevalence of stair injuries and the inherent risks associated with ascending and descending stairs calls for an increased need to examine stair climbing in high-risk populations.

Firefighters who routinely traverse stairs are already at a high risk of STF injury due to their gear. For example, firefighters have increased heat stress [35] and increased risk of trips [6] while wearing personal protective equipment (PPE) when compared to standard station blues. Firefighters may be at an even greater risk of STF injuries following significant amounts of work and fatigue and while carrying heavy loads.

Ascending and descending stairs is generally regarded as a common everyday activity; however, the U.S. Consumer Product Safety Commission estimated that there were approximately one million stair related accidents in 1990. According to Grossman et al. there were 819,000 falls suffered on stairs requiring a visit to the emergency room in 1989 [40]. The risks of trips and falls on stairs have been studied in high-risk populations, including subjects with progressive supranuclear palsy [41], knee osteoarthritis [42, 43] and the elderly [44]. The effect of fatigue [45] and compromised visual feedback [46] on stair climbing performance has also been studied. Bergmann et al. examined the effects of lower-limb fatigue (after a maximal recumbent cycling ergometer protocol on stair performance) and found that post-fatigue, overall stair performance (as measured by ankle, knee, thigh, and trunk range of motion during ascent and descent) was not influenced [45]. However, firefighters experience whole-body fatigue during firefighting activities, and examination of foot clearances over stair edges provides a better understanding of changes in the risk of STF injuries.

A major limiting factor in analyzing fatigue after firefighting activity is the extreme conditions in which firefighting takes place and the difficulty in replicating such conditions in a controlled environment. Previous researchers have developed different approaches to simulate firefighting in safe, controlled manners, but a standard has been called for and yet to be adopted [62]. Attempts to simulate firefighting include performing a single task comparable to a task that may be faced on the fireground. Examples include stair climbing in a controlled environmental chamber at 40°C and 70% relative humidity [13] and performing a simulated ceiling overhaul task in a 90°C live-fire environment [12]. Other studies have followed a walking protocol on a treadmill in a heated room [14-17].

Live-fire testing has high costs and high risks. Further, the additional weight, bulk, and risk of damage to sensitive equipment limit data collection in live-fire situations. Temperature controlled environmental chambers allow for safe, controlled data collection but can be limited in their ability to replicate temperatures and smoke conditions experienced on the fireground. Examination of the biomechanical differences between these environments can aid in determining the suitability of an environmental chamber as a surrogate for live-fire conditions.

Fatigue is common during firefighting tasks, and can be associated with increased risks on the fireground. Heat stress from firefighting has been shown to negatively impact firefighters by altering cognitive function, decreasing hydration levels, increasing strain felt by the cardiovascular system, and decreasing the delay before muscular fatigue sets in [47, 48]. The early onset of fatigue can negatively affect how the firefighter responds to a situation and put the firefighter at an increased risk of STF injuries.

The effects of fatigue on normal populations have been well documented and show increases in postural instability following fatigue [49-53]. Other studies have shown that fatigue can impact the sense of limb position and movement. For instance, in blindfolded position and movement matching tasks, subjects were unable to match the movement of a fatigued arm with the targeted positions of the non-fatigued arm [5].

The extent to which load carriage impacts gait is largely influenced by the weight of the load carried [7, 55, 56]. Oxygen consumption [57, 58] and EMG activity [58] also increase as weight is increased. Previous studies have found that loads of 15-20 percent of body-weight carried in a backpack affected gait in children (mean mass 31.8±7kg) [55, 56]. Lowering the vertical location of a 20% bodyweight backpack load was found to increase double support time in children [56]. In adults, 40 kilograms is required before erector spinae EMG activity increases above unloaded levels [58]. High erector spinae EMG activity would indicate more muscle motor units are needed to support the torso and load. Park et al. found that lighter SCBA loads carried on the back increased obstacle clearance and lowered firefighters chances of contacting an obstacle [7].

Asymmetrical load carriage negatively impacts kinematic parameters on both the loaded and unloaded sides of the body [59-61]. Ozgul et al. [59] found changes in knee biomechanics which could contribute to joint degradation when subjects carried a backpack on one shoulder. Zhang et al. [60] documented increased trunk bend and greater asymmetry with increased dumbbell carriage in either hand. DeVita et al. [61] examined the effects of asymmetrical load carriage during walking and found that load carriage of 20% bodyweight carried in a sidepack disrupted the symmetric kinetics between the left and right limb. The impacts of load carriage on gait and oxygen consumption, specifically the effects of firefighters' asymmetrical load carriage of SCBA and hose, could lead to compromised performance on the fireground and increased injury risk.

This study aimed to examine the effects of simulated firefighting testing environment, fatigue, and asymmetrical load carriage on the foot clearance of firefighters while ascending and descending stairs. From the previous motivation, it was hypothesized that:

1) Different testing conditions will have different impacts on foot clearances. Specifically, testing conditions that have simulated firefighting activities will result in decreased foot clearances relative to the condition involving walking on a treadmill because the simulated firefighting activities will require more exertion and result in higher levels of fatigue.
2) After activity simulating workloads encountered on the fireground, fatigued firefighters will have significantly decreased foot clearances relative to pre-activity.

3) Carriage of an asymmetrical hose load over the right shoulder will decrease foot clearance both before and after activity. This difference will be more drastic following activity.

METHODS

Participants

Twenty-four firefighters (23 male, 1 female, age 28.6±7.9 years, height 1.8±0.1 m, weight 90.7±14.9 kg) participated in this study. Eight were career firefighters, 14 were volunteers, one was both a volunteer and career firefighter, and one declined to respond. A majority of the subjects worked in small metropolitan areas (N=17) and rural areas (N=5), while one worked in both small metropolitan and rural areas, and one served in a large metropolitan area. All provided informed consent and approval was obtained from the University of Illinois Institutional Review Board.

Fatiguing Protocols

All firefighters participated in the same three activities designed to replicate work levels experienced on the fireground: (1) simulated firefighting task in an environmental chamber (ECFF, 47°C, 30% humidity), (2) simulated firefighting tasks in a burn building with live-fire (BBFF, 135°C at 30cm from ceiling, 85°C at 120 cm from the floor, 30°C at 30cm above the floor, very low humidity), and (3) walking on a treadmill in an environmental chamber (ECFF, 47°C, 30% humidity). Trials were presented in a counter-balanced order to minimize any potential confounding learning and familiarization effects. In the environmental chamber, subjects were fit with a portable metabolic monitoring system (K4b^2, Cosmed S.r.l.; Rome, Italy) during the first three minutes of their exposure, followed by two minutes of seated rest. To maintain the same exposure time, the first five minutes in the burn building were all seated rest, as the metabolic monitoring system could not withstand the high temperatures and smoke experienced during a live-fire and therefore could not be used. For the treadmill protocol, subjects walked at 4.5 kilometers/hour (2.8 miles per hour) at a 2.5% incline for 14 minutes following the initial five-minute rest period. This is a common protocol used to study firefighters [14, 16, 68, 69].

Simulated firefighting was comprised of four activities done on a two-minute work-rest cycle. The activities consisted of: (1) a stair climb in which the subject climbed to the second step on a three-step 1.2 m wide staircase, touched both feet to the second step, then stepped backward down to ground level; (2) a simulated hose advance, in which a section of hose was fixed to a modified weight pull machine; (3) a simulated deliberate search, which included crawling around the perimeter of the room on hands and knees; and (4) a simulated overhaul task in which a pike pole was attached to a modified weight pull machine that required pulling weight from overhead (Figure 17). For activities (2) and (4), 9.1 kg (20 lb) of weight were used to simulate the load of advancing a hose or pulling ceiling. In both cases, one repetition was counted as beginning with the weight stack at rest, touching the end of the tool (either hose or pole) to a target located 1.8 m (70 in) from the first stair edge, and returning the weight stack to the resting position. Subjects were given the opportunity to perform the tasks with a self-selected technique, as long as they completed the full movement of the tool. Subjects were given the instruction to perform all activities at a self-selected pace that simulated their effort on a fireground and were allowed to modify technique or to rest at any time throughout the activity.

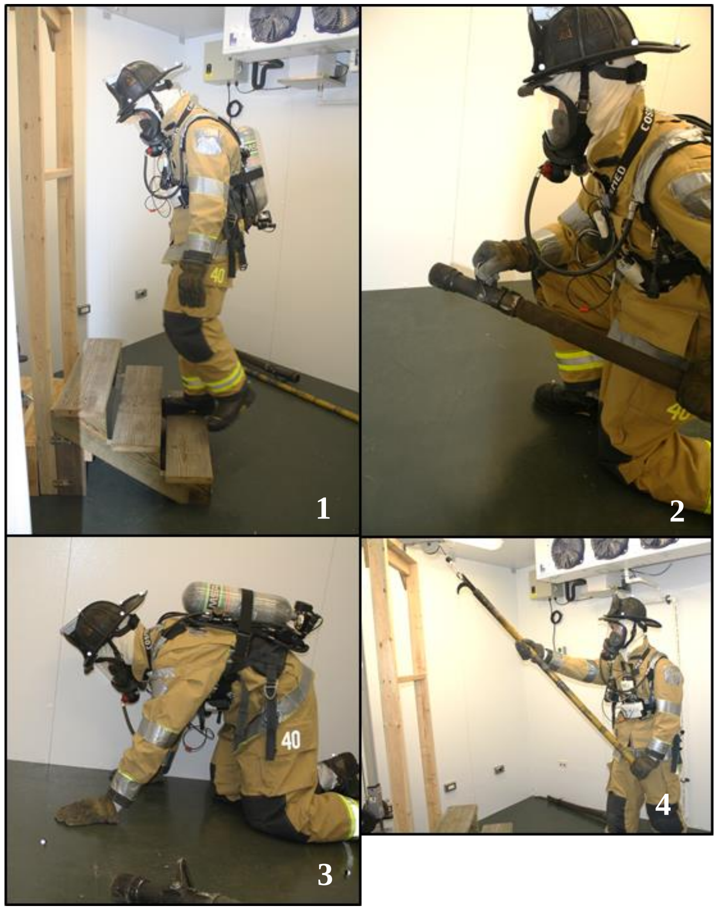

Figure 17. Simulated firefighting activities: 1) Stair climb. 2) Hose advance. 3) Search. 4) Overhaul task.

Data Collection Procedure

Obstacle Course Description

Before and immediately after the work activities the subjects completed a course consisting of six stations, which allowed assessment of a variety of gait and movement behaviors (Figure 18). Subjects were instructed to stand in a start box (taped off area of size 60 cm (24 in) by 60 cm (24 in)) and wait until instructed “3-2-1-GO”. Subjects stopped in a similar box at the end of the station. Times for completing each station were recorded. Subjects were instructed to move through the course at a pace he or she would use on the fireground, without running. Subjects passed through the full course twice, resting between full course trials, and then repeated the first three stations two more times carrying an 11.3 kg (25 lb) hose load on the right shoulder for a total of four trials before and four trials after the work activity.

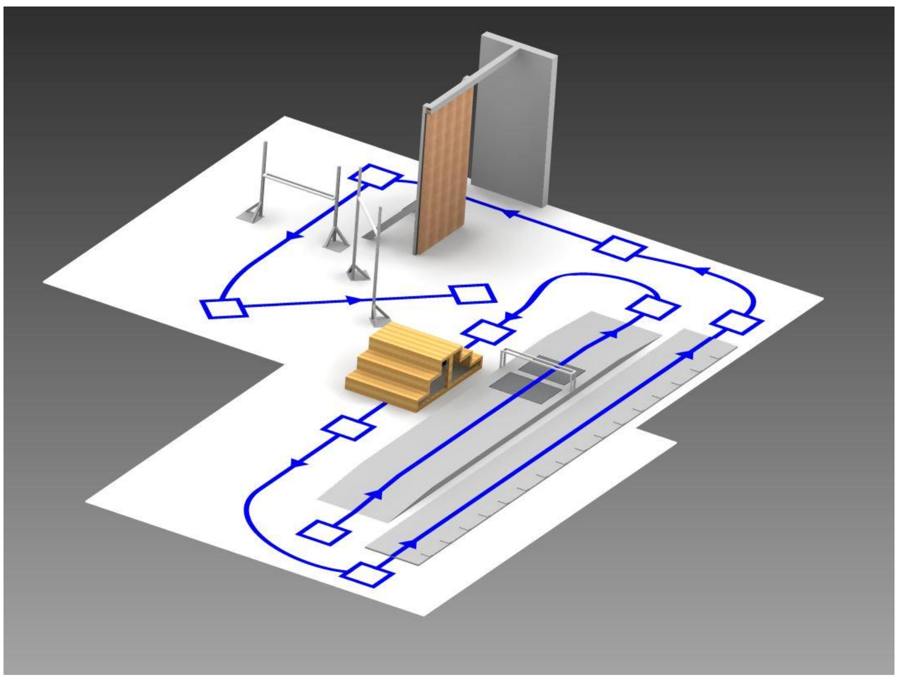

Figure 18. 3D rendering of course with six stations.

The first station involved observing obstacle crossing behaviors (foot clearance kinematics and kinetics of both feet) while walking over an obstacle that is relatively challenging but short enough to walk over. The subject started approximately 60 cm (24 in) from an elevated walkway with gentle ascending and descending grades (maximum height of 10 cm (4 in), 124 cm (49in) wide, 7.6 m (25 ft) long). A movable stick-figure frame obstacle (constructed from 1.5 cm diameter polyvinylchloride (PVC) pipe, 30 cm (11.8 in) high by 120 cm (47 in) wide by 12 cm (5 in) deep) was placed 4.9 m (16.25 ft) from the lead edge of the walkway. Immediately before the obstacle, a large embedded force plate (BP600900, Advanced Mechanical Technology, Inc. (AMTI); Watertown, MA) was placed to measure trailing foot ground reaction force (GRF) data. Immediately after the obstacle, two smaller force plates (BP400600 and BP400600NC, Advanced Mechanical Technology, Inc. (AMTI); Watertown, MA) were placed side-by-side to measure lead foot GRF data.

The second station involved walking up, over, and down a short staircase. The data from this station are the main focus in this study. At this station, subjects traversed a three step tall wooden-frame staircase (1.2 m (48 in) wide, 17.9 cm (70.5 in) rise, 27.7 cm (109 in) run) where the subject ascended one side and descended the opposite, always facing forward. The top surface was 56 cm (22 in) deep. A start box was placed 61cm (24 in) from the start of the staircase and a stop box was placed 91 cm (36 in) from the final step.

For the third station, subjects proceeded down a 7.9 m (26 ft) gait mat (GAITRite Platinum, CIR Systems Inc.; Sparta, New Jersey). For the fourth through sixth stations, the subject continued through a variable-width doorway (0 cm – 51 cm (19.5 in)), crossed over a variable height tall obstacle (50 cm (19.5 in) – 100 cm (39 in)), and finally passed under a variable-height crossbar (70 cm (28 in) – 185 cm (73 in)). An initial baseline visit was used to determine the obstacle heights and widths for the fourth through sixth stations and also to familiarize the subjects with the course to minimize the effects of learning. These obstacles were set at the most demanding settings that were passable 100 percent of the time during baseline testing.

Quantifying Stair Climbing

To determine toe and heel clearances over the edges of the stairs three-dimensional motion capture data were recorded during stair crossing. These kinematic data were sampled at 200 Hz (OQUS 100, Qualisys AB; Sweden). Reflective passive markers were placed on the boot in the vicinity of the heel, first metatarsal, fifth metatarsal and on the tip of the boot (Figure 19). For each subject, a calibration trial was conducted to determine distance from the marker locations to the ground and to determine the angle of the foot during flat stance. The vertical offset was used to determine the bottom of the boot so true vertical clearance could be calculated. The angle offset was used to determine "flat foot" orientation, and foot angle was then used with the vertical offset to determine the "true" location of the bottom of the boot at all times (Figure 20).

Figure 19. Passive reflective marker locations on the heel, first metatarsal, fifth metatarsal and tip of the boot.

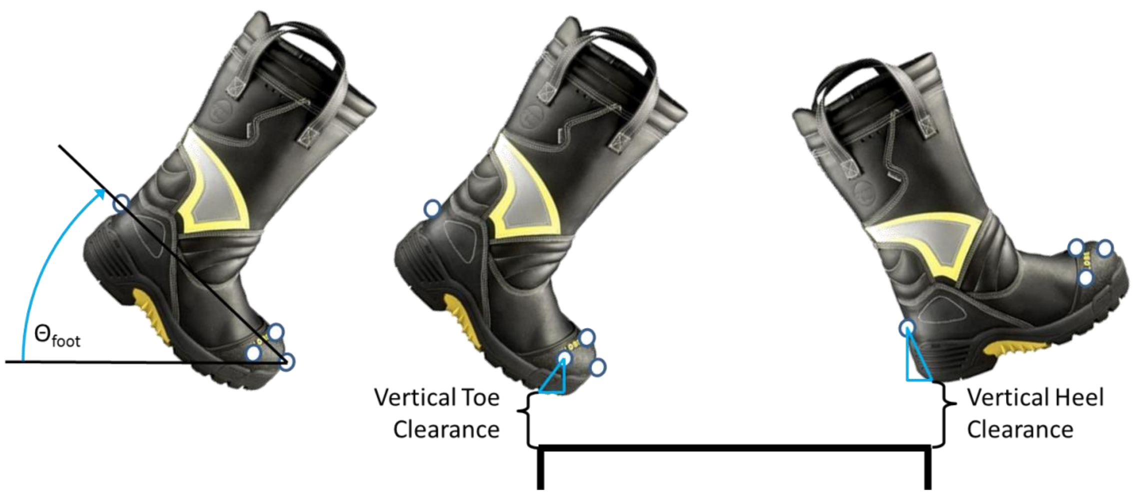

Figure 20. Foot angle (Θ_{foot}) and vertical clearance of the Toes and Heel over stair edges. Toe Clearance was examined during ascent. Heel clearance was examined during descent.

Vertical clearance of the toes (VCT) during ascent and vertical clearance of the heel (VCH) during descent were examined. VCT was calculated as the average vertical clearance of the "true" first and fifth metatarsals when each marker was vertically aligned with the stair edge. VCH was determined as the vertical clearance of the "true heel" and the stair edge when the two were vertically aligned. Considering subjects did not always begin traversing the stairs using the same foot, ‘leading’ and ‘trailing’ limbs for landing and passing stairs were compared. The first foot on stair one was considered the leading limb and used to determine the Stair 1 Landing clearance, with the first foot on stair two considered the trailing limb and used to determine the Stair 1 Passing clearance and Stair 2 Landing clearance (Figure 21). A similar naming convention was used for foot clearances during descent. The first foot on stair four was considered the lead descending limb, with the first foot to touch stair five considered the trailing descending limb. This naming convention was presented in [70].

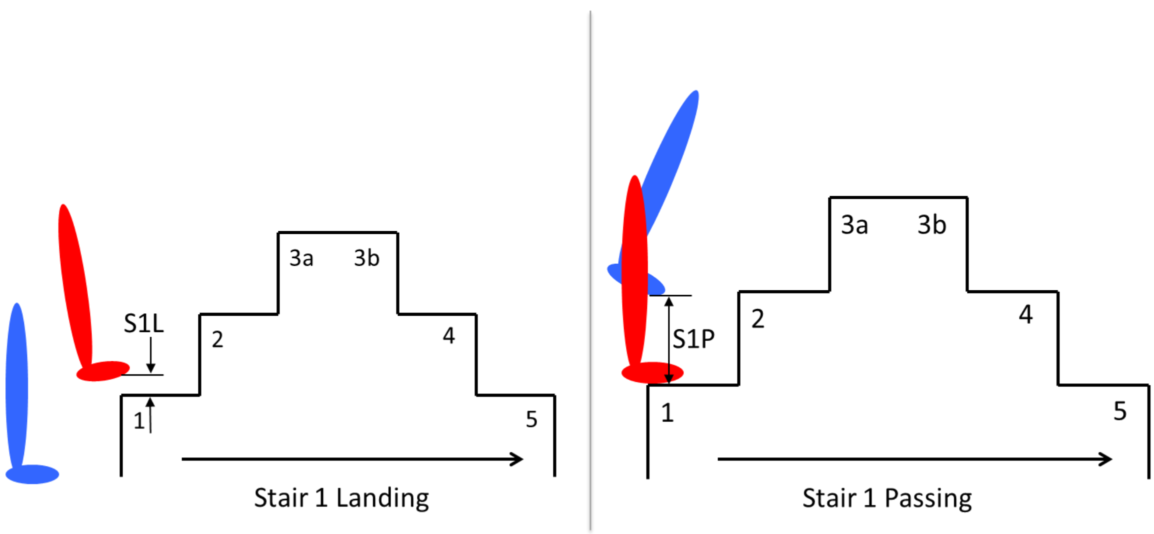

Figure 21. Visual depiction of vertical clearance for Stair 1 Landing and Stair 1 Passing. This naming convention was used across all stair edges during ascent and descent.

Data were exported from Qualisys and run through a custom MATLAB script to determine foot clearances. All clearances were exported into Excel and each set of two trials per fatiguing protocol and load carriage conditions were averaged together. The data were then analyzed using a 3 x 2 x 2 repeated measures ANOVA (i.e., 3 Conditions

(ECFF, ECTM, BBFF) by 2 Times (Pre, Post) by 2 Loads (No Hose, Hose)). Statistical significance was set at $p<0.05$. A Tukey honestly significant difference test was conducted to examine interactions.

To examine the true effects of Time, without being confounded by load condition, a separate 3 x 2 ANOVA was run (3 Conditions by 2 Times); therefore, all load carriage trials were excluded from this analysis.

To verify that Time main effects did not obscure Load data, a second 3 x 2 ANOVA was run (3 Conditions by 2 Loads). In that analysis, all pre-firefighting trials were excluded to examine the effects of load carriage when the firefighter was fatigued.

While data were collected on 24 subjects, some data were lost for each parameter. The main causes of reduced numbers of subjects were motion capture markers obscured by the stairs or knocked off while traversing the obstacle course. Therefore, a reduced number of subjects were used in the analysis of each parameter (Table 2) and each parameter was analyzed independently with separate ANOVAs.

Table 2. Number of subjects (N) used in the analysis of each parameter.

Parameter	N
1 Landing	17
1 Passing	21
2 Landing	16
2 Passing	19
3 Landing	17
3 Passing	13
4 Landing	10
4 Passing	19
5 Landing	16
5 Passing	15
Floor Landing	6
Floor Passing	12

RESULTS

Main Effects of Simulated Firefighting Condition

For the main effect of Condition, ECTM was significantly lower than ECFF and BBFF for Floor Passing (p=0.001) (Figure 22). ECTM was 18.8 mm less than ECFF (11.7% reduction) and 16.3 mm less than BBFF (10.2% reduction). There was no significant difference between ECFF and BBFF for any of the parameters examined.

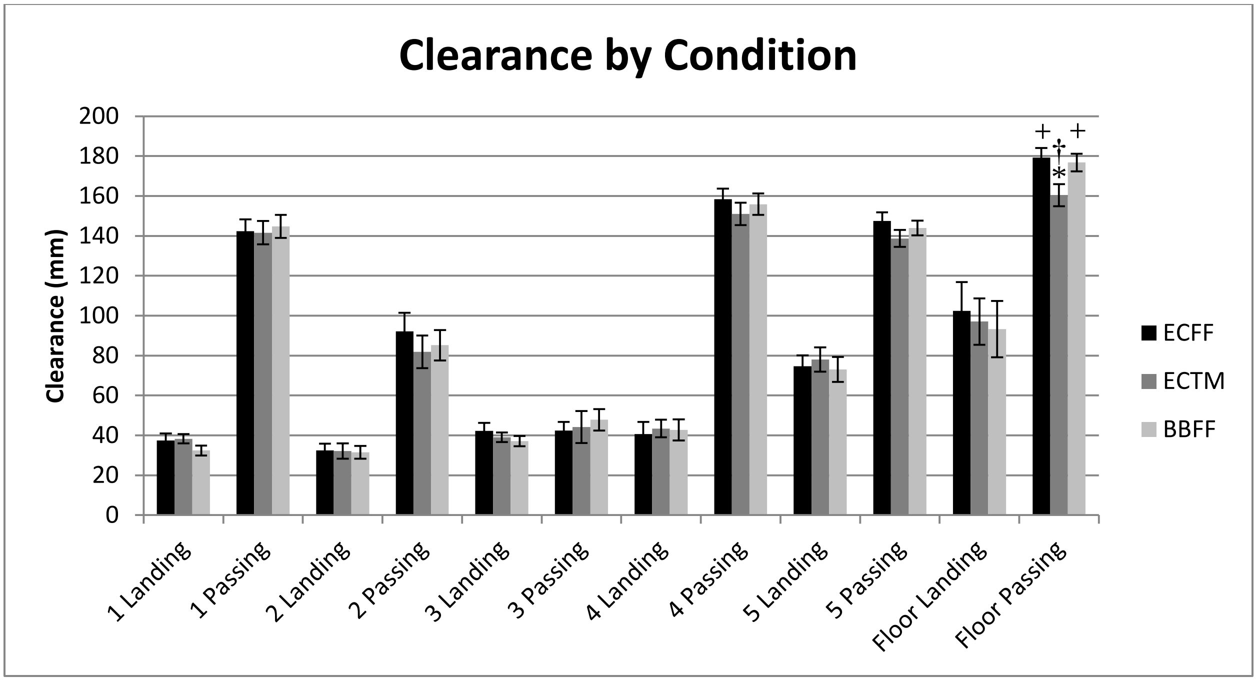

Figure 22. Clearances over stair edges by simulated firefighting condition. An asterisk (*) indicates significantly different than ECFF. A dagger (†) indicates significantly different than BBFF. A plus (+) indicates significantly different than ECTM.

Main Effects of Time (Fatigue)

There were significant differences for six parameters (three during ascent and three during descent) due to the main effect of Time. For ascent, all three Landing parameters were significantly lower following simulated firefighting. Stair 1 Landing clearances decreased 5.5 mm (14.2% reduction, p=0.006), Stair 2 Landing clearances decreased 5.0 mm (14.6% reduction, p=0.005) and Stair 3 Landing clearances decreased 3.7 mm (9.1% reduction, p=0.010).

Two Passing and one Landing parameter were significantly different following simulated firefighting for descent. Stair 4 Passing clearances increased 12.7 mm (8.5% increase, p=0.001), Stair 5 Passing increased 11.8 mm (8.6% increase, p=0.001) and Floor Landing increased 17.0 mm (19% increase, p=0.001).

When trials with load carriage were excluded similar results were found (Figure 24). A Time main effect was found for Stair 1 Landing (p=0.009), Stair 2 Landing (p=0.013), Stair 4 Passing (p=0.006), Stair 5 Passing (p=0.004) and Floor Landing (p=0.028).

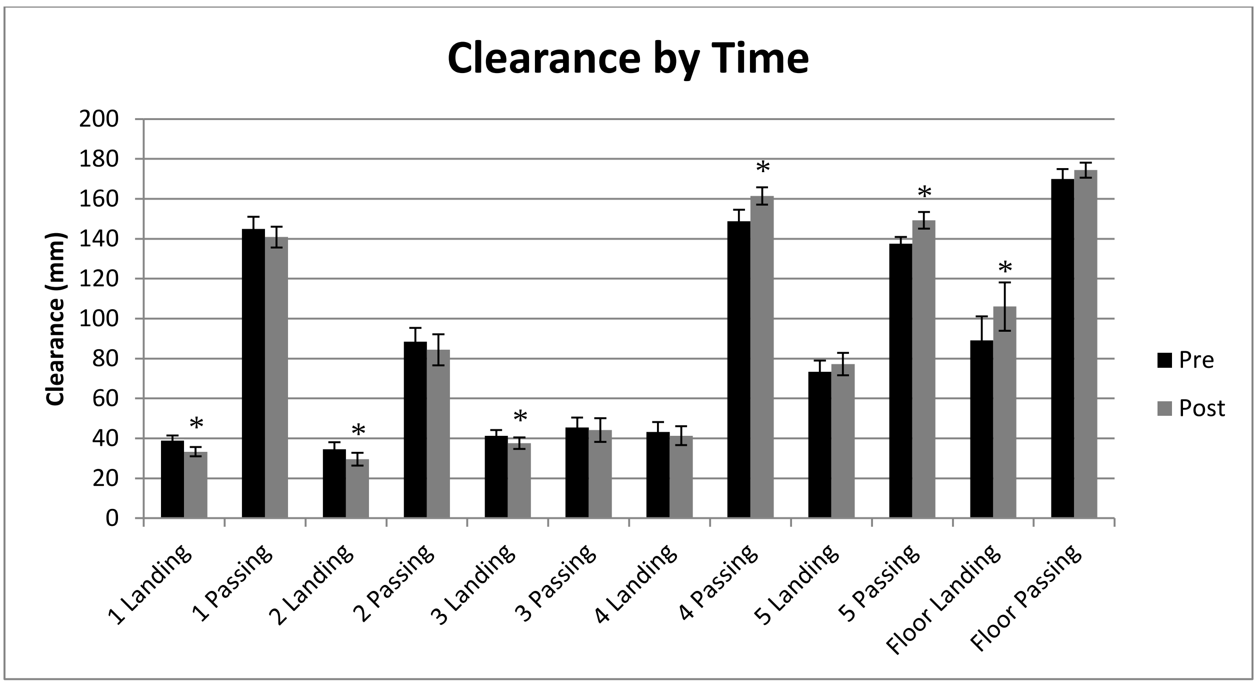

Figure 23. Clearances over stair edges pre and post simulated firefighting activities. An asterisk (*) indicates significant differences from Pre. Error bars represent standard error.

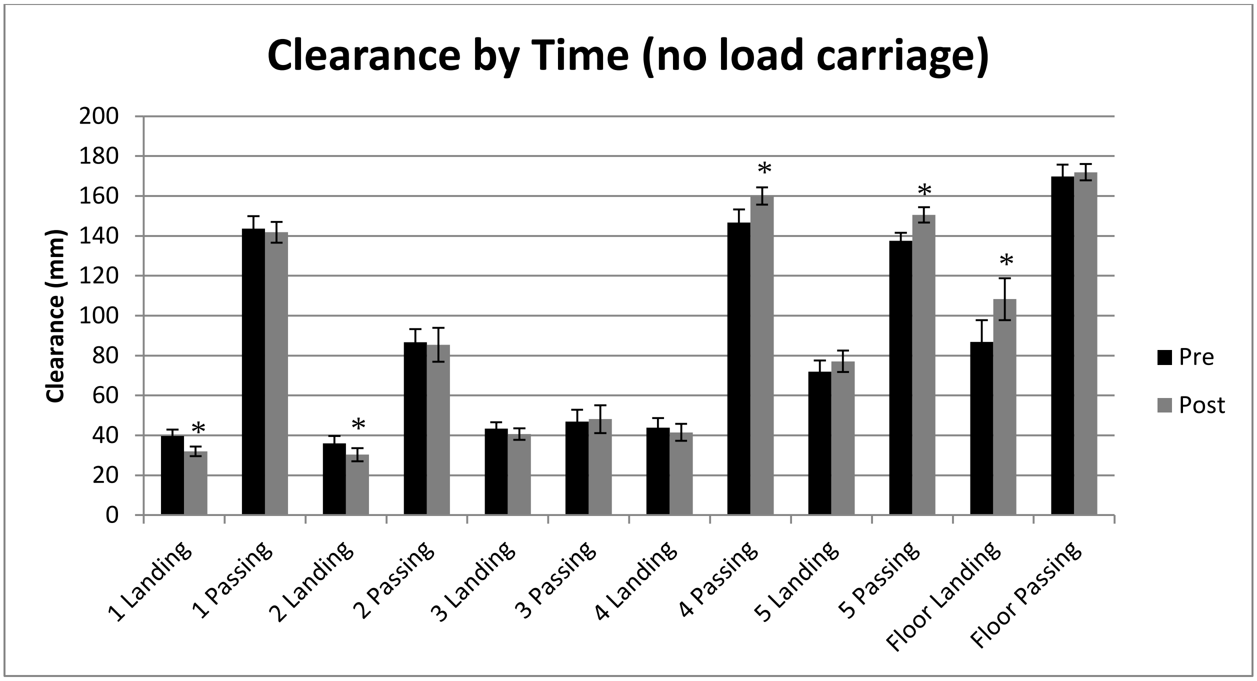

Figure 24. Clearances over stair edges pre and post simulated firefighting activities for trials without load carriage. An asterisk (*) indicates significant differences from Pre. Error bars represent standard error.

Effects of Asymmetrical Load Carriage

Three parameters had significant decreases in clearances due to the main effect of Load (Figure 25). Stair 2 Landing clearance decreased 2.3 mm (6.9%, p=0.013), Stair 3 Landing clearance decreased 5.1 mm (12.1%, p=0.006) and Stair 3 Passing clearance decreased 5.5 mm (11.5%, p=0.045).

When pre-activity data were removed (Figure 26), the main effect of Load had similar trends. The only difference in examining only post-firefighting activity data was that Stair 2 Landing was no longer significantly different. Stair 3 Landing (p=0.002) and Stair 3 Passing (p=0.019) both decreased with carriage of a hose load and were the only parameters which showed significant differences.

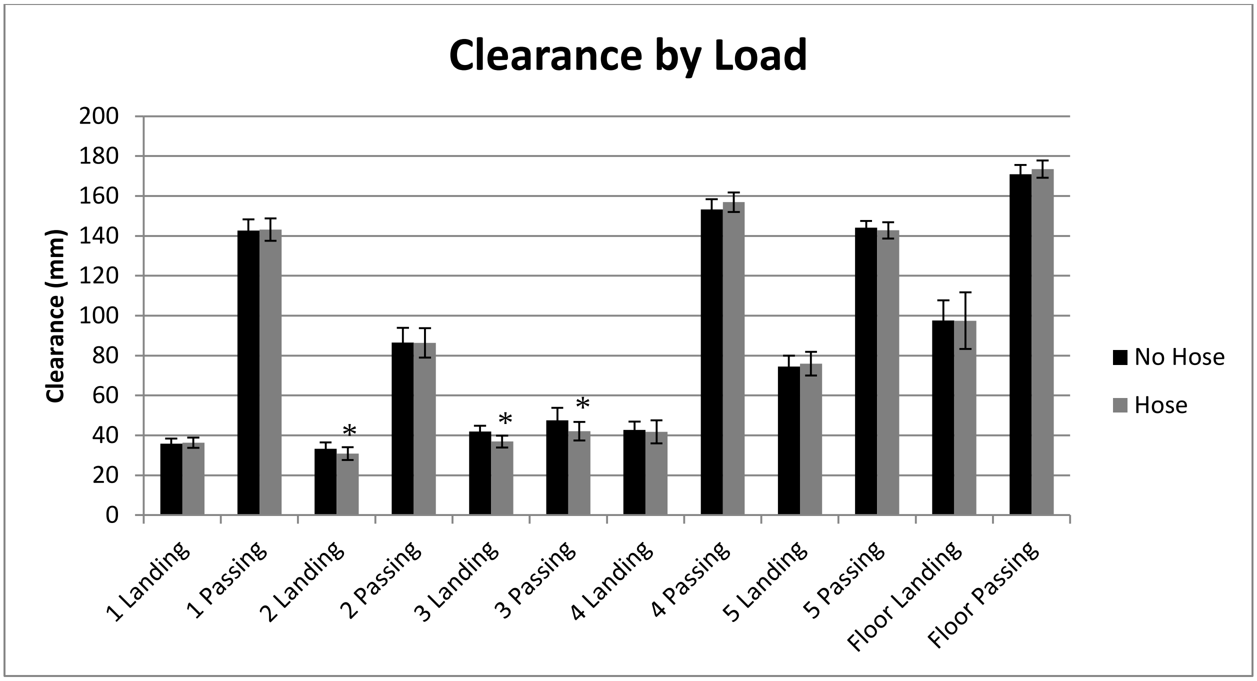

Figure 25. Clearances over stair edges with and without the carriage of an 11.3 kg hose load. An asterisk (*) indicates significant differences from No Hose condition. Error bars represent standard error.

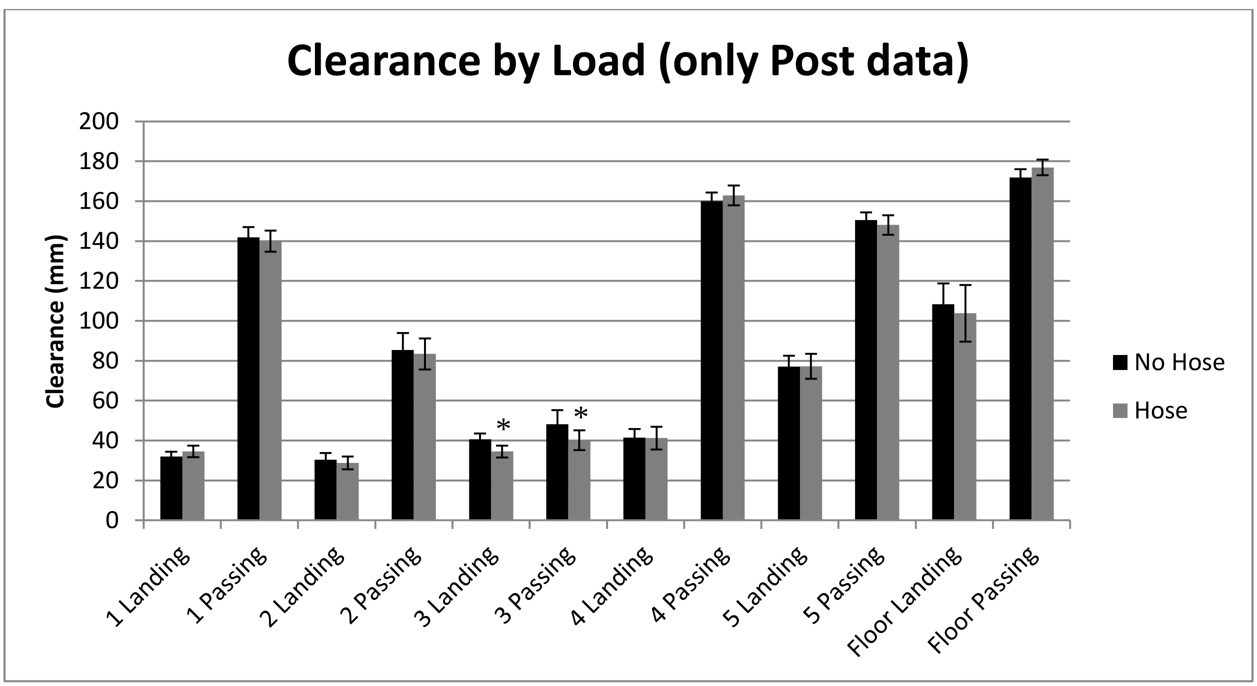

Figure 26. Clearances over stair edges following a simulated firefighting protocol with and without the carriage of an 11.3 kg hose load. An asterisk (*) indicates significant differences from No Hose condition. Error bars represent standard error.

Further Observations

Investigation into the interactions of Condition, Time and Load showed three p-values below the threshold for significance (Table 3). However, Tukey's honestly significant difference analysis showed no differences in clearances as a result of the interactions.

Table 3. Significant Condition, Time, and Load interactions.

Parameter	Interaction	P-value
Stair 1 Passing	Condition × Time	0.026
Stair 3 Landing	Condition × Time	0.010
Floor Passing	Condition × Load	0.029

DISCUSSION

The objective of this study was to examine the effects of Condition, Time, and Load carriage on foot clearances over stair edges. Some parameters did have statistically significant differences; however, overall, there were only minimal effects from these factors.

The main effects of Condition suggest that different simulated firefighting conditions had essentially no effect on foot clearances during stair climbing. The original hypothesis that ECFF and BBFF would result in significantly different stair clearances from ECTM was found for only one of the 12 total parameters. The significant difference was only found in the final step as the foot passed over the stair edges and the opposite foot was already planted on the ground (Floor Passing). The lack of significant differences across the other 11 parameters suggests that we were unable to prove that different simulated firefighting activities have a significant effect on stair clearances.

All parameters during ascent decreased following activity, although only three of the six were significant for the main effect of Time. During descent five of the six parameters examined increased following activity and three of the five were significant. When load carriage trials were excluded similar results were found. The only difference without load carriage was that Stair 3 Landing was no longer significant.

The significant changes seen in clearances over stair edges from the Time main effect may be the result of decreased stability and control as a result of the fatigue incurred during all three simulated firefighting conditions. Previous studies have shown increased postural sway following fatigue [5, 49-53] as well as decreased sense of limb position [5]. These changes in body control following intense bouts of firefighting could greatly increase a firefighter's chances of injury on the fireground.

The main effect of Load resulted in significant differences across three of the 12 parameters examined. This result indicates asymmetrical load carriage may put firefighters at an increased risk of injury while carrying hose loads. The original hypothesis that carriage of the hose load would decrease stair clearances held true for Stair 2 and Stair 3 Landing and Stair 3 Passing measures. These results suggest that carriage of an asymmetrical hose load could significantly impact firefighters' foot clearances while ascending stairs potentially increasing the risk of injury. No significant effects were detected for load carriage during descent of stairs.

This study found mean vertical clearances of 35.4 mm for Landing and 90.5 mm for Passing during ascent and 71.7 mm for Landing and 156.9 mm for Passing during descent. Landing foot clearances were much lower than Passing clearances across all stairs. This result is expected and has been reported previously by Muhaidat et al. [70]. The only exception to the differences found between Landing and Passing in this study was Stair 3 Passing, which was less than other Passing parameters. One possible explanation for this is that when the passing foot cleared the edge, it was not continuing on to a higher step edge, but rather was moving to the same level that the contralateral foot was already on. By not needing to increase clearance to land on a subsequent higher step, subjects did not raise the foot as high on Stair 3 Passing as other Passing clearances.

CONCLUSIONS

Clearances of the heels and toes were examined over each stair edge. Some significant changes occurred due to condition, pre/post activity, and load carriage. These results can lead to the development of a standard for the simulation of firefighting and lead to reduced injuries on the fireground by allowing for a better understanding of how fatigue and load carriage affect firefighters.

CHAPTER 4: CONCLUSIONS AND FUTURE WORK

To better record and understand the effects of fatigue in firefighters, two studies were performed. First, the component housing on a standard firefighting facepiece was modified to interface with a portable metabolic monitoring system. The modified component housing was then validated against the standard portable metabolic data collection mask and the metabolic cart. Second, foot clearances over stair edges were examined in an effort to better understand the response of firefighters to different simulated firefighting conditions and the carriage of an asymmetrical hose load.

Validation of the modified component housing with the portable metabolic monitoring system showed no significant differences between the modified facepiece design and the metabolic cart across five different workloads. These results suggest that the modified facepiece is an accurate and reliable tool for the collection of metabolic data across a wide range of workloads and that the device is ready for use in simulated firefighting activities.

Three protocols were examined in this study in an effort to develop a standard for simulating firefighting in a safe, controlled manor. Firefighters ascended and descend stairs so potential biomechanical differences between conditions could be evaluated. Foot clearances during the ascent and descent of stairs had minimal significant differences due to the simulated firefighting condition being performed and the carriage of an asymmetrical hose load. Fatigue did show some significant changes, with a decrease in clearances on three of the six ascent parameters and an increase on three of the six descent parameter. Further analysis into all three of the original hypotheses is necessary to fully determine the impacts of testing condition, fatigue, and asymmetrical load carriage on foot clearances. An examination into the horizontal foot clearances relative to stair edges and adjustments to experimental setup to reduce the loss of data may help to support the original hypotheses and lead to a better understanding of the impact testing condition, load carriage, and fatigue can have on firefighters.

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