OBSTACLE CROSSING BEHAVIORS IN FIREFIGHTERS: EFFECTS OF PERSONAL PROTECTIVE EQUIPMENT AND FIREFIGHTER ACTIVITY

BY

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THESIS

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ABSTRACT

Firefighting is an inherently dangerous occupation in which intrinsic hazards such as fatigue from physical exertion as well as extrinsic obstacles are commonly encountered. These hazards can lead to slip, trip, and fall (STF) related injuries, which constitute a large portion of annual severe firefighting injuries. The key objective of this work was to assess firefighters' risk of STF injuries by observing performance when crossing a stationary obstacle. Two studies were carried out to accomplish this goal.

The first of these studies examined the effects of fatigue induced by several different simulated firefighting exercise protocols, as well as the carriage of a unilateral hose load when traversing the obstacle. Three simulated firefighting protocols were implemented, with each intended to replicate the environmental conditions and required workload of actual firefighting. To examine changes in movement behavior as a result of the fatigue induced by each condition, firefighters completed a functional task course which included traversing a stationary obstacle both before and immediately after each protocol. In half of the trials, subjects carried a hose pack unilaterally. Obstacle contact errors and both horizontal and vertical clearances of each foot over the obstacle were measured. Significant changes were observed as a result of fatigue, unilateral load carriage, and protocol. The results of this study can help to develop a standard for simulated firefighting, and may ultimately help lead to a reduction in slip, trip, and fall injuries by providing a better understanding of how fatigue and load carriage can impact movement behavior on the fireground.

The second study examined the effects of different sizes and designs of SCBA as well as the fatigue effects of extended duration firefighting on obstacle crossing ability. Larger capacity

SCBA cylinders are becoming more widely available, allowing for longer periods of continuous firefighting. Furthermore, novel SCBA pack designs beyond traditional cylinder geometries are being developed to improve biomechanical compatibility. To assess biomechanical changes induced by these factors, firefighters again completed the functional task course including crossing a stationary obstacle both before and immediately after undergoing one of three simulated firefighting protocols and using varying types of SCBA. Obstacle contact errors, obstacle clearances, and peak normalized ground reaction forces (GRFs) were measured. For this study, several clearance metrics which had not been widely utilized previously were implemented and compared to the more common horizontal and vertical clearance metric. Few effects of SCBA size or design were observed, while effects of fatigue and exercise protocol were more apparent. The new clearance metrics were also observed to be more sensitive in detecting statistically significant changes than the more common clearance metrics. The results suggested that the effects of SCBA size and design on obstacle crossing ability are minimal, while fatigue – particularly that induced by extended duration firefighting, regardless of rehabilitation – increases the risk of STF injury. These results also suggest that the use of the new clearance metrics can provide useful information on changes in obstacle crossing behavior which may not be apparent from the commonly utilized metrics. These results may provide a better understanding of how equipment and varying degrees of fatigue contribute to the risk of STFs and their associated injuries, and may assist fire departments in making informed decisions when outfitting their firefighters.

DEDICATION

This work is dedicated to all of the brave men and women of the fire service who put their lives on the line every day to keep the rest of us safe. It is my hope that this work and other fire protection research will help to return the favor.

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CHAPTER 1: INTRODUCTION

1.1 Slip, Trip, and Fall Injuries on the Fireground

Slip, trip, and fall (STF) injuries are among the most prevalent types of injuries encountered on the fireground. Each year in the United States, over 20% of about 40,000 fireground injuries – approximately 8,000 injuries – are caused by STFs [1]–[3]. From 2007 to 2011, 33% of moderate to severe fireground injuries– more than any other cause – and 22% of minor fireground injuries were related to STFs [4]. Aside from the substantial safety risk posed by fireground STFs, their economic impact has also been noteworthy. A 2003 study of worker's compensation claims regarding injuries among firefighters between 1995 and 1999 estimated an average net cost of $8,662 per STF claim. In contrast, the overall mean total cost for all fireground injuries was $5,168, substantially below the STF average (both figures reported in 1997 USD) [5]. Another study has shown that STFs often lead to injuries such as knee and ankle sprains, and have been known to cause extended periods of work absence regularly reaching 160 hours or more [6]. Because STFs make up such a large portion of the total fireground injuries and due to the severity of their economic impact, investigation into their root causes is merited.

Previous studies have attempted to gain information concerning the causes of fireground STFs. In a 2008 survey of 148 firefighters, revealed that 69% had personally experienced a STF and 80% had witnessed one on the fireground. Of those who had personally experienced a STF, 9% reported that the incident took place while traversing a stationary object, while 20% had experienced a STF either carrying or tripping over a hose. Perhaps most alarming, only 16% of the firefighters surveyed reported having received training to avoid fireground STFs [7]. Investigation into high risk functional tasks commonly encountered on the fireground such as traversing stationary obstacles may assist in identifying behaviors which may increase STF risk, and could possibly contribute to the development of STF avoidance training.

1.2 Biomechanical Consequences of Firefighting Equipment

Firefighters are required to wear personal protective equipment (PPE) when responding to most calls. Standard PPE consists of insulated pants, jacket, gloves, heavy boots, hood, helmet, and a self-contained breathing apparatus (SCBA). Traditional SCBA systems consist of a compressed air cylinder, face piece, and a harness worn on the shoulders and waist to house the air cylinder on the back. The use of PPE is essential in structural firefighting, as it allows for firefighters to work in high temperature environments devoid of breathable air. That said, PPE may limit firefighters' mobility and increase the risk of injury while performing functional tasks. In the aforementioned survey, one third of firefighters felt that PPE strongly affected balance, while another 62% reported a slight effect on balance. Further studies have shown PPE to limit range of motion [8], and negatively impact balance and gait performance [9]–[12]. In addition, the use of PPE – unfamiliar configurations in particular – has been shown to decrease firefighters' proficiency in traversing obstacles [13]–[15]. Based on these results, it is reasonable to conclude that the use of PPE may make performance of functional tasks more difficult, thereby putting firefighters at a greater risk of STFs on the fireground.

Among the components of the PPE ensemble, the SCBA equipment may have the largest effect on movement capability. Huck reported that the SCBA may be the most substantial contributor to reduced range of motion among PPE components. Subjective responses from test participants also cited the SCBA as the piece of equipment which made the PPE ensemble least comfortable to the wearer [16]. A study by Punakallio et al. also noted the SCBA as the most significant contributor to reduced balance in firefighters, as the SCBA cylinder displaces the body's center of mass (COM) while the face piece restricts vision [17]. PPE and SCBA in particular have been implicated as an extrinsic factor contributing to increased risk of STFs [18]. In lieu of these results, further investigation into the role of SCBA in STFs is warranted.

Firefighters are often forced to carry loads in addition to their SCBA, including various tools and hose packs [19]. Due to the wide range of shapes and sizes of equipment, these loads often must be carried asymmetrically, which can limit firefighters carrying capacity [20]. Investigations into effects of rifle carriage among military personnel have shown increases in peak ground reaction forces, which may have detrimental effects on the lower limbs over time [21], [22]. Studies on the carriage of unilateral loads during level walking have shown increased hip and knee joint moments on the contralateral side of the body that is opposite of the load, and decreases in these moments on the ipsilateral loaded side [23], [24]. Other studies found a lack of gait symmetry between the lower limbs of the loaded and unloaded sides, indicating reduced gait performance [25]. DeVita et al. also discovered increased stress on the L5/S1 joint and altered trunk muscle activity [23]. In a study of letter carriers, Wells et al. determined that prolonged carriage of asymmetrical loads resulted in higher instances of neck, shoulder, and back disability [26]. Finally, an obstacle crossing study by Perry et al. found lead foot vertical and trailing foot horizontal obstacle clearances to increase when subjects carried anterior loads in their arms, likely to compensate for a perceived perturbation to normal obstacle crossing ability [27]. The results of these studies suggest that unilateral load carriage may have harmful effects on the body, both short term and long term. Hence, studying their effects on firefighters' ability to cross stationary obstacles may be a worthwhile endeavor.

1.3 Simulating Firefighting

A difficulty in analyzing firefighter fatigue is the replication of the extreme conditions in which live firefighting takes place in a safe, controlled environment. Many different approaches have been developed in attempts to safely simulate the fatigue and heat stress of firefighting. No standard has yet been adopted, though the National Institute for Occupational Safety and Health (NIOSH) has called for the development of such a standard [28].

One basic challenge associated with replicating the intensity of live firefighting in a laboratory setting is developing an exercise protocol which induces a comparable level of muscle fatigue to those performed during actual structural firefighting. Walking protocols using treadmills in heated rooms have been widely employed [29]–[38]. Others have implemented similar protocols using cycle ergometers in environmental chambers (37°C, 70% humidity) [39]. However, during firefighting, firefighters often must perform tasks utilizing different muscle groups than those used for treadmill walking or pedaling on a cycle ergometer. As such, it is unclear if the fatigue brought on from these protocols adequately simulates that of actual structural firefighting. Other groups have introduced exercise protocols consisting of a single simulated firefighting task, such as repeated stair climbing in an environmental chamber (40°C, 70% humidity) [40] or a simulated ceiling pull task in a live fire environment (90°C) [41]. Again, the performance of a single isolated task may not adequately simulate the wide range of tasks performed during firefighting operations or the fatigue associated with them. Other studies have implemented more complete simulated firefighting activity protocols [11], [14], [42]–[45], but differ greatly in the tasks included in these protocols, reiterating the need for the development of a standard protocol.

Another basic challenge in simulating live firefighting is utilizing a testing environment which engenders similar levels of heat strain in the firefighters as live fire conditions. As stated previously, several studies have implemented simulated firefighting protocols in ambient conditions [42]–[46], temperature and humidity controlled environmental rooms [29]–[40], and in live fire environments [11], [14]. However, testing in ambient conditions may not be able to produce a comparable amount of heat stress to that experienced during live firefighting. A study by Smith et al. revealed that the physiological and psychological demand of performing simulated firefighting activities in a live fire environment is greater than that of performing the same overhaul task in neutral conditions [41]. Live fire drills can replicate firefighting conditions, but may require a great deal more resources to carry out than performing the same tasks in an environmental chamber. Also, limitations on the temperatures at which some data collection equipment are capable of operating present obstacles to collection of metabolic data in live fire environments. With newly developed portable testing equipment, it is possible to measure metabolic output in an environmental chamber while firefighters breathe using their SCBA [47]. Furthermore, it is difficult to control for temperature and humidity in live fire environments. Petruzzello et al. examined physiological strain metrics in firefighters performing both simulated firefighting tasks in the field and treadmill walking in a heated environment, but no direct comparison between the exertion levels between the two environments was possible due to the differences in exercise protocols [48]. Thus, validation of the temperature and humidity controlled environmental chamber as a replacement for a live fire environment by way of a matched comparison of simulated firefighting activities is necessary.

1.4 Some Unconventional Obstacle Crossing Metrics Related to STFs

Typically, a common set of metrics are employed to quantify obstacle crossing performance. These metrics are referred to in this work as "classic clearances," and have been widely implemented in obstacle crossing studies [13], [49]. Other studies have also instrumented subjects with motion analysis equipment to measure joint kinematics [50], [51]. However, this was not possible in the studies presented here due to the PPE worn by the subjects.

In the second study presented here, an unconventional set of clearance metrics are also employed and compared to the classic clearances. In that study, the radial clearances vectors and peak boot heights were determined in an attempt to find new ways of identifying changes in obstacle crossing gait behavior with limited options for motion capture marker placement. Previous studies have implemented similar metrics for measuring minimum foot clearances over obstacles throughout the entire swing phase for both the lead and trailing foot [52]–[54]. It was believed that the use of the radial clearance vectors would give a better representation of the absolute minimum 2D distance between each foot and the obstacle during crossing, and thereby perhaps be a better predictor of the likelihood of obstacle contact than the classic vertical clearances. To our knowledge, the peak boot heights have not been examined in previous studies, and may assist in estimating changes in hip and knee flexion and extension in the absence of motion capture markers fixed to the body segments necessary for measuring the kinematics for those joints.

The required dynamic coefficient of friction (RCOF) has been examined as a relative indicator of slip risk. The RCOF is a nondimensional quantity obtained by dividing the resultant shear GRF in the plane of the floor surface by the vertical GRF [55]–[58].

$$RCOF = \left|\frac{\sqrt{F_{AP}^2 + F_{ML}^2}}{F_V}\right|$$

Here, F_{AP} is the AP GRF, F_{ML} is the ML GRF, and F_V is the V GRF. Previous studies have identified six distinct peaks in the RCOF curve over the course of the gait cycle during level walking, and reported the third and fifth peaks for heel strike and toe off, respectively [59]. In the past, the RCOF has been implemented in attempts to determine the probability of slip events given the characteristics of a surface. Some have looked at the effects of walking on surfaces treated with various contaminants [55], [56], [58], [60], while others have examined the effects of surface grade [56], [59] or walking speed [59], [61]. Results generally showed that slip events typically increased when the RCOF increased, presumably because at higher values the margin between the RCOF and the actual dynamic coefficient of friction of the shoe-floor interface became large [56]. In these studies, the RCOF can be applied as a relative indicator to determine if the risk of slipping changes with any of the factors examined in the two studies.

1.5 Known Obstacle Crossing Behaviors

Traversing stationary obstacles is common task required during locomotion for both firefighters on the fireground and civilians in everyday life. The literature regarding obstacle crossing gait is wide ranging. Numerous studies have suggested that vision plays a key role in obstacle crossing ability, showing that obstructed vision of the obstacle causes gait changes which may decrease performance [62]–[64]. Firefighters are routinely required to wear face pieces, which can limit peripheral vision and result in lessened safety and increased risk of obstacle contact [17]. In addition, the loads firefighters are often required to carry on the fireground may obscure peripheral visual cues, which have been shown to assist in obstacle crossing ability [62]. These studies further support that PPE may contribute to increased risk of STFs, particularly during functional tasks such as obstacle crossing.

Extensive research has been carried out to study obstacle crossing behavior in civilian populations at statistically high risk of falls. Among these high risk populations are the elderly [65]–[69] and those with neurological impairments including stroke [70]–[73], Parkinson's Disease [74]–[76], Alzheimer's Disease [77], and traumatic brain injury (TBI) [78]–[81]. Several studies found that populations of older adults typically employ more hip flexion and higher medial-lateral forces, in addition to higher lead foot vertical clearances and lower lead foot horizontal clearances, particularly when stepping over higher obstacles [67], [68]. Stroke patients displayed similar strategies, having increased lead foot vertical clearances and reduced lead foot horizontal clearances when compared to healthy matched control subjects [70], [73]. It has been suggested that these increases in lead foot clearances may be compensatory strategies to ensure vertical obstacle clearance and cross the obstacle later in the lead foot swing phase to improve visual feedback [70]. Other studies of stroke patients have observed decreased ability to successfully negotiate obstacles without making contact errors [71], and larger anterior-posterior separation between the body center of mass (COM) and center of pressure (COP) compared to matched controls [72], indicating reduced obstacle crossing ability and balance. Persons with TBI have shown similar characteristics to those of stroke patients in terms of obstacle clearances [81] and COM-COP separation [78]. Parkinson's Disease patients have been shown to reduce step length during obstacle crossing [74]–[76], employ slower gait speeds [74], [75], and increase vertical clearances over the obstacle [75] compared to matched controls. Alzheimer's Disease patients have been shown to employ similar strategies, decreasing step length and lead foot horizontal clearance, increasing vertical clearance, and slowing gait speed while crossing obstacles – particularly those of fairly challenging heights – compared to matched controls [77].

Comparing the obstacle crossing characteristics of healthy firefighters to those of the above mentioned high risk populations can help to gain understanding of how firefighter obstacle crossing behaviors may change in response to factors such as fatigue and carriage of various types of loads. Older adults and those with neurological impairments have been shown to be at higher risk of falls. As such, the behaviors commonly observed during obstacle crossing in these populations may be less safe than those employed by younger, unimpaired populations. Therefore, if the common behaviors in the high risk populations are observed in younger, healthy populations – including firefighters – it may be an indicator that some factor has led to decreased obstacle crossing ability. As a result, study and comparison of firefighter obstacle crossing behaviors to those common in populations at high risk of falls in terms of foot clearances and kinetic variables can provide valuable information concerning factors which may contribute to firefighter falls [13], [14].

1.6 Fatigue Effects

Firefighting is an intense physical activity which inevitably results in muscular and cardiovascular fatigue [38], [45]. Exposure to high temperatures and the associated heat stress has been shown to have detrimental physiological and psychological effects on firefighters, not least of which is a faster onset of muscular fatigue [35], [37], [48], [82], [83]. Earlier onset of fatigue in combination with high heat stress can have adverse effects on cognitive function [83] and balance [84]–[89], and potentially cause increased risk of an STF injury . The effects of muscular fatigue have been examined exhaustively in civilian populations, yielding the general result of a reduction in postural stability during quiet stance [84]–[89]. These reductions in balance can take as long as 20 minutes of recovery to return to normal levels [87]. This may translate to reduced balance during walking and obstacle crossing. A study by Allen and Proske showed that muscular fatigue negatively impacted subjects' sense of limb position in blindfolded movement matching tasks in the arms [90]. Skinner et al. showed similar results in a study on knee joint position sense [91]. Forestrier and Nougier observed a reduction in subjects' ability to perform coordinated multijoint movements such as accurately throwing a ball when fatigued [92]. Impaired joint position sense may lead to increased likelihood of contacting an obstacle during crossing, particularly with the trailing limb, for which visual feedback is limited [63]. Barbieri et al. showed that fatigue had a tendency to decrease obstacle clearances in normal populations and populations of older adults [65]. Other studies have shown that fatigue increased the likelihood of obstacle contact errors [14] and reduced dynamic functional balance [11]. Kong et al. have identified fatigue as an intrinsic factor contributing to increased risk of STFs [18]. Considering the outcomes of these studies, it is likely that fatigue is a major factor contributing to lack of obstacle crossing performance and, consequently, the frequency of STF injuries among firefighters.

With an increasing number of fire departments transitioning to higher capacity SCBA cylinders, firefighting for extended periods of time is becoming a progressively more common occurrence. While it is now possible for firefighters to spend more time in a fire continuously working without having to stop and change cylinders, it is likely that extended duration firefighting leads to more extreme levels of fatigue and heat stress. A study by Baker et al. showed that following longer duration exercise, a much longer recovery period was necessary for muscle performance to return to baseline levels of maximum voluntary contraction and tetanic force output [93]. Research has been carried out concerning the physiological benefits of recovery periods between multiple rounds of exercise in hot environments, highlighting changes in core temperature as a measure of thermoregulation and heat stress. Carter et al. observed no reductions in core temperature during 10-minute recovery pauses following a stair ascent/descent task, although active fan cooling did provide some advantages [40]. Other studies have demonstrated that a 15-minute recovery period between treadmill walking tasks was not sufficient in reducing firefighter core temperatures unless an aggressive cooling strategy involving forearm immersion in cool water was employed [34], [94]. Ilmarinen et al. showed limited benefits of recovery periods of 30 minutes unless carried out in a cold environment (0°C) [95] or provided with the opportunity to rehydrate [33]. Horn et al. observed that 50 minutes of rest at minimum were required before heart rate and core temperature levels returned to their baseline resting values following simulated rescue tasks, even in the presence of active cooling [82]. Based on the results of these studies, even extended periods of rehabilitation have limited effects without adequate cooling and rehydration. Thus, continuously firefighting for longer periods of time without pausing to cool off and rehydrate can potentially lead to poor thermoregulation and increased heat stress, which has been shown to expedite the onset of muscular fatigue. As mentioned previously, muscular fatigue is a likely cause of decreased obstacle crossing performance and STF fireground injuries by extension [14]. As such, it is worth examining the effects of fatigue from extended periods of firefighting – both with and without a rehabilitation break – on firefighters' ability to perform functional tasks such as stationary obstacle crossing.

1.7 Load Carriage Effects

A key piece of equipment included in the PPE ensemble is the SCBA, as it allows for a breathable air supply in environments with high concentrations of harmful compounds in the air.

While the SCBA is vital to a firefighter's survival, it also embodies a heavy load that the firefighter must bear while carrying out common fireground tasks. Also, as previously stated, many fire departments are moving toward implementing higher capacity SCBA cylinders, which provide more air at the expense of added size and weight. A study on firefighter obstacle crossing ability by Park et al. determined that carrying heavier SCBA on the back decreased lead foot vertical and horizontal and trailing foot vertical clearances in addition to causing an increase in the frequency of obstacle contact errors [13]. Perry et al. observed a similar reduction in obstacle clearances with increasing weights of loads carried anterior to the body [27]. Aside from the studies cited above, however, the literature concerning the effects of load carriage on obstacle crossing is sparse, and therefore should be validated by further study.

While the literature highlighting the effects of load carriage on obstacle crossing performance is limited, there has been an abundance of research performed on performance during other functional tasks while carrying back-borne loads. Hooper et al. observed improved physiological responses when performing an interval exercise protocol using a lightweight carbon fiber cylinder compared to a heavier steel cylinder [96]. However, Manning and Griggs observed no effects of SCBA weight on heart rate during a routine firefighting exercise [97]. Various studies have been carried out on the effects of load carriage on level walking gait performance, generally showing a proportional relationship between the severity of the effects on gait and the magnitude of the load. In studies of children carrying loads simulating book bags, higher back-borne loads have been shown to increase double support time, which may be a cautious gait adjustment in an attempt to compensate for reduced dynamic stability [98]–[101]. Increased peak ground reaction forces were also observed, which may signify higher stress on the lower limbs [102]. Studies on adult civilian and military populations have exposed similar results [21], [99]–[101], [103], [104]. Several studies have discovered increased gait variability and changes in joint kinematics as a result of increased load carriage [101], [103], [105], [106], results which have been linked to increased risk of falls [107]. Based on the results of these studies, the carriage of heavier SCBA may reduce firefighters' gait performance, placing them at greater risk of STF injury. As such, further investigation into loaded obstacle crossing is warranted.

In addition to the size of SCBA used by firefighters, the ergonomic design of the SCBA is also of interest. Recently, several SCBA prototypes have been developed to improve comfort and mobility by producing a more ergonomically favorable weight distribution. A study by Love et al. showed that firefighters tended to perform better in simulated fire rescue tasks in terms of completion of tasks and physiological responses, and provided higher subjective comfort ratings when using SCBA which generated smaller moments about the body's center of mass (COM), achieved by shifting the mass of the apparatus closer to the waist [108]. Another study by Griefahn et al. observed similar results, with firefighters performing better physically and physiologically in simulated smoke diving protocol when using a redesigned SCBA which shifted the majority of the weight toward the waist and closer to the body [46]. Further studies have examined different load distribution systems military personnel and have seen benefits such as gait patterns more similar to unloaded walking and improved physiological effects when using configurations which place the load closer to the waist [100], [109]. Further studies have shown load carriage systems which evenly distribute weight such as double packs to have similar effects on walking gait in civilian populations [99], [101]. However, Park et al. observed no advantages in obstacle crossing when using a SCBA designed to shift the COM lower toward the waist [13]. Further, another obstacle crossing study by Park et al. showed an increase in obstacle contact errors when subjects wore an unfamiliar set of PPE [14]. Most firefighters are not experienced with the novel SCBA design prototypes, so it is unclear whether their potential ergonomic advantages outweigh the detriments of firefighters' lack of familiarity at this point in their development and distribution. As a result, further investigation into the effects of novel, ergonomically designed SCBA on obstacle crossing performance is needed.

1.8 THESIS OVERVIEW

Given the aforementioned motivation, two studies were carried out for this thesis. The objectives of these studies were the following:

(Study 1) Examine the effects of simulated firefighting protocol, fatigue, and unilateral load carriage on firefighters' ability to cross stationary obstacles by measuring obstacle contact errors and clearances.

(Study 2) Examine the effects of SCBA size, SCBA design, fatigue, and extended duration firefighting – both with and without rehabilitation – on firefighters' ability to cross stationary obstacles by measuring obstacle contact errors, clearances, and peak ground reaction forces.

In response to these objectives, the following general hypotheses were formed based on the information presented in the previously discussed literature:

(Study 1a) Fatigue brought on from exercise will result in more contact errors and decreases in obstacle clearances, GRFs, and RCOFs.

(Study 1b) The carriage of an asymmetrical hose load will lead to more contact errors and lower obstacle clearances, and will cause increases in GRFs and RCOFs.

(Study 1c) Exercise protocols involving simulated firefighting tasks – independent of the exercise environment – will have a greater impact than the treadmill walking protocol on the variables of interest. More specifically, simulated firefighting tasks will lead to more contact errors and more pronounced decreases in clearances, GRFs, and RCOFs.

(Study 2a) Increasing SCBA size will result in more contact errors and decreases in obstacle clearances (distance, angles, and peak boot height), and peak GRFs.

(Study 2b) Use of a novel SCBA design will not significantly impact obstacle crossing performance in terms of contact errors, obstacle clearances, and peak GRFs.

(Study 2c) Fatigue brought on from exercise will result in more contact errors and decreases in obstacle clearances, and peak GRFs.

(Study 2d) Extended duration simulated firefighting activity protocols will result in increased contact errors and decreases in obstacle clearances, and peak GRFs.

(Study 2e) Allowance for a 5-minute rehabilitation break between rounds in extended duration protocols will not provide any advantages in obstacle crossing performance over back-to-back rounds due to the brevity of the rehabilitation period.

(Study 2f) Use of radial clearance metrics will yield results more sensitive to changes in behavior due to fatigue and load carriage than the use of classic clearance metrics.

As stated previously, two studies were carried out to assess the effects of various risk factors on firefighters' ability to traverse stationary obstacles. Below are brief descriptions of each study. Study 1 focused on the effects of fatigue and unilateral load carriage, while also examining potential differences among three exercise protocols. Study 2 examined the effects of different sizes and designs of SCBA as well as fatigue effects from single bout and extended duration exercise protocols.

Study 1:

Previous studies have attempted to simulate firefighting under safe, controlled conditions. A wide range of climates and exercise protocols have been utilized, yet no standard has been developed. Further, it is difficult to validate the efficacy of a simulated protocol versus the effects on the body of live firefighting. This study examined three simulated firefighting protocols, each intended to simulate the environmental conditions and required workload of actual firefighting. To assess any biomechanical changes as a result of the fatigue induced by each condition, firefighters completed a five-station functional task course which included traversing a stationary obstacle both before and immediately after each exercise protocol. For half of the trials, subjects carried a unilateral hose pack. Obstacle contact errors and clearances were measured during all obstacle crossing trials. Results suggested that firefighters may employ compensatory strategies to ensure obstacle clearance when fatigued or carrying unilateral loads. Results also suggested that the strain brought on by protocols including simulated firefighting tasks is similar whether performed in a live fire or an environmental chamber, but is greater than that of treadmill walking protocols. The results of this study may be applied to the development of a standard for simulated firefighting in a safe, controlled environment. These results may also ultimately lead to a reduction in fireground injuries by improving situational awareness and understanding of how fatigue and load carriage can impact movement behavior on the fireground.

Study 2:

Larger capacity SCBA cylinders are becoming more widely available, allowing for longer periods of continuous firefighting. Furthermore, novel SCBA pack designs cylinder geometries are being developed to improve biomechanical compatibility. To assess biomechanical changes induced by varying SCBA size and geometry and extended duration simulated firefighting protocols, firefighters completed a five-station functional task course which included crossing a stationary obstacle both before and immediately after undergoing one of three exercise protocols and using varying types of SCBA. Few effects of SCBA size or design were observed, while effects of fatigue and exercise protocol were more apparent. The results suggested that the effects of SCBA size and design on obstacle crossing ability are minimal, while fatigue – particularly that induced by extended duration firefighting, regardless of rehabilitation – increases the risk of STF injury.

The remainder of this thesis is broken down into three chapters. Chapter 2 contains a complete description of Study 1, the analysis of fatigue and unilateral load carriage effects on obstacle crossing. Chapter 3 consists of a detailed account of Study 2, the analysis of SCBA size and design as well as fatigue and extended duration exercise effects on obstacle crossing. Finally, Chapter 4 recounts the conclusions from each study and their possible implications, as well as the limitations of each experiment and suggestions for further study.

CHAPTER 2: EFFECTS OF ASYMMETRICAL LOAD CARRIAGE AND FATIGUE ON FIREFIGHTER OBSTACLE CROSSING

2.1 ABSTRACT

Fatigue and load carriage may affect firefighters' ability to proficiently and safely navigate the hazards associated with the fireground. In particular, firefighters' ability to cross stationary obstacles on the ground may be impaired by fatigue and load carriage in addition to wearing personal protective equipment, increasing the risk of a slip/trip/fall (STF) related injury. Further, previous studies have attempted to simulate the fatigue brought on from firefighting in safe, controlled environments, but no standard yet exists. To examine the potential differences among simulated firefighting conditions, 24 firefighters performed three exercise protocols consisting of 16 minutes of either treadmill walking (4.5 km/h, 2% grade) or simulated firefighting tasks in a temperature and humidity controlled environmental chamber (47°C, 20% humidity) or live fire conditions (~85°C). To assess any biomechanical changes among exercise protocols and investigate the effects of fatigue and unilateral load carriage, subjects walked down a walkway with and without an11.3 kg (25 lb) hose load and crossed a 30cm stationary obstacle while kinematic and kinetic data were collected before and after each exercise protocol. Major and minor contact errors, vertical and horizontal clearances over the obstacle, peak ground reaction forces (GRFs) as well as required dynamic coefficients of friction (RCOF) at heel strike and toe off for the lead and trailing foot were calculated. Significant changes due to fatigue, hose load, and protocol fatigue and hose load × fatigue were observed. These results may assist in the development of a standard simulated firefighting protocol. In addition, they may contribute to a better understanding of the biomechanical effects of fatigue and load carriage on firefighters, and thereby lead to a reduction in fireground STF injuries.

2.2 INTRODUCTION

Slip, trip, and fall (STF) injuries are among the most prevalent types of injuries encountered on the fireground. Each year in the United States, over 20% of about 40,000 fireground injuries are caused by STFs [1]–[3]. From 2007 to 2011, 33% of moderate to severe fireground injuries– more than any other cause – and 22% of minor fireground injuries were related to STFs [4]. A 2003 study of worker's compensation records of firefighter injuries determined that STF injuries had a mean total cost of $8,662 per incident, well above the mean total cost for all injuries of $5,168 (both figures reported in 1997 USD) [5]. Another study has shown that STF injuries often lead to work absences in excess of 160 hours [6]. A 2008 survey revealed that among 148 firefighters, 9% had experienced a STF while traversing a stationary object, while 20% had experienced a STF either carrying or tripping over a hose [7]. The high prevalence, severity, and economic impact of STF fireground injuries calls for further investigation into their occurrence during high risk tasks such as obstacle crossing.

Firefighters are required to wear personal protective equipment (PPE) when responding to most calls, consisting of insulated pants, jacket, gloves, heavy boots, hood, helmet, and self-contained breathing apparatus (SCBA). PPE has been shown to limit mobility and range of motion [8], negatively impact balance and gait performance [9]–[12] and decrease firefighters' proficiency in traversing obstacles [13]–[15]. Firefighters' risk of injury may be even greater following strenuous activity, when fatigued and carrying heavy loads in addition to their PPE, necessitating further investigation.

Traversing stationary obstacles is a fairly common activity, both on the fireground and in everyday life. Extensive research has been carried out on the relationship between vision and obstacle crossing, generally showing that obstructed vision of the obstacle drastically decreases performance [62]–[64]. Firefighters routinely are required to wear face pieces which impair vision, and may negatively impact obstacle crossing ability. Motor behavior during obstacle crossing has also been studied in populations at higher risk of falls, including the older adults [49], [65]–[69], stroke patients [70]–[73], and those who have experienced brain trauma [78]–[81]. Many of these studies have identified obstacle crossing behaviors in the high risk populations which differ from those of matched controls, possibly employed as compensatory strategies for the subjects' impairments [70], [73], [81]. Study and comparison of firefighter obstacle crossing behaviors to those of the populations at high risk of falls in terms of foot clearances and kinetic variables can provide valuable information concerning factors which may contribute to firefighter falls [13], [14].

A difficulty in analyzing firefighter fatigue is the replication of the extreme conditions in which live firefighting takes place in a safe, controlled environment. Several different approaches have been developed in attempts to safely simulate the fatigue and heat stress of firefighting, but no standard has yet been adopted [28]. Several studies have used treadmill walking protocols [29]–[37] or cycle ergometer routines [39] in environmental chambers. However, these protocols are largely different from common fireground tasks, so it is unclear if these protocols adequately simulate firefighting. Others have introduced protocols of single simulated firefighting tasks, such as repeated stair climbing in an environmental chamber [40] or a simulated overhaul task in a live fire environment [41]. Again, the performance of a single isolated task may not adequately simulate the wide range of tasks performed during firefighting or the fatigue associated with them. Further studies have implemented full protocols of simulated firefighting activities in ambient conditions [42]–[44], [46] and live fire environments [11], [14]. Testing in ambient conditions may not be able to produce comparable heat stress to that experienced during live firefighting. Live fire drills can replicate the environmental conditions of firefighting, but at a higher cost and risk of injury. Moreover, limitations on the operational temperature ranges of some data collection equipment present restrictions to the capturing of metabolic data in live fire environments. Finally, in both ambient and live fire environments, it is difficult to control for temperature and humidity. Thus, performing a more comprehensive set of simulated firefighting activities in a temperature and humidity controlled environmental chamber may provide a safe, controlled alternative to live fire testing still capable of replicating the workloads and heat stresses experienced during live fire activity. Such a protocol could be applied toward the development of a standard for fatigue testing in firefighters.

Fatigue is a common occurrence during firefighting tasks due to their intense nature. Exposure to high temperatures and the associated heat stress has been shown to have detrimental physiological and psychological effects on firefighters, not least of which is a faster onset of muscular fatigue [35], [37], [48], [82], [83]. Earlier onset of fatigue can have adverse effects on situational awareness and balance, and potentially cause increased risk of an STF injury. The effects of fatigue on civilian populations have been studied extensively, and have been shown to cause decreases in postural stability [84]–[89]. Other studies have shown fatigue to cause poor sense of joint position which may lead to increased likelihood of contacting an obstacle during crossing [90], [91].Fatigue has also been shown to decrease obstacle clearances in normal and elderly populations [65] and increase the frequency of obstacle contact errors [14]. Based on the results of these studies, fatigue could possibly cause increased risk of STF injury during obstacle crossing in firefighters, necessitating further study.

Firefighters are commonly required to carry heavy loads in the form of their SCBA while performing duties on the fireground. The effects of load carriage on gait performance have been shown to be proportional to the weight of the load. Increasing loads carried on the back have been shown to decrease dynamic stability during level walking [21], [98]–[104]. Some studies have also reported increased gait variability and changes in joint kinematics [101], [103], [105], [106]. Park et al. determined that carrying heavier SCBA on the back decreased lead foot vertical and horizontal and trailing foot vertical clearances [13]. These results suggest that firefighters may be at greater risk of falls when carrying loads during obstacle crossing. Furthermore, the limited quantity of literature available calls for additional investigation into loaded obstacle crossing.

Firefighters are often forced to carry loads in addition to their SCBA, such as tools and hose packs. Oftentimes it is impossible to carry these loads symmetrically. Studies on the carriage of unilateral loads during level walking have shown asymmetry in joint kinematics between the sides of the body ipsilateral and contralateral to the load, indicating reduced gait performance [23]–[25]. Studies have also shown that asymmetrical loads increase stress on the back [23], and that prolonged carriage of asymmetrical loads result in higher instances of neck, shoulder, and back disability [26]. Based on these results, carriage of asymmetrical loads may have detrimental short term and long term effects. Thus, their influence on obstacle crossing performance is worth studying.

The objective of this study was to examine the effects of simulated firefighting exercise protocol, fatigue (pre to post exercise), and the presence of an asymmetrical hose load on contact errors, obstacle clearances, peak normalized ground reaction forces (GRFs), and RCOFs. Based on the aforementioned literature, the following results were expected:

1) Fatigue brought on from exercise will result in more contact errors and decreases in obstacle clearances, GRFs, and RCOFs.
2) The carriage of an asymmetrical hose load will lead to more contact errors and lower obstacle clearances, but will cause increases in GRFs and RCOFs.
3) Exercise protocols involving simulated firefighting tasks – independent of the exercise environment – will have a greater impact than the treadmill walking protocol on the variables of interest. More specifically, simulated firefighting tasks will lead to more contact errors and more pronounced decreases in clearances, GRFs, and RCOFs.

2.3 METHODS

2.3.1 Subjects

A total of 24 firefighters (23 male, 1 female; age 28.6 ± 7.9 years; height 1.82 ± 0.07m; weight 90.7 ± 14.9 kg) participated in this study. Subjects self-identified as volunteer (n = 14), career (n=8) firefighters, both (n=1), or declined to respond (n=1). Subjects served small metropolitan (n=17), rural (n=5) areas, both (n=1), or large metropolitan areas (n=1). All reported no history of balance or gait impairments, neurological diseases, or vision problems. In addition, none reported any injuries in the two months prior to testing. Each subject signed an informed consent waiver. The study was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign.

Each subject was outfitted in appropriately sized PPE, consisting of boots, pants, jacket, hood, gloves, and helmet (G-Xtreme and Structure Supreme; Globe Manufacturing Company, LLC, Pittsfield, NH, USA). The subject was also equipped with a SCBA system with a standard 4500 psi carbon fiber cylinder rated to provide 45 minutes of air when breathing at a rate of 40 L/min (Firehawk M7; MSA, Inc., Murrysville, PA, USA).

2.3.2 Exercise Protocols

Each subject had a total of four visits to the Illinois Fire Service Institute (IFSI) research center. The first visit served to gather baseline data and to familiarize the subject with the testing equipment and procedure. On each of three subsequent visits, the subject underwent a different exercise protocol. Exercise protocols consisted of one of the following: (1) ECTM - walking on a treadmill in a lighted, temperature and humidity controlled environmental chamber (Frost Environmental Rooms, Houston, TX, USA; 2.9 m wide x 3.4 m long x 2.7 m high; 47°C, 20% humidity), (2) ECFF - simulated firefighting tasks in the same environmental chamber, and (3) BBFF - the same simulated firefighting tasks in a live-fire burn building (135°C at 30 cm below the ceiling, 85°C at 120 cm above the floor 30°C at 30 cm above the floor, and breathing off of the SCBA). Lighting in the burn building was provided only by ambient light from a stoked fire and a flashlight held by a research assistant observer. The three exercise protocols were presented in counterbalanced order to control for learning effects over the course of testing. Visits were separated by a minimum of 24 hours to avoid any potential lingering effects of fatigue or soreness from previous visits.

The specific tasks performed in each exercise protocol were as follows. During the treadmill protocol, subjects walked continuously at 4.5 km/h on a 2.5% incline for 14 minutes after five minutes of seated rest. Several previous studies have used a similar protocol to study the effects of heat stress and hydration on firefighters [29], [31], [33], [37], although the temperature in our study was higher and exposure duration shorter. For the simulated firefighting exercise protocols, four tasks were performed in the following order (***Figure 1***). The first was a stair climb, where subjects climbed the first two steps of a 1.2 m wide three-step staircase, touched both feet to the second step, then descended the steps backwards and touched both feet to the ground. Next was a simulated hose advance, in which subjects kneeled – on one knee and maintaining one foot in contact with the bottom step of the staircase at all times – and extended a section of hose connected to a suspended weight (9.1 kg), touched a target 1.8 m away, and returned the weight to its original position. Third was a secondary search, where subjects crawled about the perimeter of the room while sweeping the wall with a hand, simulating a thorough search. The final task was a ceiling pull, where subjects stood and extended a pike pole connected to a suspended weight (9.1 kg), touched a target 1.8 m away, and returned the weight to its original position. For the hose advance and ceiling pull tasks, subjects were allowed to use any self-selected technique as long as they completed the required range of motion. Each task was performed continuously for two minutes, with a two minute period of seated rest following the first three tasks. The tasks were always presented in this order because the tasks that they are intended to simulate are generally performed in this order during a live fire situation. Upon completion of the fourth task or 14 minutes of treadmill walking, the subject began the functional task course (described below) within 3 minutes. Subjects were instructed to perform the tasks at a self-selected pace intended to match their ordinary effort on the fireground, and were permitted to rest at any point during a task. Subjects were permitted to exit the chamber at any point if they felt that they could not continue or if core temperature rose above a threshold temperature (40°C). For this study, no subjects needed extra rest breaks or terminated testing early.

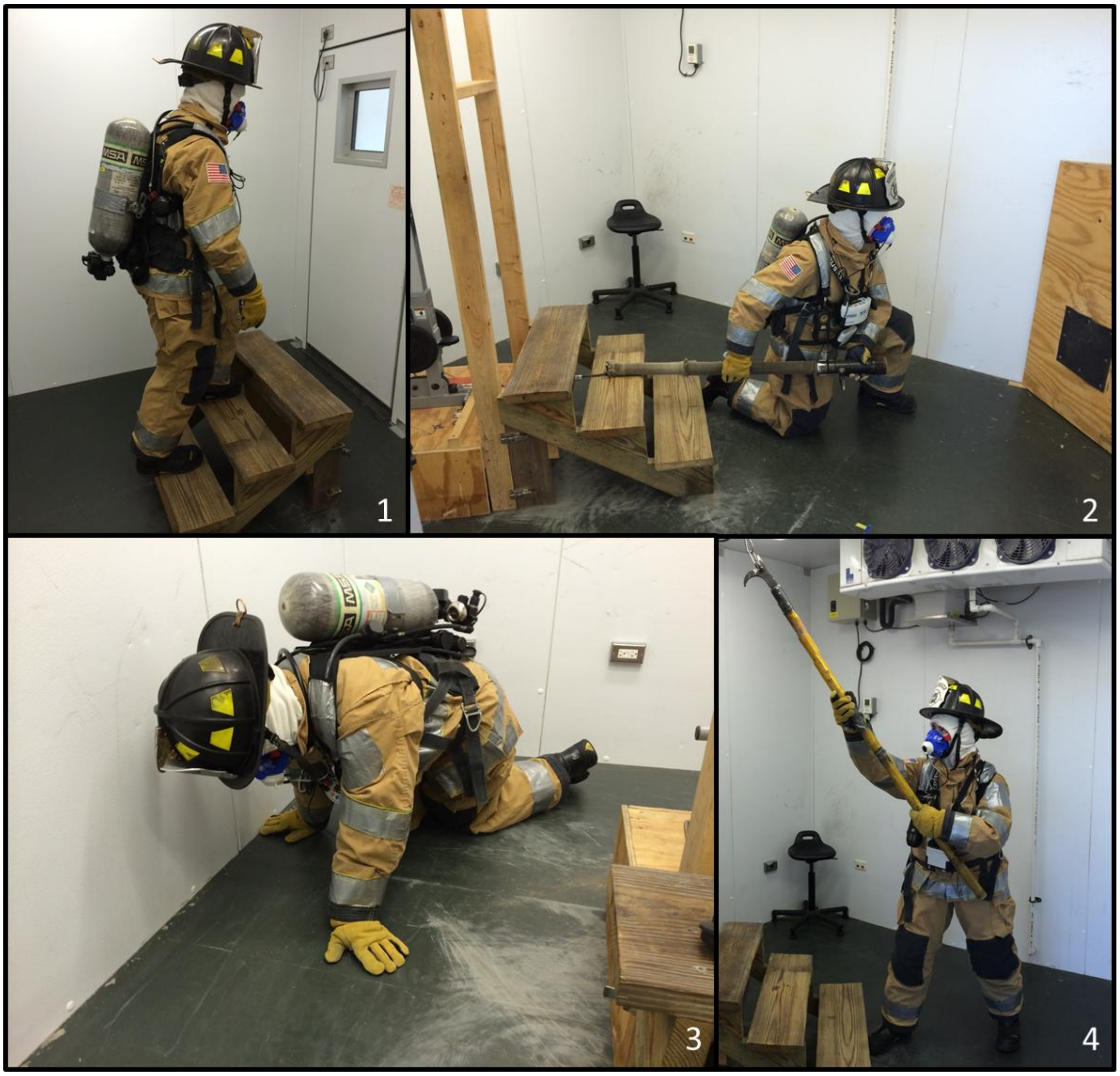

Figure 1. Simulated firefighting tasks: (1) stair climb, (2) hose advance, (3) secondary search, (4) ceiling pull.

Metabolic data were recorded in protocols involving the environmental chamber. Subjects were fitted with a portable respiratory metabolic monitoring system ($K4b^2$; Cosmed, SRL, Rome, Italy) during the first three minutes, followed by a two minute period of seated rest before beginning the exercise protocol. The metabolic monitoring system was calibrated inside the chamber and allowed to acclimate to its environment for approximately 20 minutes prior to the exercise protocol. Due to temperature restrictions on the metabolic monitoring equipment, it was not usable in the burn building. Therefore for the BBFF condition, subjects simply began with five minutes of seated rest in order to maintain a consistent time of exposure to the heated environment. Because firefighters were not able to breathe on air from the SCBA while fitted with the metabolic data collection equipment, full SCBA cylinders were used during the ECTM and ECFF exercise protocols.

2.3.3 Data Collection Procedure

2.3.3.1 Functional Task Course Description

This experiment was a part of a larger study of firefighter biomechanics, consisting of moving through a course of several functional tasks performed in succession by each subject during the data collection trials [110]. The tasks consisted of the following: (1) the obstacle crossing task presented here, (2) ascending and descending a three-step staircase, (3) level walking on an instrumented gait mat (GAITRite; CIR Systems, Inc., Sparta, NJ, USA), (4) passing through an adjustable width gap against a wall, (5) stepping over an adjustable height obstacle, and (6) passing under an adjustable height obstacle.

Each subject's first visit to the IFSI research center was mainly dedicated to determining maximum metabolic output and – after allowing for adequate recovery time – performing pre-testing assessments for several of the functional tasks. One such assessment was finding an appropriate starting position for the obstacle crossing task. One trial in each loading condition was performed in full PPE during this visit, but no obstacle crossing data were collected.

For each exercise protocol test session, data were collected for two sets of four trials – one set before and one set after undergoing an exercise protocol. Within each set, the subject first carried no additional load for two trials, and then carried an 11.3 kg (25 lb) hose load over the right shoulder for the remaining two trials. The PPE hood and SCBA face piece were not worn during these data collection trials.

2.3.3.2 Obstacle Crossing Procedure

For the obstacle crossing task, the subject walked down an elevated walkway (8.25 cm high x 7.5 m long x 1.2 m wide) with one 60 x 90 cm force plate and two 40 x 60 cm force plates (BP 600900 and BP 400600; AMTI, Watertown, MA, USA) embedded on each side of a stationary rectangular frame obstacle (***Figure 2***). Force plates were set up on each side of the obstacle in such a way that when the subject walked down the walkway and stepped over the obstacle, the trailing foot landed on the larger plate and the lead foot landed on one or both of the two smaller plates. The obstacle (30 cm high x 14 cm long x 124.5 cm wide) was constructed from lightweight 1.5 cm diameter PVC pipe. It was not rigidly fixed to the ground so that it would fall away if contacted hard enough, and would not cause subjects to trip and fall.

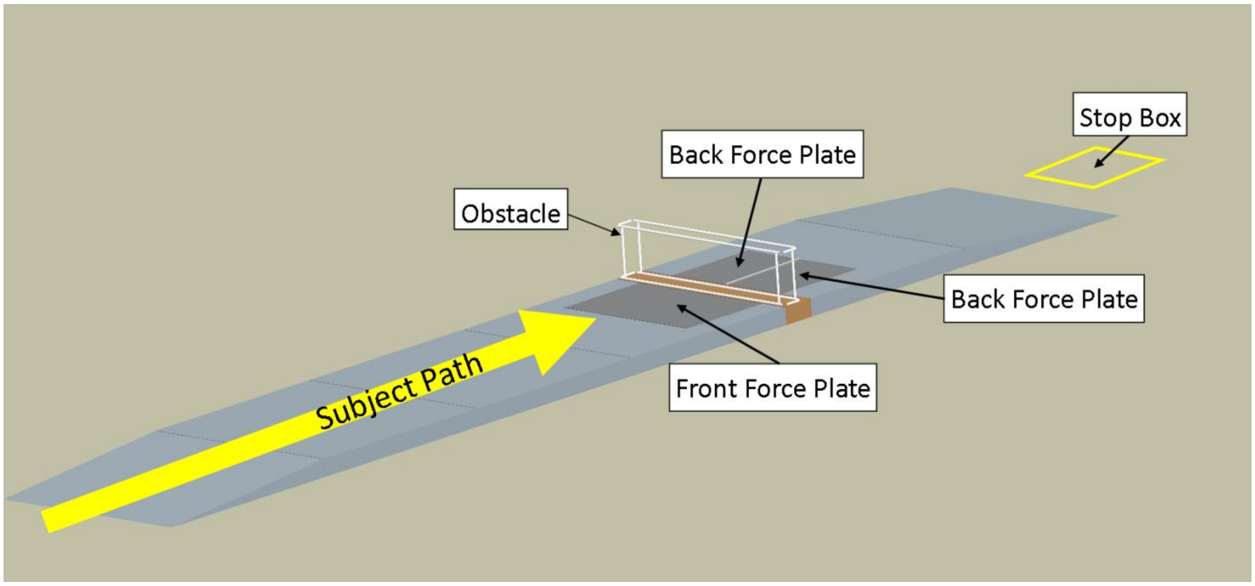

Figure 2. 3D sketch of experimental obstacle crossing apparatus

Each subject began from a start line determined individually on the familiarization day in order to maximize the likelihood of clean force plate strikes. The subject was instructed to walk down the walkway at fireground pace without running or compromising safety, step over the obstacle, and stop in a 60 cm x 60 cm box 12.7 cm from the end of the walkway. Trials in which the subject did not cleanly contact the force plates – i.e. the whole foot did not contact the plate – were excluded from analysis. Further, trials in which the subject contacted or knocked over the obstacle were excluded from analysis of clearances.

Kinematic and kinetic data were collected during each obstacle crossing trial. Ground reaction force (GRF) data were collected via the three force plates, and were sampled at 1000 Hz. Motion data were collected using an eight-camera motion capture system (Oqus 100-Series; Qualisys Motion Capture Systems, Gothenburg, Sweden) and were sampled at 200 Hz. To track the trajectories of the subject's feet and measure obstacle clearances, motion capture markers were fixed to the top four corners of the obstacle and each boot (***Figure 3***).

Figure 3. Boot marker setup. For reference only, offset distances between marker centers and relevant surfaces are identified as A-D. Table lists average (± standard deviation) offset distances in mm over six boot sizes. Reflective areas on boots were covered to prevent cameras from falsely identifying them as markers.

2.3.4 Quantifying Obstacle Crossing

Several measures were employed in order to quantify obstacle crossing performance. Contact errors were defined as any time a subject contacted the obstacle. These were further broken down into minor errors (contacted the obstacle but did not knock it over) and major errors (obstacle fell over).The horizontal and vertical clearances of the lead and trailing feet in the sagittal plane were calculated from the motion capture data (***Figure 4***). The horizontal clearance of the lead foot (HCL) was defined as the horizontal distance between the heel marker of the lead foot at mid stance and the average horizontal position of the two back obstacle markers. Horizontal clearance of the trailing foot (HCT) was defined similarly as the horizontal distance between the toe marker of the trailing foot at mid stance and the average horizontal position of the two front obstacle markers. Previous studies have calculated the horizontal clearances at heel strike [13]. However, calculating the clearances at mid stance may provide a better representation of the positions of the feet during the actual obstacle crossing motion. Vertical clearances of the lead (VCL) and trailing (VCT) feet were defined as the minimum of four values over the obstacle – the vertical distance from the toe marker to the average front obstacle position, the heel marker to the average front obstacle position, the toe marker to the average back obstacle position, and the heel marker to the average back obstacle position when each respective marker crosses the plane of the front or back of the obstacle [13], [49].

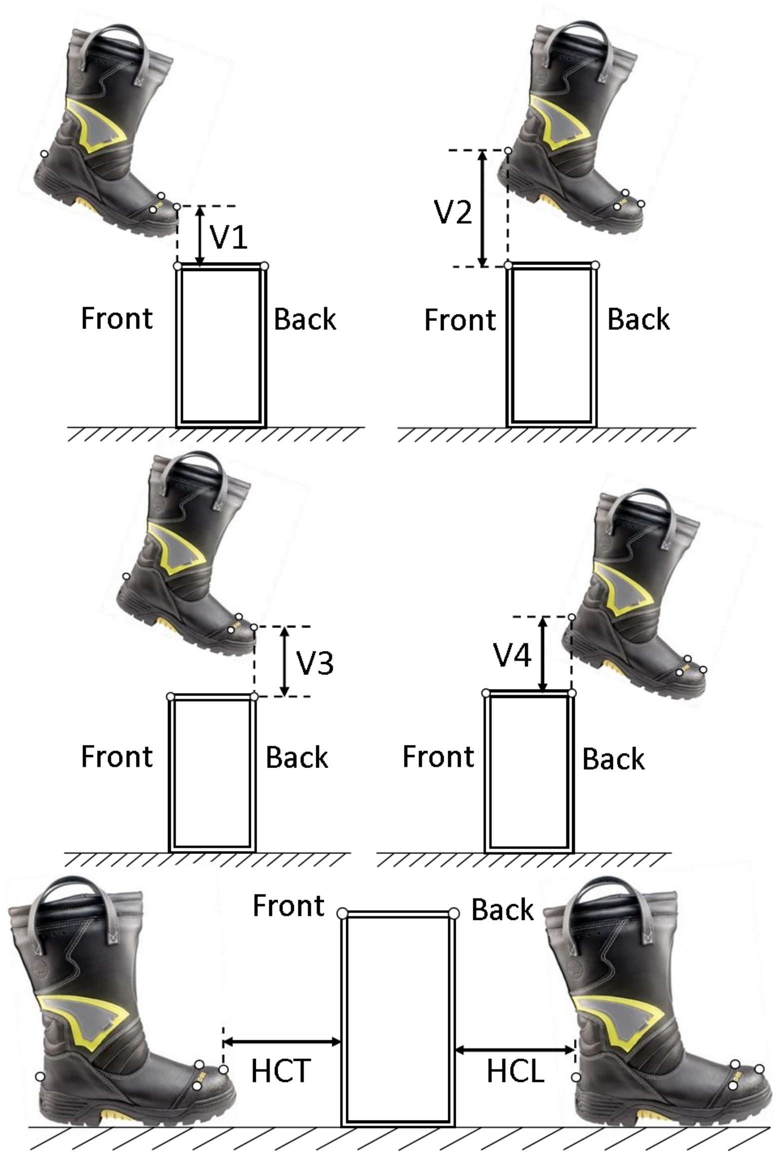

Figure 4. Horizontal and vertical clearance definitions. VCL and VCT are defined as the minimum of V1, V2, V3, and V4.

Several kinetic metrics were also examined. For trailing and lead foot, the early and late stance vertical (GRF_{VTE}, GRF_{VTL}, GRF_{VLE}, GRF_{VLL}) and anterior-posterior (GRF_{APTE}, GRF_{APTL}, GRF_{APLE}, GRF_{APLL}) and total peak medial-lateral (GRF_{MLT}, GRF_{MLL}) normalized peak GRFs were determined using the a similar procedure as in [13]. The vertical GRF mid stance point was identified as the local minimum of the GRF curve. The AP GRF mid stance point was identified as the point at which the force changed direction from posterior to anterior. Because there was no distinct mid stance point in the ML GRF curve, only the total peak force was recorded in that direction (***Figure 5***). The lead foot GRFs were determined by adding together the readings from the two smaller force plates on the far side of the obstacle, which has been shown to be a valid procedure[111]. The peak GRFs were normalized by the subject's weight in full PPE with SCBA.

The required coefficient of friction (RCOF) was determined at heel strike and toe off. The RCOF was defined as follows:

$$RCOF = \left|\frac{F_{AP}}{F_V}\right|$$

Here, F_{AP} is the AP GRF and F_V is the vertical GRF. Several previous studies have defined the RCOF in this manner [56], [58], [112]. Others have used the vector sum of the shear force in the plane of the force plate in place of the AP GRF [55], [57]. However, this approach was not used here due to the small magnitude of the ML GRF relative to the AP GRF. Previous studies have identified six distinct peaks in the RCOF curve over the course of the gait cycle during level walking, and reported the third and fifth peaks for heel strike and toe off, respectively [59]. The same technique was utilized in this study.

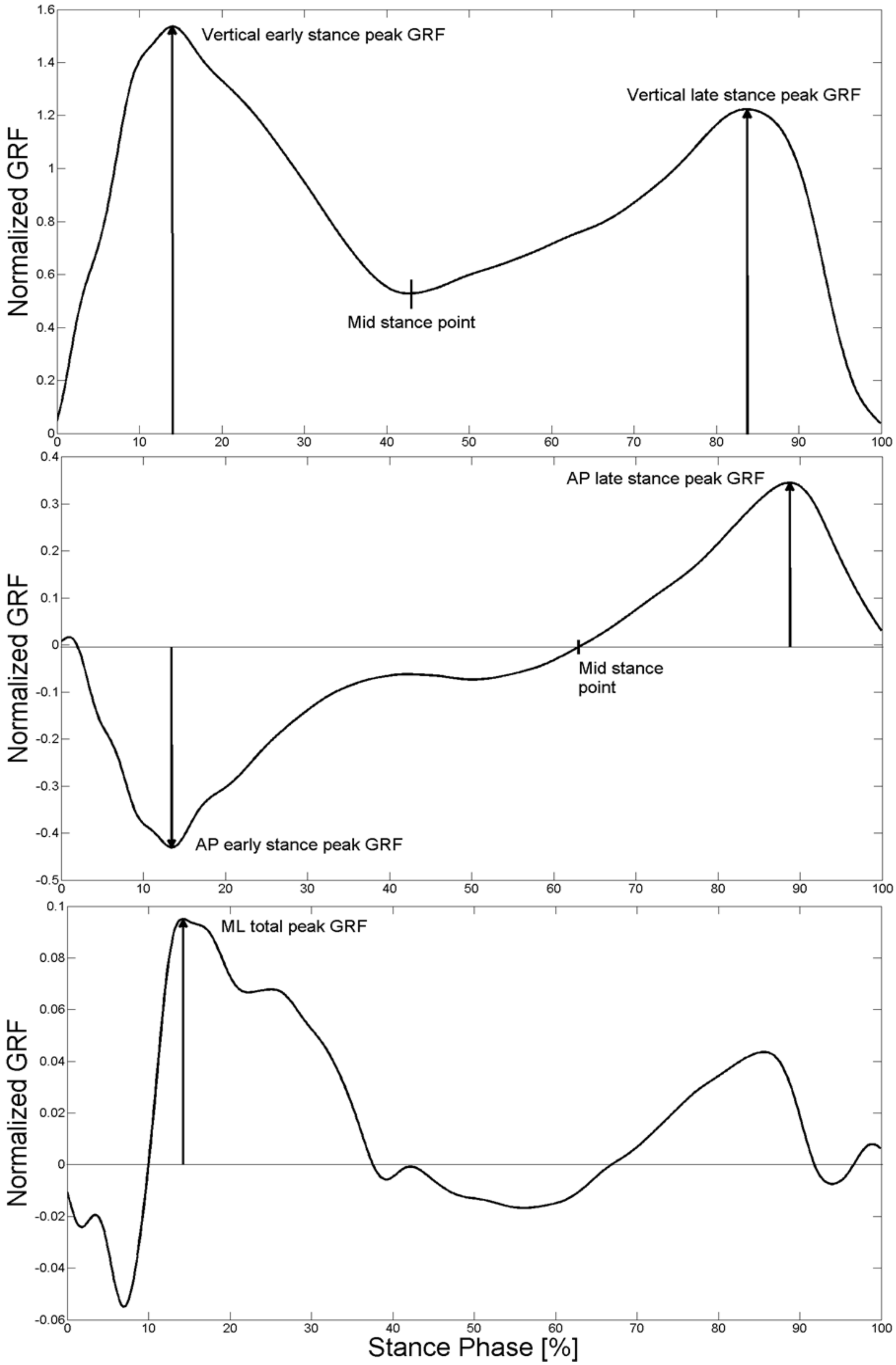

Figure 5. Early and late stance vertical and AP normalized peak GRFs and total normalized peak ML GRFs.

2.3.5 Data/Statistical Analysis

Several analysis techniques were employed in this study to assess contact errors and obstacle clearances in cases when no contact occurred. Unfortunately, much of the kinetic data were not able to be analyzed due to technical problems. As a result, no analyses of GRF or RCOF data were performed.

Obstacle contact errors were recorded and totaled both by testing conditions and by individual subjects. Error totals were analyzed by testing condition simply by separating them into major and minor categories and considering the contribution to the total number of errors made up by each condition. Analysis by subject was carried out by dividing the subjects into three groups depending on the number of errors committed over the course of all three testing sessions (0 errors, 1-3 errors, and 4+ errors). A one-way multivariate analysis of variance (MANOVA) was performed to identify any differences among subject groups in terms of age, experience, height, leg length, weight, and BMI.

A three-way (3×2×2) repeated measures (RM) MANOVA was performed to study the effects of exercise protocol (3), asymmetrical load carriage (2), and fatigue (2) on the obstacle clearance variables (HCT, HCL, VCT, VCL). Clearances were averaged over two trials per condition prior to statistical analysis. Because there were minor differences among the average pre-exercise results, the percent differences between pre- and post-exercise measures were computed, and two-way (3×2) RM MANOVAs were also performed. Percent increase with fatigue for a given variable was defined as follows:

$$D = \frac{P_{post} - P_{pre}}{P_{pre}} 100\%$$

Here, P_{pre} is the value of the variable before undergoing an exercise protocol, and P_{post} is the value of the variable after the exercise protocol. These MANOVAs served as a check to ensure that any exercise protocol effects seen in the original MANOVA were not due to differences in pre-exercise conditions across different visit days.

A significance level of $\alpha = 0.05$ was selected for all statistical analyses. Tukey honestly significant difference (HSD) tests were performed to examine interaction effects. All statistical tests were carried out using SPSS v20 (IBM Corp., Armonk, NY, USA).

2.4 RESULTS

This study aimed to quantify obstacle crossing by measuring contact errors, obstacle clearances, peak GRFs, and RCOFs. All of the subjects completed all three exercise protocols start to finish.

2.4.1 Contact Errors

Contact errors were broken down into minor and major categories, and analyzed in terms of the test conditions in which they occurred. Individual subjects were then separated into groups based on the number of contact errors they committed over the course of testing to identify any potential subject characteristics which may be related to the frequency of the occurrence of obstacle contact. All of the original 24 subjects were included in the analyses of contact errors.

Contact errors appeared to be most dependent on exercise protocol and fatigue (Table 1). There were slightly fewer contact errors following the ECTM condition compared to the ECFF and BBFF conditions (9 contact errors vs. 12 contact errors for both other cases). More contact errors occurred post-activity versus prior, with 27 of 58 minor contact errors (56%) and 6 of 7 (85.7%) of major contact errors occurring post-activity. However, eight contact errors – an unusually high number in comparison to the other two exercise protocols – occurred during the unloaded, pre-activity trials for the BBFF protocol. The presence of an asymmetrical hose load did not appear to influence contact error counts, with approximately equal numbers of both minor and major contact errors occurring in the unloaded and loaded cases. However, four of the six post activity major contact errors occurred during trials with hose load present. Approximately 87% of all contact errors were considered minor. Trailing foot contact errors were far more frequent, accounting for over 92% of all contact errors committed (51 / 55) (***Figure 6***).

Table 1. Contact error totals by condition and fatigue.

	ECTM		***ECFF***		***BBFF***		
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	***Totals***
Minor	5	9	4	8	12	10	**48**
Major	0	0	0	4	1	2	**7**
Totals	**5**	**9**	**4**	**12**	**13**	**12**	**55**

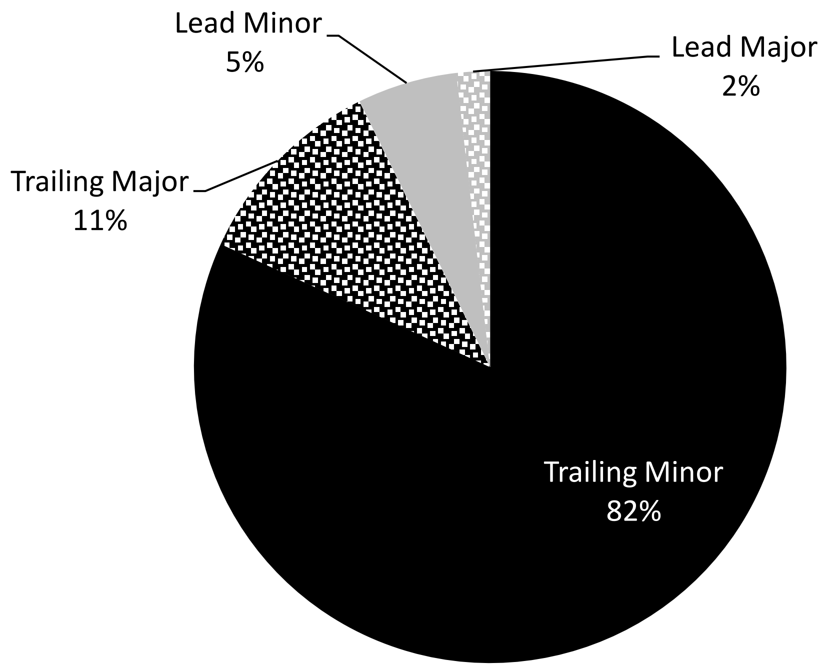

Figure 6. Breakdown of total contact errors by lead / trailing foot and severity.

Subjects were binned into three groups based on the number of contact errors that they committed over the course of the study (No errors, 1-3 errors, or 4+ errors). The one-way MANOVA revealed that the group of subjects (n=10) who committed no contact errors over the course of the study were significantly taller(average of 9.6 cm; p = 0.002) and had longer legs (average of 5.6 cm; p = 0.024) than the other two groups (n=8, n=6).This group was also, on average, significantly older than the other two groups (average of 8.4 years; p = 0.024), although the standard deviation of age in this group was also much larger than that of the other two groups (***Table 2***).

Table 2. Contact errors by subject characteristics. Data presented as average standard deviation. An asterisk (*) denotes significant difference from the 1-3 errors group. A plus ($^+$) denotes significant difference from the 4+ errors group.

	Age [years]	***Experience [years]***	***Height [cm]***	***Leg Length [cm]***	***Weight [kg]***	***BMI [kg/m^2]***
0 Errors (n=10)	$*^+$33.6 ± 9.0	7.9 ± 6.5	$*^+$187.7 ± 5.8	$*^+$99.9 ± 3.7	97.0 ± 13.7	27.5 ± 3.4
1-3 Errors (n=8)	24.4 ± 2.9	3.2 ± 1.9	177.6 ± 4.3	93.8 ± 5.2	90.1 ± 11.2	28.4 ± 2.9
4+ Errors (n=6)	26.0 ± 4.9	7.3 ± 4.2	178.6 ± 5.2	94.9 ± 4.0	81.2 ± 14.5	25.3 ± 3.3

2.4.2 Clearances

Of the original 24 subjects for whom data were collected, 17 were included in the analysis of the clearances. The other seven subjects were excluded because they had made errors during two trials of the same condition.

Horizontal and vertical obstacle clearances of each foot (HCL, HCT, VCL, VCT) were analyzed via a three-way (3 ×2×2) RM MANOVA. The MANOVA revealed significant main effects due to asymmetrical hose load carriage ($p < 0.001$) and fatigue ($p = 0.017$), but not due to exercise protocol. It also showed significant interaction effects of exercise protocol× fatigue ($p = 0.012$) and asymmetrical load × fatigue ($p = 0.014$). Follow up univariate RM ANOVAs revealed significant effects of load carriage on HCL ($p < 0.001$) and VCL ($p = 0.043$) (***Figure 7***). HCL decreased by an average of 3.1 cm when the hose load was applied, while VCL increased 0.9 cm. Univariate ANOVAs also revealed significant effects of fatigue on HCL ($p = 0.012$) and VCT ($p = 0.025$) (***Figure 8***), causing average reductions of 1.8 cm and 1.6 cm, respectively, after exercise.

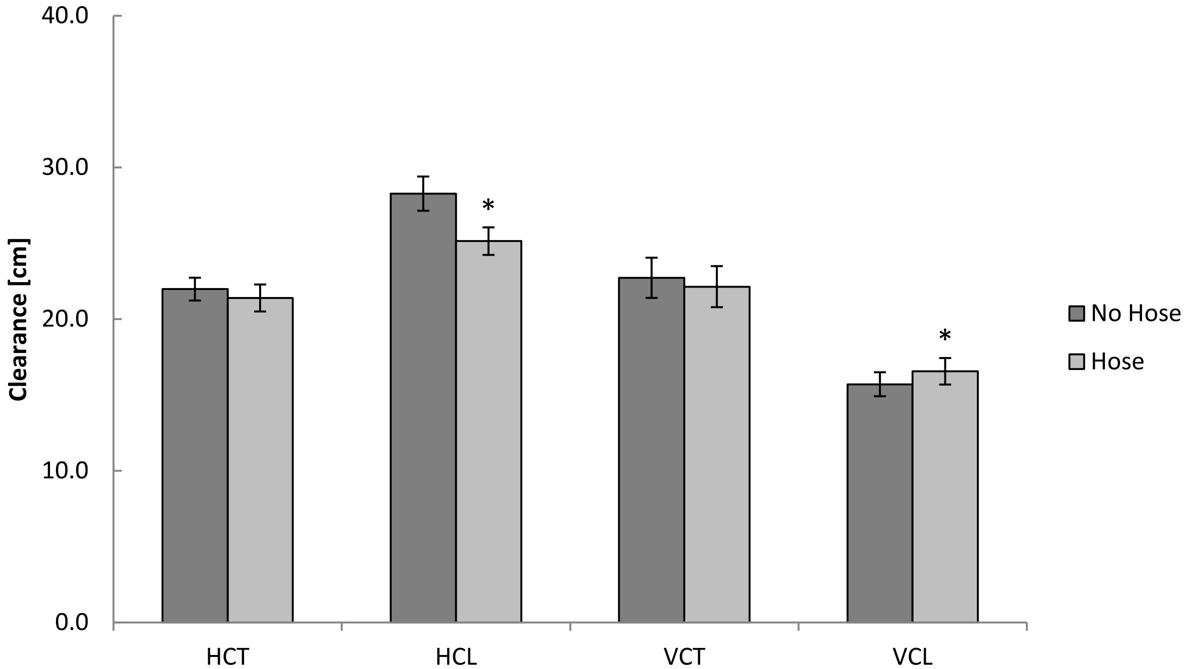

Figure 7. *Obstacle clearances by presence of an asymmetrical hose load. An asterisk (*) indicates significant difference from the unloaded condition. Error bars represent standard error.*

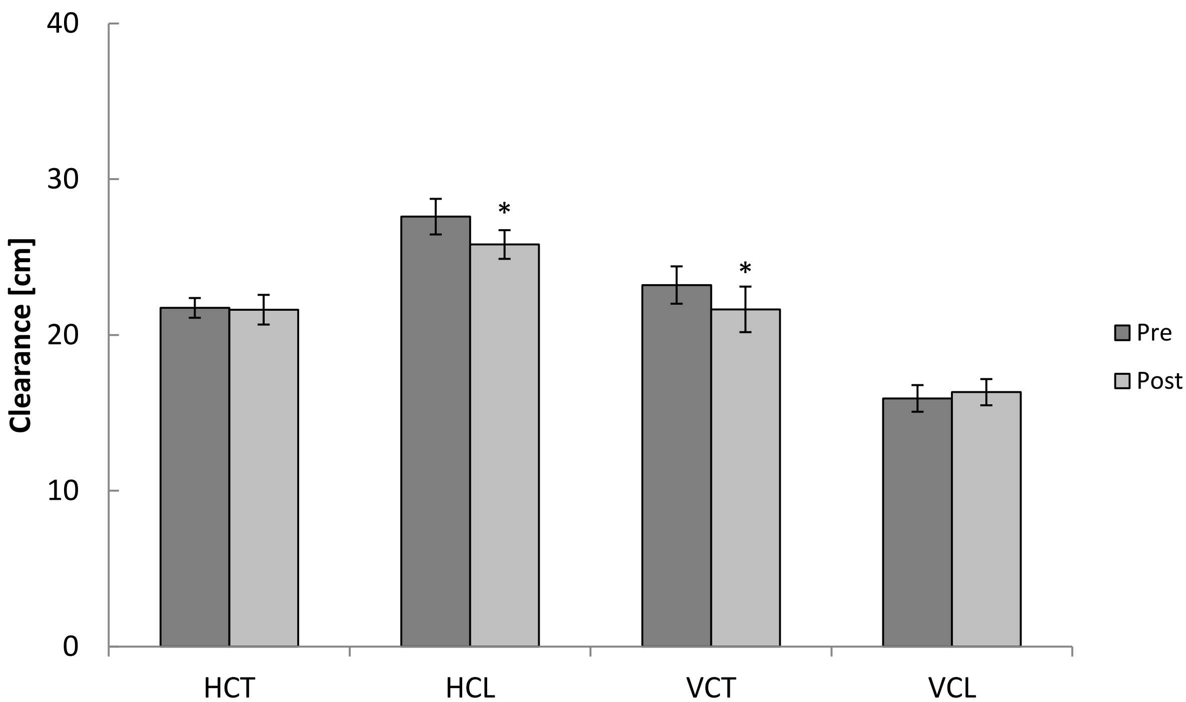

Figure 8. *Obstacle clearance by testing period. An asterisk (*) indicates significant difference from the pre-exercise condition. Error bars represent standard error.*

Follow up univariate ANOVAs also revealed significant interaction effects of protocol × fatigue on HCL ($p = 0.035$) and VCL ($p = 0.036$) (***Figure 9***) and of asymmetrical load × fatigue on VCT ($p = 0.024$) and VCL ($p = 0.003$) (***Figure 10***). Results showed that HCL generally decreased from pre to post activity for the ECFF and BBFF protocols, but stayed approximately the same before and after activity for the ECTM protocol. VCL generally remained consistent before and after activity for the ECFF and BBFF protocols, but increased from pre to post activity for the ECTM protocol.

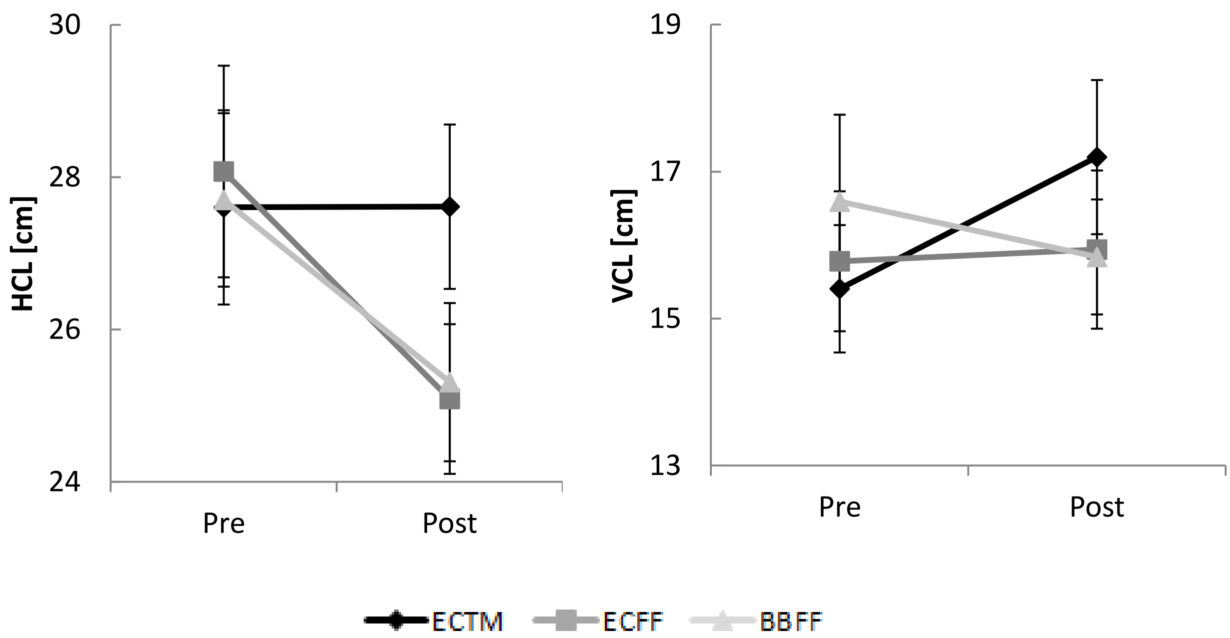

Figure 9. HCL and VCL by condition × fatigue. Error bars represent standard error.

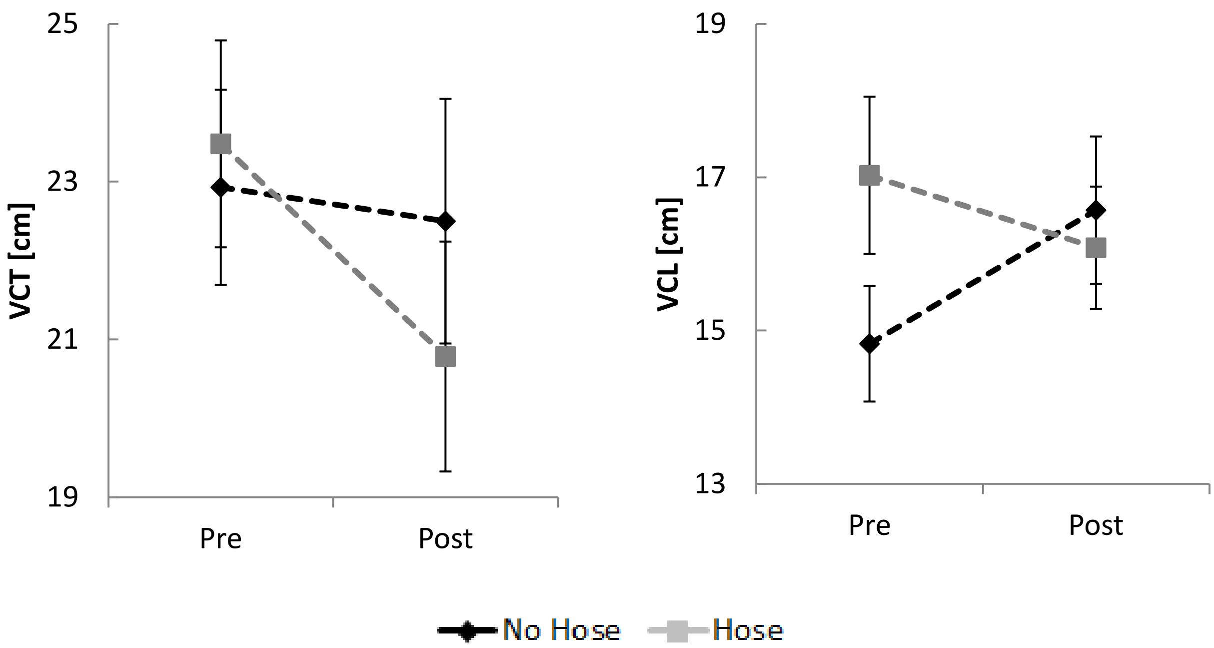

Figure 10. *VCT and VCL by load × fatigue. Error bars represent standard error.*

As a side study, clearance variables were normalized by individual subject leg lengths to attempt to control for the wide range of heights among subjects. Normalization by leg length did not change the significance of the results. Therefore, we chose to report the non-normalized data, as it may be more intuitive to view the changes in clearances as centimeter values rather than nondimensional quantities.

2.4.3 Kinetic Data Acquisition Issues

Unfortunately, technical problems with kinetic data acquisition equipment resulted in saturation of much of the GRF data. As a result, the majority of the kinetic data were rendered unusable. Acceptable data were only collected from six subjects. Among these, three would have been excluded from analysis as a result of not cleanly striking the force plates. Therefore, kinetic analysis was not carried out for this study as a result of the limited availability of serviceable data.

2.5 DISCUSSION

The goal of this study was to examine the effects of exercise protocol, asymmetrical load carriage, and fatigue on obstacle crossing performance, quantified by contact errors and foot clearances. Contact error totals appeared most affected by exercise protocol and fatigue. Clearances showed statistically significant differences due to asymmetrical load carriage and fatigue, as well as interactions of exercise protocol × fatigue and load × fatigue.

Contact error totals increased with fatigue. These results are in agreement with previous studies which have shown that frequency of contact errors is related to fatigue [14]. Fatigue has also been shown to reduce stability and lower limb control [85], [86], [91], [105]. The majority of contact errors were committed with the trailing foot. A possible cause is that limited visual feedback is available for control of the trailing foot during obstacle crossing. Visual feedback has been shown to be important for maintaining dynamic stability and control during many locomotion tasks, including obstacle crossing [62], [63], [113], [114], and plays an important role in compensating for muscle fatigue in postural control [115]. Muscular fatigue has been shown to detrimentally affect sense of joint and limb position [90], [91] – an effect which is likely compounded by the lack of visual feedback. This combined effect may have contributed to the higher occurrence of post-exercise trailing foot errors. These results indicate an increased risk of obstacle contact when fatigued, which can potentially lead to STF occurrences. The literature suggests that lead foot errors pose a greater threat to safety than trailing foot errors [116]. However, this is not to say that trailing foot errors do not result in falls, and their high frequency only increases the odds of an STF injury.

Contact error totals increased after exercise, with larger increases following the simulated firefighting activity protocols ECFF and BBFF (***Table 1***). There were no differences in the visual information available following each protocol, so the higher contact error totals with the ECFF and BBFF protocols may suggest that performing simulated firefighting activities induces a higher degree of fatigue than the ECTM protocol, resulting in poorer control of the lower limbs. The simulated firefighting activities protocols involve more anaerobic tasks which force the subject to use a wider variety of muscle groups compared to the more aerobic treadmill task. It can also be inferred from the lack of apparent differences between the ECFF and BBFF protocols in post-exercise error totals that the physical fatigue induced by simulated firefighting activities performed in an environmental chamber versus a live-fire environment is similar. Analysis of the physiological data (e.g. heart rate, core temperature and oxygen consumption) collected in this study may help to support this conclusion. These physiological data can provide insight into physical exertion levels by quantifying metabolic output during each protocol. These results suggest that fatigue may be the most critical risk factor for obstacle contact, which can potentially lead to STF fireground injuries.

The lack of apparent effects of the asymmetrical hose pack on the contact error totals is somewhat surprising, as previous studies have shown that unilateral loads negatively affect level gait performance by inducing asymmetries between the loaded and unloaded sides of the body [23]–[26], [117]–[119]. However, unlike level ground walking, the motions required for successful obstacle crossing differ between the lead and trailing foot. As such, it is possible that the gait asymmetries induced by carrying the asymmetrical hose load may not have had as serious of implications on obstacle crossing safety as have been observed in level ground walking.

Several of the obstacle clearance variables significantly decreased with fatigue. The decrease in HCL shows that the lead foot landed closer on average to the obstacle following crossing, which may be an indicator of increased risk of obstacle contact with the lead foot. In addition, the decrease in HCL and lack of significant change in HCT following exercise for all three protocols points to a decrease in step length when crossing the obstacle, and may indicate that subjects tended to cross the obstacle later in the stance phase. Studies have seen this behavior in elderly individuals [67], [68], [120] and populations with neurological impairments [70], [73], [75], [81], and have suggested that it is a compensatory strategy to account for a loss of lower limb control. Crossing the obstacle later in the stance phase allows for a longer period for which visual feedback is available, which may facilitate control of the lead foot during crossing [120].The significant decrease in VCT with fatigue is in agreement with the increased contact error totals, indicating that the trailing foot came closer on average to contacting the obstacle when the subjects were fatigued. This result in combination with the lack of significant changes in VCL further supports the conclusion that fatigue compounded with a lack of visual feedback increases risk of trailing foot obstacle contact.

In contrast to the contact error results, clearances also showed significant effects of asymmetrical load carriage (***Figure 7***). The effects of the presence of the hose load were similar to those of fatigue on the horizontal clearances, with HCL decreasing significantly while HCT changed little. This, again, may signify increased risk of lead foot obstacle contact when carrying the hose load, as the lead foot landed closer to the obstacle after crossing. These results also indicate shorter step length and crossing of the obstacle later in the stance phase, which implies a more cautious strategy which may provide better visual information during lead foot crossing [120]. VCL increased significantly in the presence of the hose load. This may be another compensatory strategy employed by lifting the lead foot higher above the ground to ensure obstacle clearance [70]. Also, if subjects chose to cross the obstacle with their left foot leading (opposite the hose load), the presence of the load may actually have facilitated lead foot crossing. It has been shown that carriage of an asymmetrical load resulted in larger hip and knee joint moments on the limb opposite of the load [23]. These joints are known to contribute most to lead limb obstacle crossing [121]. However, it has been suggested that this strategy may be inefficient from an energetics standpoint [114]. It also may place larger stability demands on the trailing limb by increasing single leg stance time while crossing [70], an unstable behavior which can be hazardous on the fireground, particularly when dealing with uneven terrain.

The protocol × fatigue interaction effects on HCL and VCL support the original hypothesis that exercise in the ECFF and BBFF conditions results in similar degrees of fatigue, while exercise in the ECTM condition is less strenuous (***Figure 9***). For both variables, the trends from pre to post exercise are similar for ECFF and BBFF, but are clearly different for ECTM. These results suggest that the ECFF protocol is a suitable substitute for the BBFF as a method for simulating fireground activities and inducing fatigue.

The load × fatigue interaction effects on VCT and VCL suggest that the effects of fatigue are amplified by the application of an asymmetrical load (***Figure 10***). Reduction in VCT from pre to post exercise was larger in the presence of the load. Further, VCL increased following exercise in the absence of the load, but decreased following exercise when the load was applied. The literature suggests that asymmetrical load carriage results in decreased hip and knee joint moments on the loaded side. It has also been shown that asymmetrical load carriage can cause muscles opposite from the load to contribute to stabilization when they are typically used for maintaining proper pelvic orientation [23], [24]. If subjects crossed the obstacle with their lead foot contralateral to the load, it is possible that fatigue further decreased the trailing knee joint moment, resulting in lower VCT. Fatigue may also have reduced subjects' ability to maintain proper hip height in the presence of the load, negating the compensatory strategy likely employed without the load and causing VCL to decrease following exercise. If subjects crossed the obstacle with their loaded side foot leading, it may be that, when fatigued, subjects were unable to maintain hip height during trailing foot swing over the obstacle, leading to lower VCT. They also may not have been able to generate the necessary lead limb hip and knee moments with the load applied to employ strategies to compensate for fatigue, resulting in the decrease in VCL.

There are several implications of these results. First, it appears that the ECFF and BBFF protocols induce a similar level of fatigue, greater than that induced by the ECTM protocol. The ECFF protocol facilitates control of the environment and may be safer and less expensive to operate than the BBFF protocol as it eliminates live fire and its associated dangers. Thus, ECFF may provide a safer and more economical alternative to BBFF while still prompting workloads comparable to those experienced in live fire conditions, and can be considered for the development of a standard protocol for simulated firefighting activities. In addition, fatigue can have negative effects on a firefighter's ability to cross stationary obstacles by impairing limb position sense and potentially inciting compensatory strategies which may reduce dynamic stability. Finally, the carriage of unilateral loads can result in gait asymmetries which may lead to decreased obstacle crossing ability, particularly when fatigued. Understanding and spreading awareness of these effects may be an important step in reducing the occurrence of STF fireground injuries.

2.6 CONCLUSIONS

This study aimed to quantify the effects of exercise protocol, asymmetrical load carriage, and fatigue on firefighters' ability to traverse stationary obstacles. Results showed increases in contact errors following exercise, particularly for ECFF and BBFF protocols. Clearances were significantly affected by both fatigue and the presence of a unilateral hose load. These results suggest that firefighters may employ compensatory strategies to ensure obstacle clearance when fatigued or carrying unilateral loads. These results also support the hypothesis that the strain brought on by the ECFF and BBFF protocols is similar, but greater than that of the ECTM protocol, and can thus be applied to the development of a standard for simulated firefighting in a safe, controlled environment. These results may also ultimately lead to a reduction in fireground injuries by improving situational awareness and understanding of how fatigue and load carriage can impact movement behavior on the fireground.

CHAPTER 3: EFFECTS OF SCBA DESIGN, FATIGUE, AND EXTENDED DURATION FIREFIGHTING ON OBSTACLE CROSSING

3.1 ABSTRACT

Increasing numbers of fire departments are moving toward larger capacity self-contained breathing apparatus (SCBA), allowing for longer periods of continuous firefighting. Designs with novel pack and cylinder geometries are being developed to improve biomechanical compatibility. This study analyzed the effects of varying SCBA size and design as well as fatigue levels on obstacle contact errors, clearances, and peak ground reaction forces (GRFs). Thirty firefighters used each of four SCBA: standard cylinders providing 30-, 45-, and 60-minutes of air when breathing at 40 L/min (S30, S45, S60), and low-profile prototype (P45, 45-minute) (MSA, Inc.; Murrysville, PA, USA). Before and after an exercise protocol, participants completed two trials of a five station functional task course, one station of which included traversing a stationary obstacle (30 cm high x 14 cm long x 125 cm wide). Participants performed a simulated firefighting activity protocol consisting of two minutes each of four tasks with two-minute rests between tasks. Stair task: stepping up/down a 2-step stair. Hose advance: kneeling, repeated extension-retraction of hose end attached to 9.1kg. Secondary search: floor crawling about room perimeter. Ceiling pull: standing, extension-retraction of 1.7 m pole attached to 9.1kg. On separate days, firefighters completed one round of the simulated firefighting activity protocol (1R), two rounds with a five-minute rehabilitation break and bottle change(2R), or two rounds back-to-back without a break or bottle change (BB) in an environmental chamber (47°C, 20% humidity).Obstacle contact errors, radial lead and trailing foot obstacle clearance magnitudes (CL, CT) and angles (θ_L, θ_T), peak boot heights (hL, hT), classic lead and trailing foot horizontal and vertical clearances (HCL, HCT, VCL, VCT) and normalized peak GRFs were recorded.

Effects of SCBA size or design were minimal on all outcome variables. CL and θ_L increased significantly following exercise (average increase 1.25cm, $p<0.05$) for every test condition. CT decreased from 1R to 2R for both S30 and S60 (1.8cm ($p=0.023$) and 2.2cm ($p=0.046$), respectively). There were no significant differences between 2R and BB. GRFs showed significant effects following exercise, with more pronounced changes following extended duration protocols. These results suggest that the effects of SCBA size and design on obstacle crossing ability are minimal, while fatigue – particularly that induced by extended duration firefighting – increases the likelihood of obstacle contact and thus risk of STF injury.

3.2 INTRODUCTION

Slip, trip, and fall (STF) injuries are some of the most commonly occurring fireground injuries. Approximately 8,000 fireground injuries per year are the results of STFs [1]–[3]. About one third of moderate to severe (the highest rate among all injury types) and over 20% of minor fireground injuries were attributed to STFs from 2007 through 2011 [4]. Not only do STFs pose a safety risk on the fireground, but their economic impact has also been substantial. A 2003 study of worker's compensation claims regarding injuries among firefighters between 1995 and 1999 estimated an average net cost of $8,662 per STF claim. In contrast, the overall mean total cost for all fireground injuries was $5,168, substantially below the STF average (both figures reported in 1997 USD) [5]. Because the injuries associated with STFs are often moderate to severe, they also often result in extended periods of work absence, reportedly up to 160 hours [6]. A 2008 survey conducted by Petrucci et al. discovered stepping over stationary obstacles and hose lines to be among the leading causes of STF fireground injuries [7]. Based on the high frequency and generally severe medical and economic impacts of STF fireground injuries, further examination of the risk factors leading to such injuries during potentially risky tasks such as the crossing of stationary obstacles is warranted.

While responding to most calls, firefighters are generally required to wear full personal protective equipment (PPE), which is composed of insulated pants, jacket, gloves, boots, fire resistant hood, helmet, and self-contained breathing apparatus (SCBA). Studies have shown numerous detrimental effects on locomotor ability caused by donning PPE including limited mobility and range of motion [8], [16], reduced balance and stability during gait [9]–[11] and weakened performance in the negotiation of stationary obstacles [13]–[15]. The SCBA has been cited as the single piece of equipment most detrimental to movement capability [16]. Based on these negative impacts of PPE, it can be reasonably concluded that wearing PPE increases firefighters' risk of STF injury. This risk may be amplified while fatigued from carrying out strenuous activity. Further study is needed to investigate these factors.

The traversing of stationary obstacles is common task required during locomotion, both on the fireground and in everyday life. The literature regarding obstacle crossing gait is wide ranging. Numerous studies have shown that vision plays a key role in obstacle crossing ability, with obstructed vision of the obstacle causing gait changes which may decrease performance [62]–[64]. Firefighters' face pieces limit peripheral vision, which could result in lessened safety and increased risk of obstacle contact. Obstacle crossing gait has also been studied in populations at higher risk of falls, including older adults and those with neurological impairments such as stroke [70]–[73], Parkinson's [74]–[76], Alzheimer's [77], and traumatic brain injury [78]–[81]. Many of those studied displayed differences in obstacle crossing gait when compared to matched controls, likely due to compensatory strategies for their impairments. Comparing the characteristics of firefighter obstacle crossing and how they change in response to factors such as fatigue and load carriage to the obstacle crossing behaviors of populations at higher fall risk may help to identify those factors that contribute most significantly to firefighter STF injuries involving stationary obstacles.

A key piece of equipment included in the PPE ensemble is the SCBA, as it provides a breathable air supply in harmful environments. While the SCBA is vital to a firefighter's survival, it also embodies a heavy load that the firefighter must carry on the fireground. Furthermore, higher capacity SCBA cylinders, which provide more air at the expense of added size and weight, are becoming more widely available. Park et al. determined that carrying heavier SCBA decreased obstacle clearances and increased the frequency of obstacle contact errors [13]. Perry et al. showed a similar reduction in obstacle crossing performance with increasing weights of loads carried anterior to the body [27]. Aside from these studies, however, the literature concerning loaded obstacle crossing is sparse and calls for validation. Various studies have been carried out on the effects of load carriage on gait performance, generally showing a direct relationship between the severity of the effects and the weight of the load. Higher back-borne loads have led to poor dynamic stability during level walking [21], [98]–[104]. Several studies have discovered increased gait variability and changes in joint kinematics as a result of increased load carriage [101], [103], [105], [106], results which have been linked to increased risk of falls [107]. Based on the results of these studies, the carriage of heavier SCBA may reduce firefighters' gait and obstacle crossing performance, placing them at greater risk of STF injury. As such, further investigation into loaded obstacle crossing is warranted.

In addition to the size of SCBA used by firefighters, the ergonomic design of the SCBA is also of interest. Studies have shown that firefighters tended to perform better in simulated fire rescue tasks when equipped with SCBA which distributed weight closer to the body's natural center of mass [46], [108].Further studies have examined different load distribution systems for military personnel. These studies have shown benefits such as gait patterns being more similar to unloaded walking and improved physiological performance when using configurations which place the load closer to the waist [100], [109]. Others have shown load carriage systems which evenly distribute weight between the anterior and posterior sides of the body to have similar effects on walking gait in civilian populations [99], [101]. However, Park et al. observed no advantages in obstacle crossing when using a SCBA designed to shift the COM lower toward the waist [13], and decreased obstacle crossing performance when subjects wore unfamiliar PPE [14]. Most firefighters are not experienced with novel SCBA designs, so their ergonomic benefits may not be immediately apparent. As a result, further investigation into the effects of novel, ergonomically-designed SCBA on obstacle crossing performance is needed.

Firefighting is an intense physical activity which inevitably results in muscular and cardiovascular fatigue [38], [45]. The high temperatures encountered during firefighting induce heat stress, which several studies have shown to cause earlier onset of muscular fatigue [35], [37], [48], [82], [83]. Muscular fatigue has been examined abundantly in civilian populations, and has been shown to reduce postural stability during quiet stance [84]–[89]. This may translate to reduced balance during walking and obstacle crossing. Other studies have observed an impaired sense of joint position [90], [91], which may increase the probability of obstacle contact during crossing. In obstacle crossing studies, Barbieri et al. have shown lower limb muscle fatigue to decrease obstacle clearances among younger and older adults [65], while Park et al. have shown fatigue from simulated firefighting tasks to increase the likelihood of obstacle contact errors in firefighters [14]. Considering the outcomes of these studies, it is likely that fatigue is a major factor contributing to obstacle crossing performance and, consequently, the frequency of STF injuries among firefighters.

With higher capacity SCBA cylinders becoming more widely available, firefighting for extended periods of time may become more common. While larger SCBA allow for longer continuous firefighting, it is likely that extended duration firefighting leads to more extreme levels of fatigue and heat stress. Baker et al. have shown that a much longer recovery period was necessary for muscle performance to return to baseline levels following longer duration exercise [93]. Research has been carried out concerning the physiological benefits of recovery periods between multiple rounds of exercise in hot environments, highlighting changes in core temperature as a measure of thermoregulation and heat stress. Many of these studies observed no noticeable effects of rehabilitation on thermoregulation [29], [33], [34], [40], [82], [94], [95], but some have highlighted the importance of cooling [29], [34], [40], [94], [95] and rehydration [33]. The results of these studies suggest that even extended periods of rehabilitation have limited effects without adequate cooling and rehydration. Thus, longer periods of continuous firefighting without pausing to cool off and rehydrate can potentially lead to increased heat stress, which has been shown to expedite the onset of muscular fatigue [40], [42]. As mentioned previously, muscular fatigue is a likely cause of decreased obstacle crossing performance [14], [65]. As such, it is worth examining the effects of fatigue from extended periods of firefighting – both with and without a rehabilitation break – on firefighters' ability to perform functional tasks such as stationary obstacle crossing.

Obstacle crossing kinematics have typically been measured using classic horizontal and vertical foot clearance metrics [13], [49], but these are not the only available metrics. Other studies have implemented novel metrics for measuring minimum foot clearances over obstacles throughout the entire swing phase for both the lead and trailing foot [52]–[54]. However, to the author's knowledge, there has yet to be a systematic comparison of the sensitivity of the classic clearances and radial clearance vectors. As such, it may be worthwhile to calculate foot clearances using both methods and compare them in order to assess the sensitivity of each to changes in obstacle crossing behavior.

The objectives of this study were to examine the effects of SCBA size and design, simulated firefighting exercise duration, and fatigue (pre to post exercise) on contact errors, obstacle clearances, and peak ground reaction forces (GRFs). Based on the information presented previously, the following results were expected:

1) Increasing SCBA size will result in more contact errors and decreases in obstacle clearances (distance, angles, and peak boot height), and peak GRFs.
2) Use of a novel SCBA design will not significantly impact obstacle crossing performance in terms of contact errors, obstacle clearances, and peak GRFs.
3) Fatigue brought on from exercise will result in more contact errors and decreases in obstacle clearances, and peak GRFs.
4) Extended duration simulated firefighting activity protocols will result in increased contact errors and decreases in obstacle clearances, and peak GRFs.
5) Allowance for a 5-minute rehabilitation break between rounds in extended duration protocols will not provide any advantages in obstacle crossing performance over back-to-back rounds due to the brevity of the rehabilitation period.
6) Use of radial clearance metrics will yield results more sensitive to changes in behavior due to fatigue and load carriage than the use of classic clearance metrics.

3.3 METHODS

3.3.1 Subjects

Thirty firefighters (29 male, 1 female; age 30.7 ± 7.9 years; height 1.82 ± 0.07m; weight 91.2 ± 15.1 kg) participated in this study. Twenty-one of these 30had also participated in the study presented in Chapter 2. All participants were volunteer (n=14), career (n=14), or both volunteer and career (n=2) firefighters. All subjects served small metropolitan (n=21), rural areas (n=7), or both of these types of communities (n=2). All subjects reported no history of balance or gait impairments, neurological diseases, or vision problems, or any injuries during the two months prior to the study. Each subject signed an informed consent waiver. The study was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign.

Each subject was provided appropriately sized PPE, consisting of boots, pants, jacket, hood, gloves, and helmet (G-Xtreme and Structure Supreme; Globe Manufacturing Company, LLC, Pittsfield, NH, USA).

3.3.2 SCBA Configurations

On each visit, subjects were equipped with one of four SCBA in addition to the PPE described above (***Figure 11***). Three were standard 4500 psi carbon fiber cylinders rated to provide 30, 45, and 60 minutes of air, when breathing at 40 L/min of air(S30, S45, S60, respectively). Standard cylinders were carried using a standard SCBA system (Firehawk M7; MSA, Inc., Murrysville, PA, USA). The fourth was a low-profile prototype (P45) design consisting of two rows of five interconnected carbon fiber cylinders enclosed in a Kevlar cover with attached shoulder and waist straps. The P45 was designed to provide 45 minutes of air when breathing at 40 L/min. Due to certification issues, the P45 pack could not be filled with air during the study, so it was left empty over the course of testing. Its empty weight was comparable to the weight of the S60 assembly when the cylinder was filled to capacity with pressurized air (***Figure 11***).

Weights and Dimensions of SCBA Configurations			
SCBA Configuration	*Filled Weight [kg]*	*Cylinder Length [cm]*	*Cylinder Diameter [cm]*
S30	9.9	55.2	14.1
S45	11.8	59.7	16.0
S60	13.3	60.3	18.6
		Pack Length [cm]	*Pack Width [cm]*
P45	13.1*	76.2	34.7
** empty weight*			

Figure 11. SCBA configurations and their respective dimensions. Reported weight for standard cylinders includes harness and cylinder filled with air to 4500 psi. Reported weight for P45 includes harness and empty cylinders.

3.3.3 Exercise Protocols

Each subject visited the Illinois Fire Service Institute (IFSI) research center a total of eight times. The first visit was to find each subject's maximum metabolic output during a treadmill test and to familiarize the subject with the testing equipment and procedure. The subject did not undergo a simulated firefighting activity protocol on the first visit.

On the subsequent four days of experimental testing, each subject underwent a single round of simulated firefighting tasks (1R) with all four SCBA configurations (S30 1R, S45 1R, S60 1R, P45 1R). A round of exercise consisted of two minutes of each of four simulated firefighting tasks with two minutes rest between each task. The specific tasks for the exercise protocol were: (1) stair climb, (2) hose advance, (3) secondary search, and (4) ceiling pull (Chapter 2). The tasks were presented in this order in every round because the tasks which they were intended to simulate are generally performed in this order in a live fire situation. If at any point during testing the subjects felt that they could not safely complete the exercise protocol, they were allowed to cease immediately and exit the environmental chamber. The SCBA presentation order for these four SCBA configurations was counterbalanced to control for learning effects over the course of testing, with the P45 always presented on the first or last of these visits.

During the final three visits, the subject only used either the S30 or S60 SCBA configurations, and underwent one of two extended duration exercise protocols. One protocol consisted of two rounds of simulated firefighting activities with a five-minute break between rounds (2R). During the break, the subject exited the environmental chamber and removed the helmet, hood, face piece, and gloves. While seated outside the chamber, the subject was cooled by a fan and provided with a choice of water or a sports drink. The SCBA bottle was swapped for a full to capacity cylinder during this break period. This protocol was implemented with both the S30 and S60 SCBA configurations (S30 2R, S60 2R). The other protocol consisted of two back-to-back rounds of simulated activities with no break between rounds (BB). Upon completion of the first round of activities, the subject was given two minutes of seated rest within the chamber before beginning the second round. This protocol was only implemented with the S60 SCBA configuration, as the S60 was the only cylinder with a large enough capacity to last for the duration of two rounds of continuous activity (S60 BB). The extended duration SCBA and exercise protocol combinations (S30 2R, S60 2R, S60 BB) were presented in counterbalanced order.

All exercise protocols were performed in a darkened, temperature and humidity controlled environmental chamber (Frost Environmental Rooms, Houston, TX, USA; 47°C, 20% humidity; 2.9 m wide x 3.4 m long x 2.7 m high). The subject breathed air from a SCBA while inside the chamber. In the event that subject depleted the air supply prior to completion of the protocol, the air supply line was swapped with an extended line connected to an extra 45-minute air supply carried in a Rapid Intervention Team bag by an investigator inside the chamber. This method of air supply was used for the entirety of tests involving the P45, since it could not be filled with air. In all cases, the subject was fitted with a metabolic monitoring system ($K4b^2$; Cosmed, SRL, Rome, Italy) during the first three minutes in the chamber. The metabolic monitoring equipment was connected to a custom face piece attachment which allowed for data collection while the subject breathed from the SCBA [47]. The metabolic monitoring system was calibrated within the environmental chamber and acclimated to its climate for approximately 20 minutes before execution of all exercise protocols. The subject was then given two minutes of seated rest in the chamber prior to beginning the round of four simulated firefighting activities.

3.3.4 Data Collection Procedure

3.3.4.1 Functional Task Course Description

This experiment was a part of a larger examination of firefighter movement, consisting of five functional task stations performed consecutively by each subject. Movement was investigated via the following task stations: (1) the obstacle crossing task presented here, (2) ascending and descending a three-step staircase, (3) level walking on an instrumented gait mat (GAITRite; CIR Systems, Inc., Sparta, NJ, USA), (4) passing through a standard 40.6 cm (16 in) stud space in a wall, and (5) a functional balance task presented with and without an overhead obstacle at 75% of each subject's height. All subjects performed these tasks in full PPE with the exception of the SCBA facepiece and hood.

Each subject's first visit to IFSI served the purpose of determining the subject's maximum metabolic output and making some necessary assessments for several of the functional tasks. The subject was also given the opportunity to become familiar with the S60 and P45 SCBA configurations before collecting data, as these SCBA currently are not widely used in structural firefighting. For those subjects who had not participated in the study presented in Chapter 2, one of these assessments was determining an appropriate starting location for the obstacle crossing task; those who had participated in the previous study used the same starting locations they had previously used. Each subject was given three practice runs through the obstacle course to become familiar with the apparatus and procedure in order to decide on strategies and techniques for completing each functional task and prevent learning effects during later trials. The original intent was to use the data from these trials as a baseline no-exercise condition; however, the analyses in this paper do not use the data from these trials.

Data were collected during each of the following seven visits. On each of these visits, the subject underwent two sets of two recorded trials using one of the four SCBA configurations; one set of trials was performed before an exercise protocol, and the other was performed after. A fully charged cylinder was used for all trials involving S30, S45, or S60, while the P45 was left empty at all times. Each data collection visit took place at least 24 hours after the previous visit to control for lingering effects of fatigue.

3.3.4.2 Obstacle Crossing Procedure

The obstacle crossing testing procedure matched that of the study in Chapter 2, except that no hose load was used in this investigation. Each subject carried one of the four SCBA configurations down an elevated walkway (8.25 cm high x 7.5 m long x 1.2 m wide) instrumented with force plates (BP 600900 and BP 400600; AMTI, Watertown, MA, USA) on each side of a stationary rectangular frame obstacle (***Figure 2***). The obstacle (30 cm high x 14 cm long x 124.5 cm wide) was made from 1.5 cm diameter PVC pipe and was not rigidly fixed to the ground for safety purposes. Each subject began from a previously determined starting position selected to maximize the likelihood of clean force plate strikes. Instructions were given for the subject to walk at fireground pace without running or compromising safety, step over the obstacle, and stop in a designated 60 cm x 60 cm square stop box located 12.7 cm from the end of the walkway. Trials in which the subject's whole foot did not cleanly contact the force plates were excluded from analysis of kinetic data. Trials in which the subject contacted the obstacle were excluded from analysis of clearances and peak heights.

Kinetic and kinematic data were collected for each trial. Force data were sampled at 1000 Hz from each of the three force plates. Motion data were collected at 200 Hz using an eight-camera motion capture system (Oqus 100-Series; Qualisys Motion Capture Systems, Gothenburg, Sweden). Motion capture markers were fixed to the top four corners of the obstacle and four locations on each boot (***Figure 3***).

3.3.5 Obstacle Crossing Metrics

Numerous measures were employed in an attempt to quantify obstacle crossing performance. We looked at contact errors with the obstacle, foot clearances between the obstacle and ground, and ground reaction forces generated during obstacle crossing.

Contact errors were defined as in the previous study in Chapter 2 – as any instance in which the subject contacted the obstacle. Contact errors were once again further broken down into minor (instances of contact not resulting in an obstacle fall) and major (obstacle fell over) categories, as well as by lead or trailing foot.

A radial clearance metric was also employed. Radial clearance vectors were defined by finding the minimum distances between (1) the toe marker and the front edge of the obstacle, (2) the heel marker and the front edge of the obstacle, (3) the toe marker and the back edge of the obstacle, or (4) the heel marker and the back edge of the obstacle for each foot at any point during crossing, and taking the minimum among these four distances (***Figure 12A***). Radial clearance magnitude was calculated for both the lead and trailing foot (CL, CT). Previous studies have successfully defined minimum foot clearance variables in a similar manner in both stair climbing [52], [122] and obstacle crossing [52]–[54]. In addition to the magnitude of the radial clearances, a new metric, the angle of the radial clearance vector was also determined for each foot in the sagittal plane with respect to the horizontal direction of travel. The radial clearance angle was defined for the lead and trailing foot (θ_L, θ_T) (***Figure 12A***).

As the radial clearances have not yet been widely adopted in obstacle crossing analysis, the horizontal and vertical obstacle clearances for the trailing and lead foot (HCT, HCL, VCT, and VCL) – or "classic clearances" – were also calculated from the motion data in the same manner as in Chapter 2 (***Figure 4***). Measuring radial clearances may give a better representation of a subject's proximity to the obstacle throughout crossing, and thus may be a better indicator of the likelihood of contacting the obstacle than the traditional clearance metrics utilized in the previous study (VCL, VCT).

An additional new clearance metric, the peak boot height, was also developed. The peak boot height was defined as the lesser of the maximum height of the heel or toe marker above the ground at any point during crossing (***Figure 12B***). The peak boot height was recorded for the lead and trailing foot (hL, hT).This measurement may be a better metric for identifying compensatory strategies than the vertical clearances utilized previously (VCL, VCT).

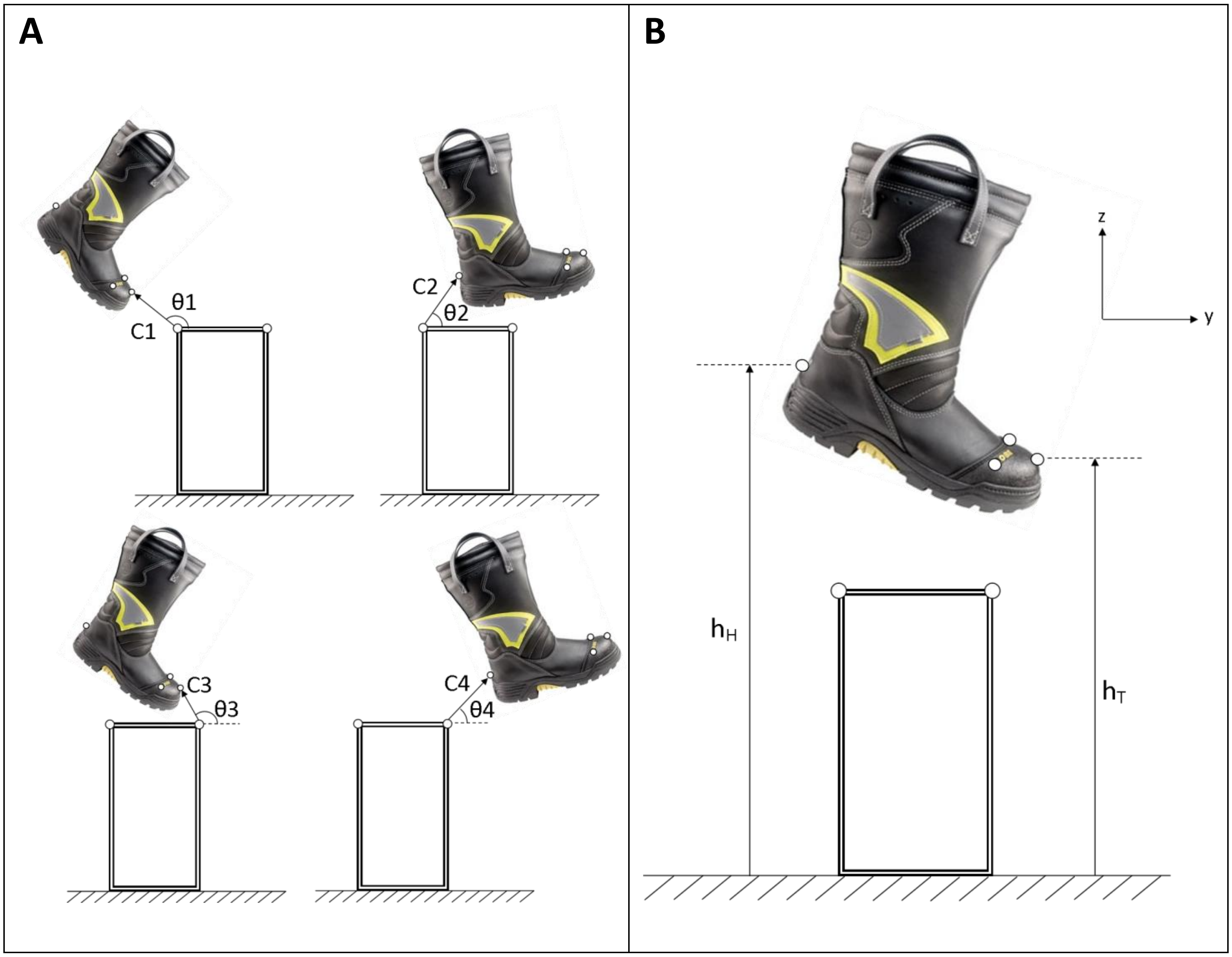

Figure 12. (A) The minimum radial clearance vector was defined from the minimum radial clearance magnitude among C1-4.Radialclearance angle θ was defined as the angle corresponding to this vector. (B) Peak boot height defined as the lesser of the maximum heights of the heel (h_H) and toe (h_T) markers above the ground.

Peak ground reaction forces (GRFs) in the vertical (V), anterior-posterior (AP) and medial-lateral (ML) directions were examined under each foot while crossing the obstacle; peak GRFs were identified using similar methods as those employed in [13] (***Figure 5***).In the V and AP directions, peak values of normalized GRFs during early and late stance were recorded. In the ML direction, only the maximum normalized GRF over the entire stance phase was analyzed. These different GRF variables are denoted as "GRF" with subscripts denoting direction, foot, and stance phase, e.g., GRF_{VTL} represents the peak GRF in the vertical direction for the trailing foot during late stance phase. If the participant stepped on both smaller force plates with the lead foot, then the force data from the two smaller plates were added together to determine the lead foot GRFs [111]. In the vertical direction, the transition point separating the early and late peaks was identified as the local minimum of the vertical GRF curve (***Figure 5***). In the AP direction, the transition point was defined as the point at which the AP GRF changed direction from posterior to anterior. No discernible transition point exists for the ML GRF, so only the total peak (maximum) GRF magnitude in that direction was examined (***Figure 5***). All GRF data were normalized by the static weight of the subject in full PPE with SCBA. Average subject bodyweight data are provided in (***Table 3***). Previous studies have normalized by subject body weight alone and found significant effects of SCBA weight [13]. However, we wished to eliminate any potential effects due solely to the increase in static weight associated with wearing PPE and heavier SCBA, so normalization involving this static weight was preferred.

Table 3. Average ± standard deviation of subject body weights with each SCBA configuration and without SCBA.

	kg		
Body Weight	*87.6*	±	*21.4*
Weight w/ S30	*97.5*	±	*21.4*
Weight w/ S45	*99.4*	±	*21.4*
Weight w/ S60	*100.9*	±	*21.4*
Weight w/ P45	*100.7*	±	*21.4*

3.3.6 Comparison Groups

In order to address the specific research aims of this study, the various combinations of SCBA and exercise protocols were broken down into four comparison groups (***Table 4***). The groupings were based on the several independent variables introduced in this study (cylinder size, SCBA design, and exercise duration, in addition to fatigue). Group I examined the effects of differing cylinder size in similar SCBA designs by comparing the S30, S45, and S60 conditions with one round of exercise. Group II examined effects of different SCBA designs of similar weight by comparing the S60 and P45 with one round of exercise. Group III examined effects of exercise duration by comparing the three different exercise protocols employed with the S60 SCBA configuration. Finally, group IV examined the combined effects of SCBA size and exercise duration by comparing the 1R and 2R protocols for both the S30 and S60 SCBAs.

Table 4. Groupings of test conditions based on the specific factors examined.

	Group I Size	***Group II Design***	***Group III Duration***	***Group IV Size × Duration***
S30 1R	X			X
S45 1R	X			
S60 1R	X	X	X	X
P45 1R		X		
S30 2R				X
S60 2R			X	X
S60 BB			X	

3.3.7 Data/Statistical Analysis

Several techniques were used to analyze how the different obstacle crossing metrics were affected by cylinder size, SCBA design, exercise duration, and fatigue. Contact error totals were examined in terms of the four comparison groups. However, no statistical analysis on the contact error totals was performed. In addition, subjects were binned into three groups based on the total number of errors that they committed over the course of testing (0 errors, 1-9 errors, and 10+ errors). A one-way multivariate analysis of variance (MANOVA) was performed to identify if any specific characteristics, i.e., age, experience, height, leg length, weight, and BMI, differed among these binned error groups. All other outcome variables were averaged over two trials prior to statistical analysis. These outcome variables were analyzed using appropriate repeated measures (RM) MANOVAs to assess any potential changes in obstacle crossing gait brought about by the various factors introduced in the four comparison groups. The outcome variables were grouped for analyses as follows: (1) radial clearance magnitudes and peak boot heights, (2) classic clearances, (3) radial clearance angles, and (4) normalized peak GRFs. These RM MANOVAs were performed as two- or three-way analyses based on the four comparison groups and testing period to assess the added effect of fatigue:

Group I: SCBA size (3) × testing period (2)

Group II: SCBA design (2) × testing period (2)

Group III: exercise duration (3) × testing period (2)

Group IV: exercise duration (2) × SCBA size (2) × testing period (2).

For test conditions in which the same SCBA configuration (S30 or S60) was used multiple times with different exercise protocols, the pre-exercise conditions were essentially the same(e.g., S60 1R, S60 2R, and S60 BB). Thus, RM MANOVAs were also run on Groups III (exercise duration (3)) and IV (exercise duration (2) × SCBA size (2)) using the percent change from pre to post exercise. These values served as a check to ensure that similar pre-exercise conditions for different protocols involving the same SCBA did not cause any significant protocol or interaction effects in the original RM MANOVAs. Percent change with testing period for a given variable was defined as follows:

$$D = \frac{P_{post} - P_{pre}}{P_{pre}} 100\%$$

Here, P_{pre} is the value of the variable before undergoing an exercise protocol, and P_{post} is the value of the variable after the exercise protocol.

A significance level of $\alpha = 0.05$ was selected for all statistical tests. If a RM MANOVA was statistically significant, then univariate ANOVAs were examined for each variable. Tukey honestly significant difference (HSD) tests were performed on all variables for which a univariate ANOVA revealed significant interaction effects to identify specific differences among cell means. All statistical tests were carried out using SPSS v20 (IBM Corp., Armonk, NY, USA).

3.4 RESULTS

This study aimed to quantify the effects of SCBA size and design, extended duration exercise, and fatigue (via testing period) on obstacle crossing performance by measuring contact errors (***Table 5***), obstacle clearances (***Table 6***), and normalized peak GRFs (***Table 7***). Data were originally collected for 30 subjects, but due to contact errors and lack of clean force plate strikes, several subjects were excluded from the different analyses (***Table 8***). Of the 30 total subjects, 19 completed the exercise protocol from start to finish on each visit to IFSI. All participants who stopped prior to completion did so during one of the extended duration exercise protocols (S30 2R, S60 2R, S60 BB).

Table 5. Contact error totals by severity and foot for all test conditions.

		Minor		**Major**		**Total**		**Net**
		Lead	*Trailing*	*Lead*	*Trailing*	*Lead*	*Trailing*	
S30 1R	*Pre*	0	2	1	0	1	2	3
	Post	1	5	0	0	1	5	6
S45 1R	*Pre*	2	7	0	1	2	8	10
	Post	0	5	0	1	0	6	6
S60 1R	*Pre*	0	4	0	0	0	4	4
	Post	0	5	0	1	0	6	6
P45 1R	*Pre*	1	1	0	0	1	1	2
	Post	0	5	0	0	0	5	5
S30 2R	*Pre*	0	3	0	0	0	3	3
	Post	0	9	0	0	0	9	9
S60 2R	*Pre*	0	4	0	0	0	4	4
	Post	0	11	0	0	0	11	11
S60 BB	*Pre*	1	4	0	0	1	4	5
	Post	0	9	0	0	0	9	9
Net		5	74	1	3	6	77	**83**

Table 6. Average (± standard deviation) clearance and peak boot height variables for all test conditions.

		HCT [cm]	***HCL [cm]***	***VCT [cm]***	***VCL [cm]***	***CT [cm]***	***CL [cm]***	***θ_T [°]***	***θ_L [°]***	***hT [cm]***	***hL [cm]***
S30 1R	*Pre*	19.7 ± 3.4	29.5 ± 5.7	20.9 ± 9.5	14.2 ± 4.0	15.4 ± 6.1	11.2 ± 3.6	143.3 ± 19.7	54.1 ± 8.7	56.3 ± 8.3	55.0 ± 4.6
	Post	20.0 ± 4.3	28.7 ± 7.1	21.2 ± 9.4	15.4 ± 3.4	15.7 ± 5.2	12.5 ± 3.0	147.3 ± 21.5	59.7 ± 10.8	54.9 ± 9.2	54.2 ± 3.7
S45 1R	*Pre*	20.4 ± 4.4	27.2 ± 5.0	23.1 ± 9.8	14.9 ± 4.7	16.9 ± 5.7	11.0 ± 3.4	153.0 ± 26.8	51.7 ± 12.3	56.6 ± 8.7	55.1 ± 4.5
	Post	20.9 ± 4.5	27.5 ± 5.1	21.5 ± 8.8	15.1 ± 4.2	15.8 ± 5.5	12.1 ± 3.5	146.0 ± 20.5	57.1 ± 9.3	56.0 ± 7.9	54.5 ± 4.4
S60 1R	*Pre*	20.2 ± 3.5	28.2 ± 4.3	21.1 ± 9.0	13.9 ± 4.7	15.8 ± 5.7	10.7 ± 3.5	145.4 ± 17.4	52.2 ± 9.4	55.8 ± 8.4	55.1 ± 4.5
	Post	19.7 ± 4.2	28.2 ± 5.4	21.8 ± 9.6	15.1 ± 4.1	16.2 ± 5.4	12.2 ± 3.6	149.1 ± 23.4	58.4 ± 13.4	55.9 ± 8.9	54.3 ± 3.9
P45 1R	*Pre*	20.8 ± 5.2	28.3 ± 4.5	22.2 ± 10.2	14.6 ± 3.8	16.5 ± 6.7	11.0 ± 2.6	145.0 ± 26.1	51.6 ± 9.7	56.8 ± 8.7	55.8 ± 4.1
	Post	19.5 ± 5.0	27.9 ± 5.0	22.2 ± 9.1	16.0 ± 4.0	16.3 ± 5.6	13.1 ± 3.2	143.8 ± 25.7	56.9 ± 10.0	56.9 ± 8.6	55.5 ± 4.0
S30 2R	*Pre*	21.5 ± 5.3	30.7 ± 6.4	20.2 ± 8.6	14.7 ± 4.2	15.4 ± 5.5	11.4 ± 2.8	142.5 ± 16.7	53.7 ± 9.5	55.7 ± 8.0	55.0 ± 4.3
	Post	20.0 ± 5.6	28.0 ± 5.8	19.9 ± 8.3	14.8 ± 4.0	14.5 ± 5.2	12.1 ± 3.1	143.4 ± 24.5	58.7 ± 10.6	53.3 ± 7.9	53.4 ± 3.5
S60 2R	*Pre*	21.5 ± 5.8	29.3 ± 6.7	20.0 ± 9.5	14.1 ± 4.2	14.9 ± 6.3	11.0 ± 2.9	143.5 ± 13.9	53.8 ± 9.3	55.1 ± 8.7	55.0 ± 4.3
	Post	20.6 ± 4.9	26.9 ± 6.6	20.0 ± 8.0	14.8 ± 3.1	14.6 ± 5.2	12.1 ± 2.7	141.6 ± 19.6	60.7 ± 13.1	53.7 ± 7.7	53.4 ± 3.2
S60 BB	*Pre*	19.7 ± 4.3	28.8 ± 6.1	21.5 ± 9.5	14.3 ± 4.7	15.7 ± 6.1	10.8 ± 3.2	142.8 ± 25.4	51.3 ± 8.9	56.5 ± 8.8	54.8 ± 4.3
	Post	19.8 ± 6.3	25.9 ± 7.6	19.3 ± 11.0	14.9 ± 4.1	14.1 ± 5.6	12.5 ± 2.8	150.4 ± 26.3	59.4 ± 12.4	55.2 ± 9.7	53.6 ± 3.8

HCT = trailing foot horizontal clearance, HCL = lead foot horizontal clearance, VCT = trailing foot vertical clearance, VCL = lead foot vertical clearance, CT = trailing foot radial clearance magnitude, CL = lead foot radial clearance magnitude, θ_T= trailing foot radial clearance angle, θ_L = lead foot radial clearance angle, hT = trailing foot peak boot height, hL = lead foot peak boot height

Table 7. Average (± standard deviation) normalized peak GRFs for all test conditions. GRFs are normalized by the weight of the subject in full PPE, including SCBA.

		GRF_{VTE}	GRF_{VTL}	GRF_{APTE}	GRF_{APTL}	GRF_{MLL}	GRF_{VTL}	GRF_{VLL}	GRF_{APLE}	GRF_{APLL}	GRF_{MLL}
S30 1R	*Pre*	1.52 ± 0.13	1.52 ± 0.16	0.36 ± 0.07	0.35 ± 0.05	0.11 ± 0.02	1.29 ± 0.13	1.19 ± 0.11	0.27 ± 0.08	0.35 ± 0.06	0.12 ± 0.03
	Post	1.54 ± 0.14	1.54 ± 0.15	0.39 ± 0.07	0.33 ± 0.05	0.10 ± 0.03	1.30 ± 0.12	1.15 ± 0.09	0.29 ± 0.11	0.35 ± 0.05	0.13 ± 0.03
S45 1R	*Pre*	1.50 ± 0.13	1.50 ± 0.14	0.34 ± 0.09	0.34 ± 0.05	0.10 ± 0.02	1.28 ± 0.10	1.18 ± 0.10	0.28 ± 0.07	0.34 ± 0.05	0.12 ± 0.03
	Post	1.52 ± 0.17	1.52 ± 0.17	0.38 ± 0.08	0.33 ± 0.05	0.10 ± 0.02	1.25 ± 0.11	1.15 ± 0.09	0.30 ± 0.08	0.35 ± 0.04	0.13 ± 0.04
S60 1R	*Pre*	1.47 ± 0.14	1.47 ± 0.15	0.34 ± 0.06	0.35 ± 0.05	0.10 ± 0.03	1.25 ± 0.11	1.19 ± 0.10	0.28 ± 0.06	0.34 ± 0.05	0.11 ± 0.03
	Post	1.52 ± 0.14	1.52 ± 0.18	0.38 ± 0.07	0.33 ± 0.05	0.10 ± 0.03	1.27 ± 0.12	1.13 ± 0.10	0.32 ± 0.06	0.36 ± 0.05	0.12 ± 0.03
P45 1R	*Pre*	1.48 ± 0.17	1.38 ± 0.14	0.33 ± 0.09	0.34 ± 0.05	0.10 ± 0.02	1.28 ± 0.14	1.18 ± 0.10	0.29 ± 0.09	0.34 ± 0.05	0.12 ± 0.03
	Post	1.56 ± 0.13	1.32 ± 0.13	0.35 ± 0.11	0.32 ± 0.05	0.10 ± 0.02	1.28 ± 0.15	1.14 ± 0.11	0.29 ± 0.10	0.36 ± 0.06	0.13 ± 0.03
S30 2R	*Pre*	1.50 ± 0.13	1.37 ± 0.13	0.35 ± 0.06	0.35 ± 0.05	0.11 ± 0.02	1.28 ± 0.08	1.18 ± 0.10	0.26 ± 0.10	0.34 ± 0.06	0.11 ± 0.03
	Post	1.48 ± 0.14	1.25 ± 0.17	0.38 ± 0.07	0.30 ± 0.05	0.10 ± 0.02	1.29 ± 0.13	1.09 ± 0.11	0.30 ± 0.10	0.37 ± 0.07	0.13 ± 0.03
S60 2R	*Pre*	1.48 ± 0.14	1.34 ± 0.13	0.36 ± 0.07	0.34 ± 0.05	0.10 ± 0.02	1.30 ± 0.12	1.17 ± 0.11	0.29 ± 0.07	0.35 ± 0.07	0.13 ± 0.03
	Post	1.43 ± 0.13	1.24 ± 0.17	0.37 ± 0.07	0.30 ± 0.05	0.09 ± 0.02	1.27 ± 0.14	1.10 ± 0.09	0.32 ± 0.06	0.36 ± 0.07	0.12 ± 0.02
S60 BB	*Pre*	1.49 ± 0.13	1.37 ± 0.13	0.35 ± 0.06	0.34 ± 0.05	0.10 ± 0.03	1.26 ± 0.11	1.16 ± 0.10	0.27 ± 0.08	0.35 ± 0.07	0.12 ± 0.04
	Post	1.46 ± 0.12	1.20 ± 0.15	0.38 ± 0.07	0.30 ± 0.05	0.10 ± 0.02	1.28 ± 0.15	1.09 ± 0.09	0.33 ± 0.07	0.37 ± 0.07	0.12 ± 0.03

Table 8. Number of subjects included in analysis of each variable by comparison group.

	Contact Errors	***Clearances & Heights***	***Clearance Angles***	***GRFs***
Group I	30	26	25	25
Group II	29	28	27	27
Group III	30	25	24	29
Group IV	30	24	23	25

3.4.1 Group I: SCBA Size

The first comparison group aimed to examine the effects on obstacle crossing performance due to SCBA cylinder size, as well as the fatigue brought on from one round of simulated firefighting activities, on obstacle crossing performance. Tests using the S30, S45, and S60 SCBA for 1R exercise protocols were included in this group (***Table 4***).

Trends in contact error totals were somewhat difficult to determine. No discernible trend in contact error totals appeared due to SCBA size for the S30 and S60 cylinders, with approximately the same number of errors committed over the course of testing (***Table 5***). More contact errors were committed post-exercise for both of these cylinders. The exception was the S45, with which ten contact errors were committed pre-exercise, with two subjects accounting for four of these errors. Across all SCBA sizes, the majority of contact errors were minor errors (88.6%), and most with the trailing foot (90.3%).Major errors were committed using all three cylinders, and occurred both before and after exercise. Only four major contact errors were committed over the course of the entire study, all of which occurred during test conditions included in comparison group I.

The two-way RM MANOVAs revealed no significant main effects of SCBA size or interaction effects between SCBA size and fatigue on any of the clearance variables examined. The MANOVA on the classic clearance metrics also revealed no significant main effects of fatigue. However, the MANOVA run on the radial clearances and peak boot heights indicated significant main effect of fatigue ($p < 0.001$), but no interaction effects. Follow up univariate ANOVAs revealed that CL significantly increased with fatigue ($p < 0.001$) by an average of 1.5 cm (***Figure 13A***). Further, the MANOVA run on the clearance angles also revealed a significant main effect of fatigue ($p = 0.009$). Follow up univariate ANOVAs indicated a significant increase with fatigue in θ_L ($p = 0.002$) of 6.3° on average (***Figure 13B***). No significant main effects of fatigue were observed on any trailing foot clearance or peak boot height variables in this comparison group.

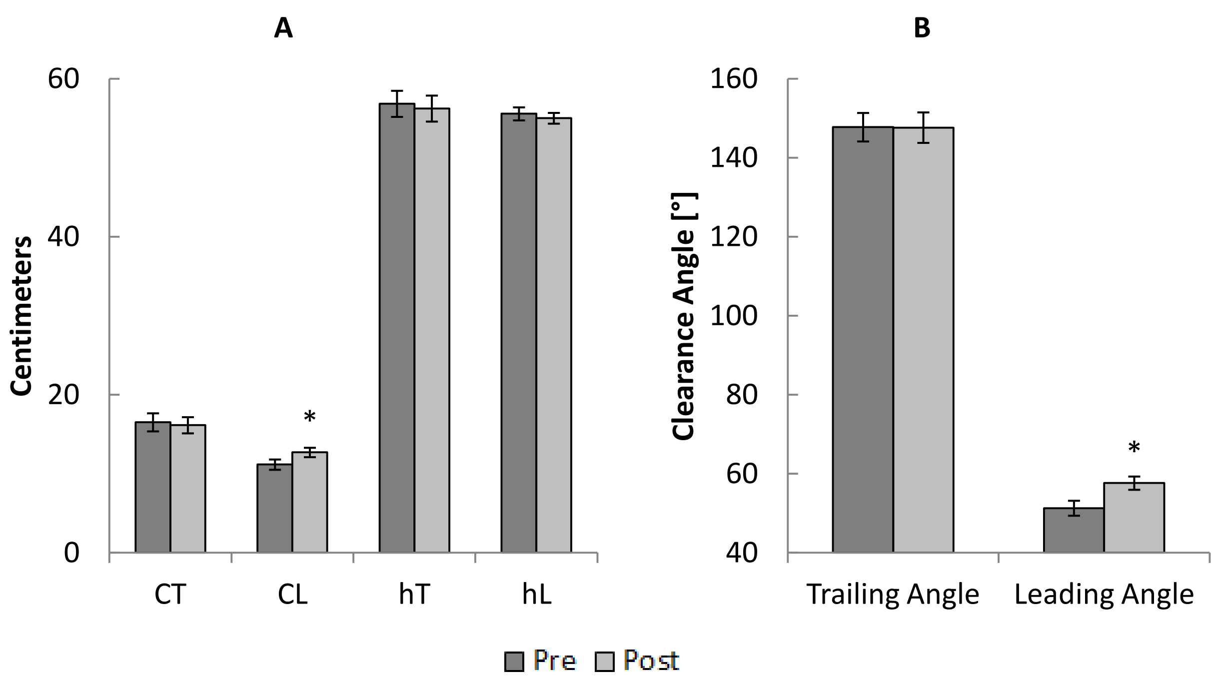

Figure 13. Group I clearances by testing period. (A) Radial clearances and peak boot heights. (B) Radial clearance angle. An asterisk (*) indicates significant difference from pre-exercise.

No significant main effects of SCBA size or interaction effects were observed for any of the GRF variables examined in this comparison group. However, the MANOVA revealed significant main effects of fatigue on several of the GRF variables ($p < 0.001$) (***Figure 14***). Follow up univariate ANOVAs indicated that GRF_{VTE} and GRF_{APTE} increased significantly with fatigue ($p = 0.004$, $p = 0.001$) by respective averages of 0.042 (2.9%) and 0.029 (8.3%). Follow up tests also indicated that GRF_{VTL} and GRF_{APTL} decreased significantly with fatigue ($p = 0.002$, $p < 0.001$) by averages of 0.048 (3.5%) and 0.019 (5.4 %), respectively. Univariate ANOVAs also indicated that GRF_{VLL} decreased significantly with fatigue ($p < 0.001$) by an average of 0.048 (4%), while GRF_{APLE} and GRF_{MLL} increased with fatigue ($p < 0.001$ in both cases) by respective averages of 0.031(11%) and 0.010 (9.2%).

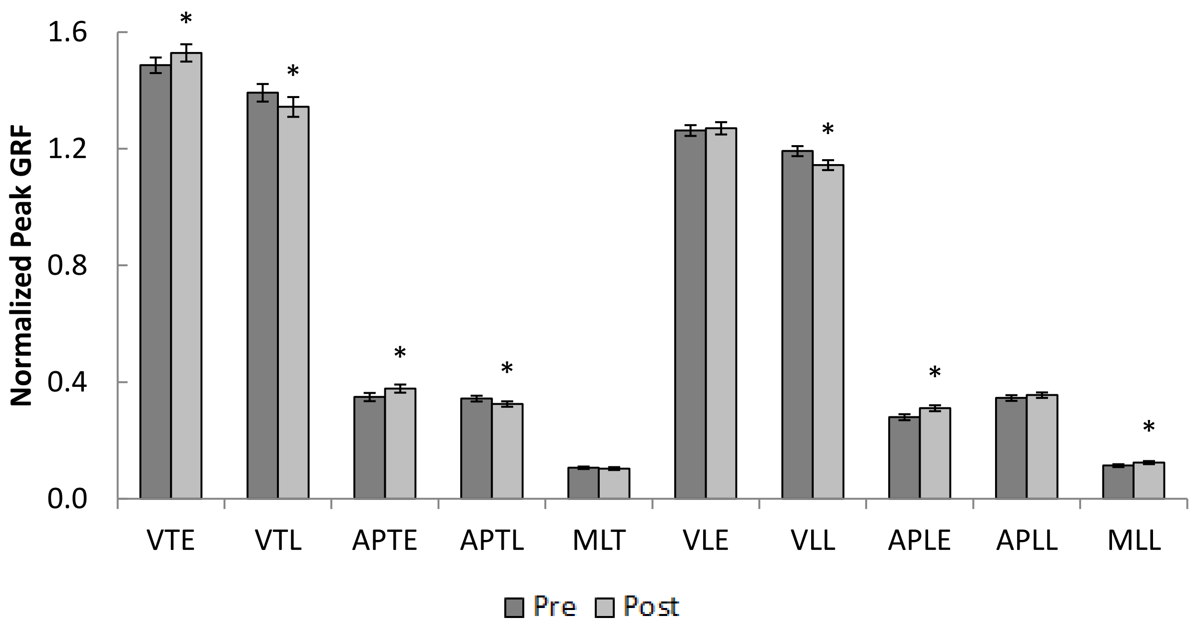

Figure 14. Group I normalized peak GRFs by fatigue. An asterisk (*) indicates significant difference from pre-exercise.

3.4.2 Group II: SCBA Design

The second comparison grouping examined the effects of different SCBA designs but with similar weight on obstacle crossing performance. Tests using the S60 and P45 SCBA for 1R exercise protocols were included in this group (***Table 4***).

Slightly fewer total contact errors were committed during tests using the P45 both pre and post exercise (***Table 5***). More contact errors were committed post exercise with both SCBA in this group. Nearly all contact errors were classified as minor (94.1%), all but one of which was committed with the trailing foot (93.8%).

The MANOVAs revealed no significant main effects of SCBA design or interaction effects on any of the clearance metrics. The MANOVA performed on the classic clearance calculations revealed a significant main effect of fatigue ($p = 0.004$). Follow up univariate ANOVAs revealed a significant effect of fatigue on VCL ($p = 0.007$), causing an average increase of 1.3 cm after exercise (***Figure 15A***). The MANOVA performed on the radial clearances and peak boot heights also revealed significant main effects of fatigue ($p < 0.001$). Follow up univariate ANOVAs indicated significant increases in CL ($p < 0.001$) with fatigue, resulting in an average increase of 1.9 cm following exercise (***Figure 15B***). The MANOVA performed on clearance angles also revealed a significant effect of fatigue ($p = 0.013$). Univariate analyses revealed a significant increase in θ_L ($p = 0.002$) of 5.8° on average due to fatigue (***Figure 15C***).

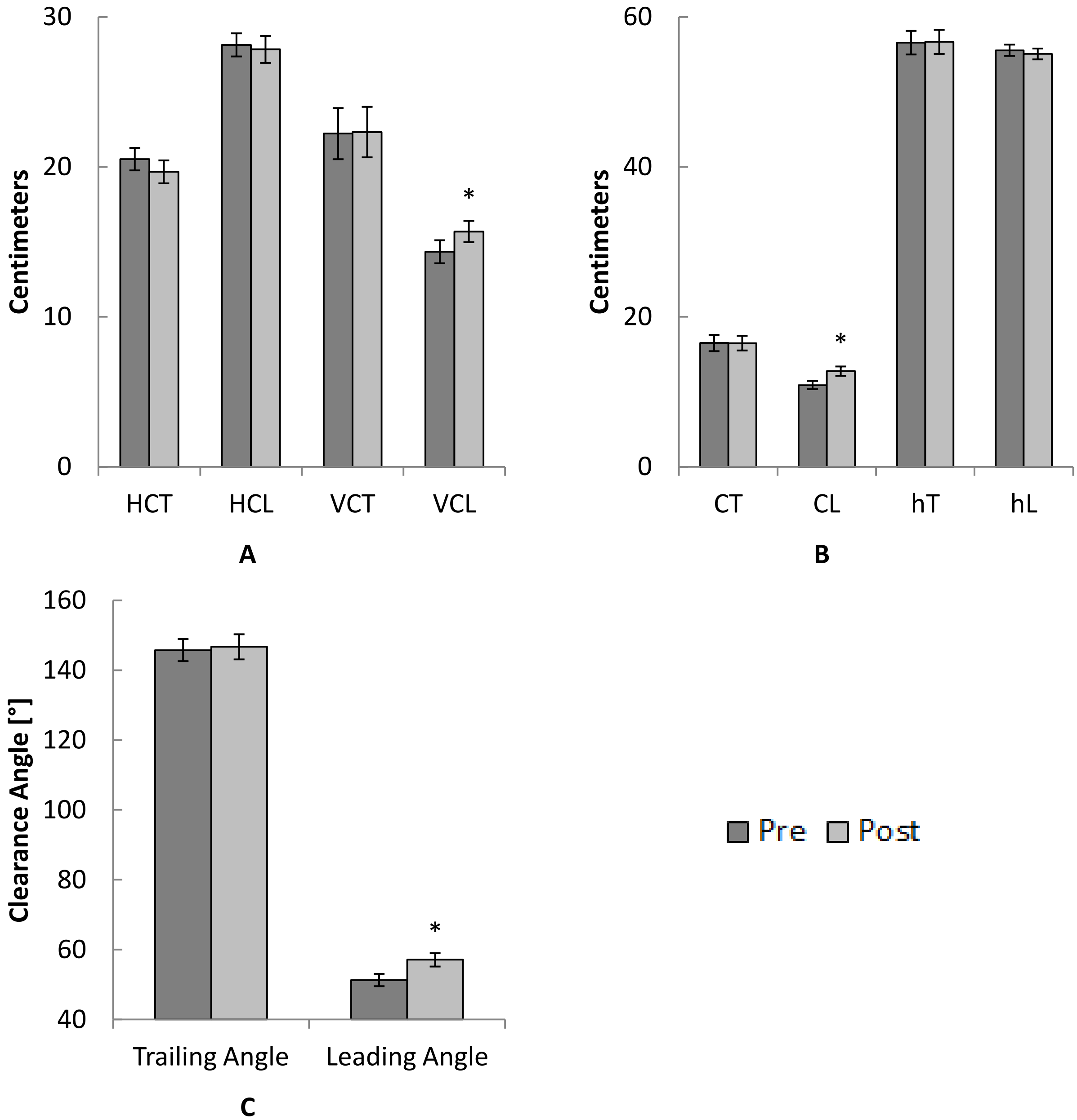

Figure 15.Group II clearance metrics by fatigue. (A) Classic clearances. (B) Radial clearances and peak boot heights. (C) Radial clearance angle. An asterisk (*) indicates significant difference from pre-exercise.

The group II MANOVA on GRF variables revealed significant main effects of both SCBA design ($p = 0.031$) and fatigue ($p < 0.001$), but no interaction effects. Follow up univariate ANOVAs indicated that GRF_{VTL} was the only variable significantly affected by SCBA design ($p = 0.046$), and was greater on average for trials involving the S60 compared to the P45 by 0.037 (2.7%) (***Figure 16***).

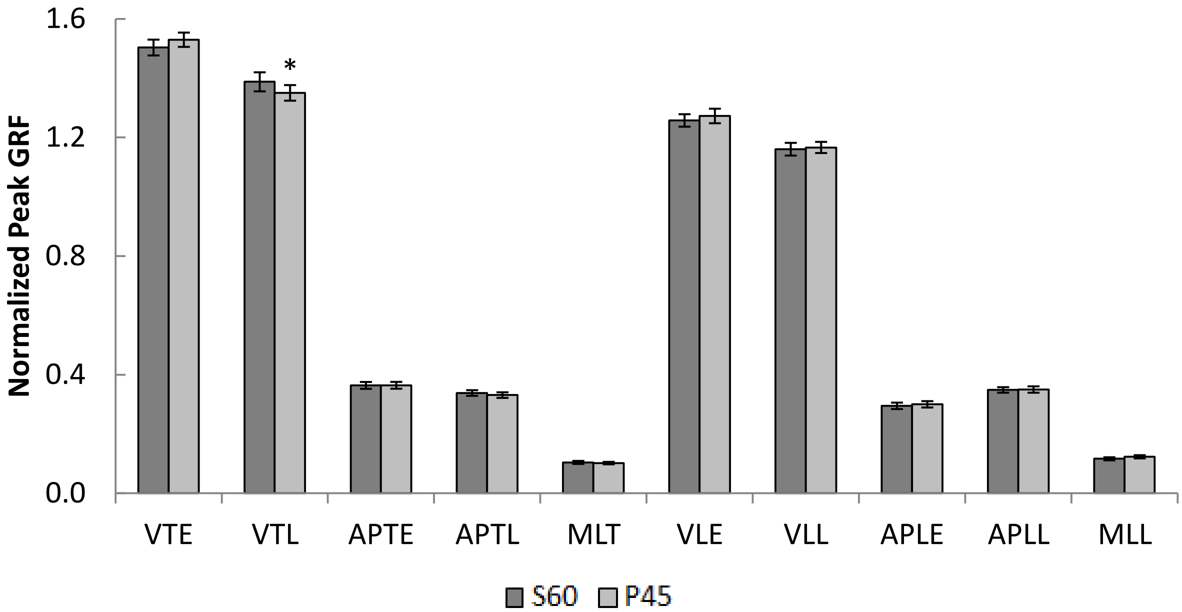

Figure 16. Group II normalized peak GRFs by SCBA design. An asterisk (*) indicates significant difference from S60.

Univariate ANOVAs indicated that numerous GRF metrics changed significantly with respect to fatigue (***Figure 17***). GRF_{VTE} and GRF_{APTE} increased significantly with fatigue ($p = 0.001$, $p < 0.001$) by averages of 0.051 (3.4%) and 0.032 (9.1 %), respectively. GRF_{VTL} and GRF_{APTL} decreased significantly with fatigue ($p = 0.002$, $p = 0.004$) by averages of 0.046 (3.3%) and 0.017 (4.8%), respectively. GRF_{VLL} decreased significantly ($p < 0.001$) by 0.053 (4.5%) on average with fatigue. GRF_{APLE}, GRF_{APLL} and GRF_{MLL} all increased significantly with fatigue ($p < 0.001$, $p = 0.034$, $p = 0.001$) by averages of 0.030 (10.4%), 0.016 (4.6%), and 0.011 (9.2%), respectively.

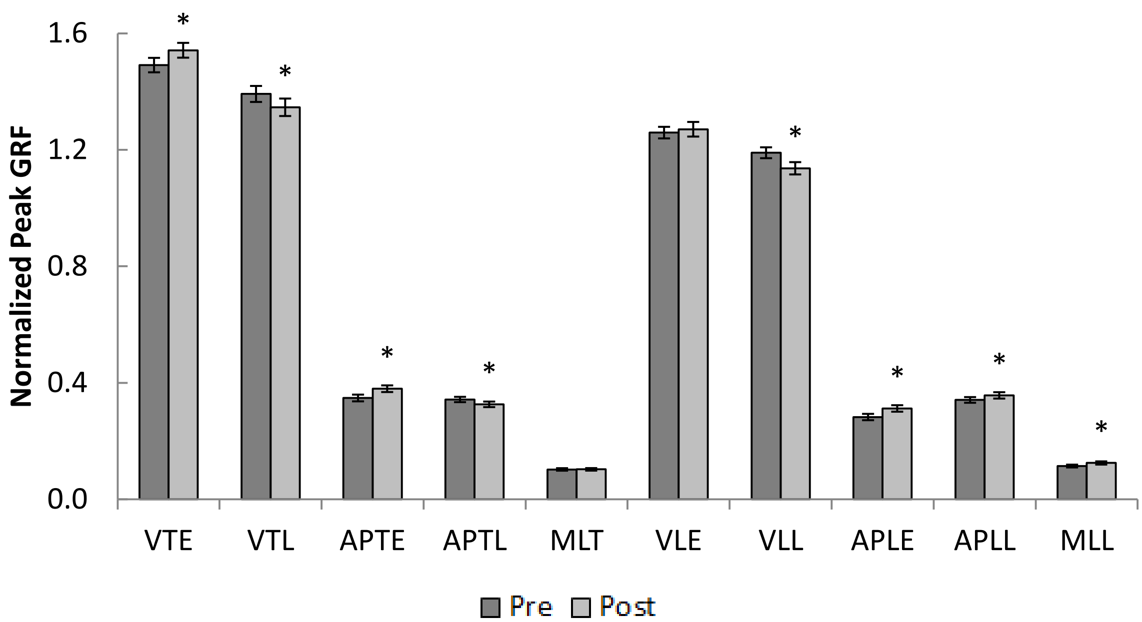

Figure 17. Group II normalized peak GRFs by fatigue. An asterisk (*) indicates significant difference from pre-exercise.

3.4.3 Group III: Exercise Duration

The third comparison group sought to address the effects of extended duration exercise protocols on obstacle crossing performance. Tests using the S60 SCBA for 1R, 2R, and BB exercise protocols were included in this comparison group (***Table 4***).

Contact error totals appeared to be related to exercise duration. For all three exercise protocols, more contacts were committed post exercise, with larger increases in contact error totals for the extended duration protocols (***Table 5***). Slightly more contact errors occurred following the 2R exercise protocol versus the BB protocol (11 vs. 9).The pre exercise conditions were essentially the same since all trials started with a full S60 cylinder, and approximately the same number of errors was committed before each exercise protocol. All but one contact error committed during tests included in this comparison group were minor errors (97.4%), with all but one of these caused by the trailing foot (97.3%).

The MANOVA revealed significant main effects of exercise duration (p = 0.019) and fatigue (p < 0.001), but not interaction effects, on radial clearances and peak boot heights. However, the MANOVA performed on the classic clearance metrics revealed no significant main or interaction effects. Follow up univariate ANOVAs revealed CT to be significantly lower for the 2R and BB exercise protocols than for the 1R protocol (p = 0.046) by averages of 1.6 cm and 1.2 cm, respectively (***Figure 18***), although the average CT for 2R and BB protocols were not significantly different from each other. Follow up ANOVAs based on test period also indicated that CL increased significantly with fatigue (p < 0.001) by an average of 1.5 cm, while hL decreased significantly with fatigue (p = 0.003) by an average of 1.3 cm (***Figure 19A***). The MANOVA on clearance angles also revealed significant main effects of fatigue (p = 0.002). θ_L again increased significantly with fatigue (p = 0.002) by an average of 7.2° (***Figure 19B***).

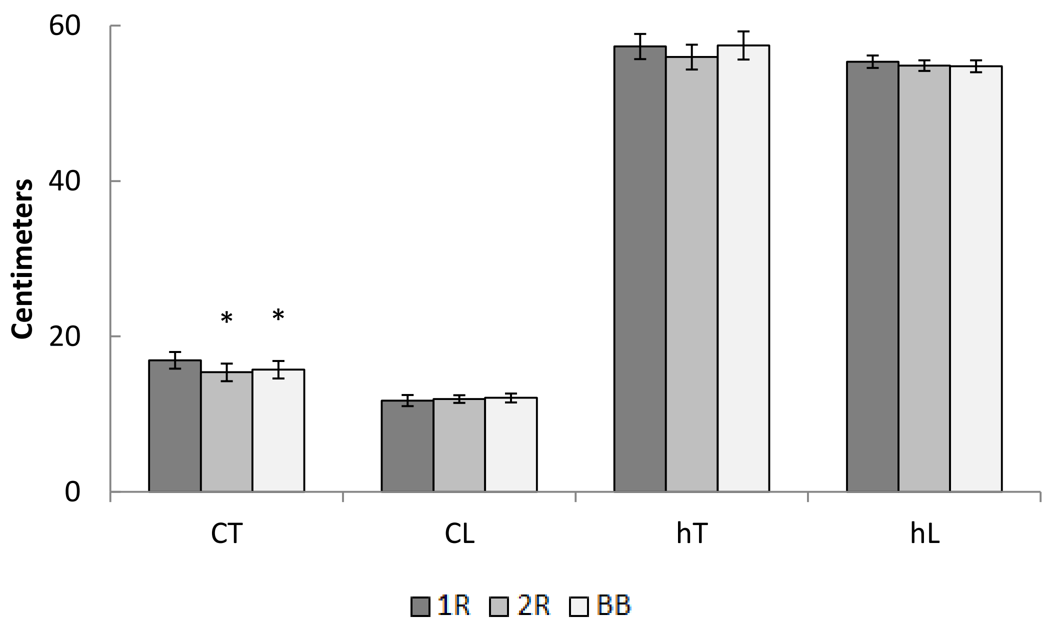

Figure 18.Group III radial clearances and peak boot heights by exercise duration. An asterisk (*) indicates significant difference from 1R.

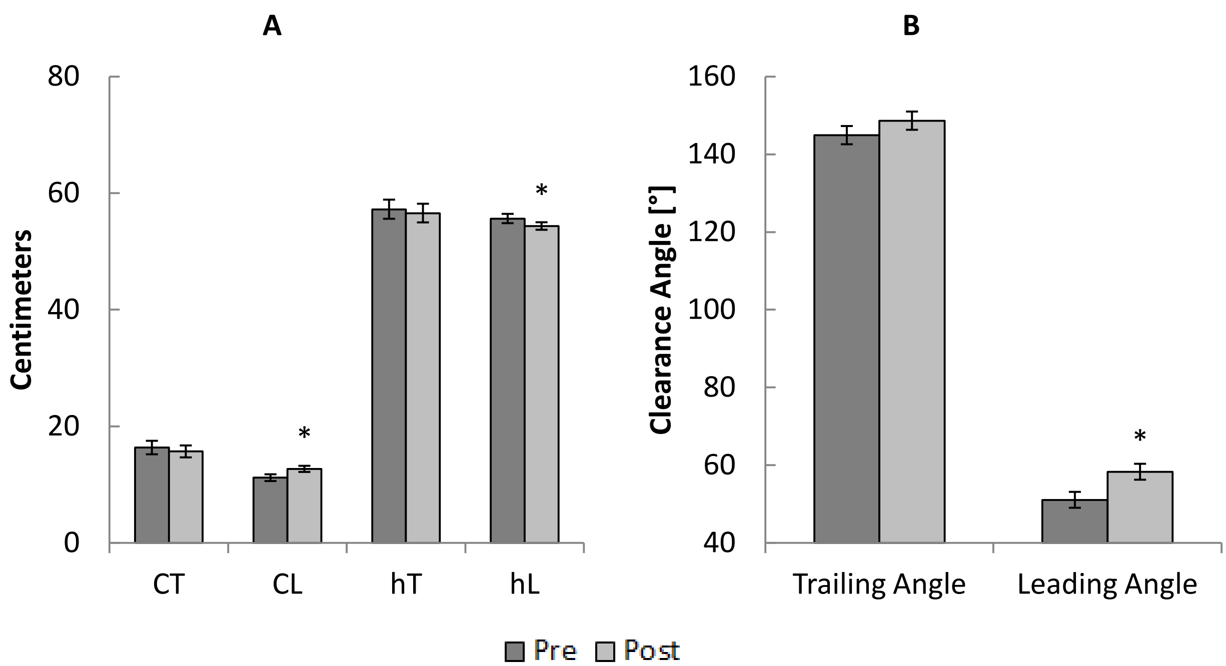

Figure 19.Group III clearance metrics by fatigue. (A) Radial clearances and peak boot heights. (B) Clearance angles. An asterisk (*) indicates significant difference from pre-exercise.

The group III MANOVA performed on the peak GRF variables revealed several significant main effects of exercise duration ($p = 0.002$) (***Figure 20***). GRF_{VTL} and GRF_{APTL} were both significantly lower for 2R and BB exercise protocols relative to 1R ($p < 0.001$ for both variables). The average differences in GRF_{VTL} for 1R versus 2R and 1R versus BB were 0.095 (7.1%) and 0.094 (7.0%), respectively. Average differences in GRF_{APTL} for 1R versus 2R and 1R versus BB were 0.018 (5.6%) and 0.020 (6.2%), respectively. GRF_{MLT} also showed significant main effects of exercise duration ($p = 0.033$). GRF_{MLT} was lower for the 2R protocol than for the 1R or BB, but the 1R and BB means were not significantly different from each other. Average differences for 1R vs. 2R and BB vs. 2R were 0.007 (6.8%) and 0.008 (7.7%), respectively. GRF_{VLL} were significantly lower for the BB protocol relative to the 1R protocol ($p = 0.045$), but not the 2R protocol. The 1R and 2R protocol means were not significantly different from each other, but were very close to the significance threshold ($p = 0.052$). The average difference in GRF_{VLL} between 1R and BB was 0.033 (2.9%).

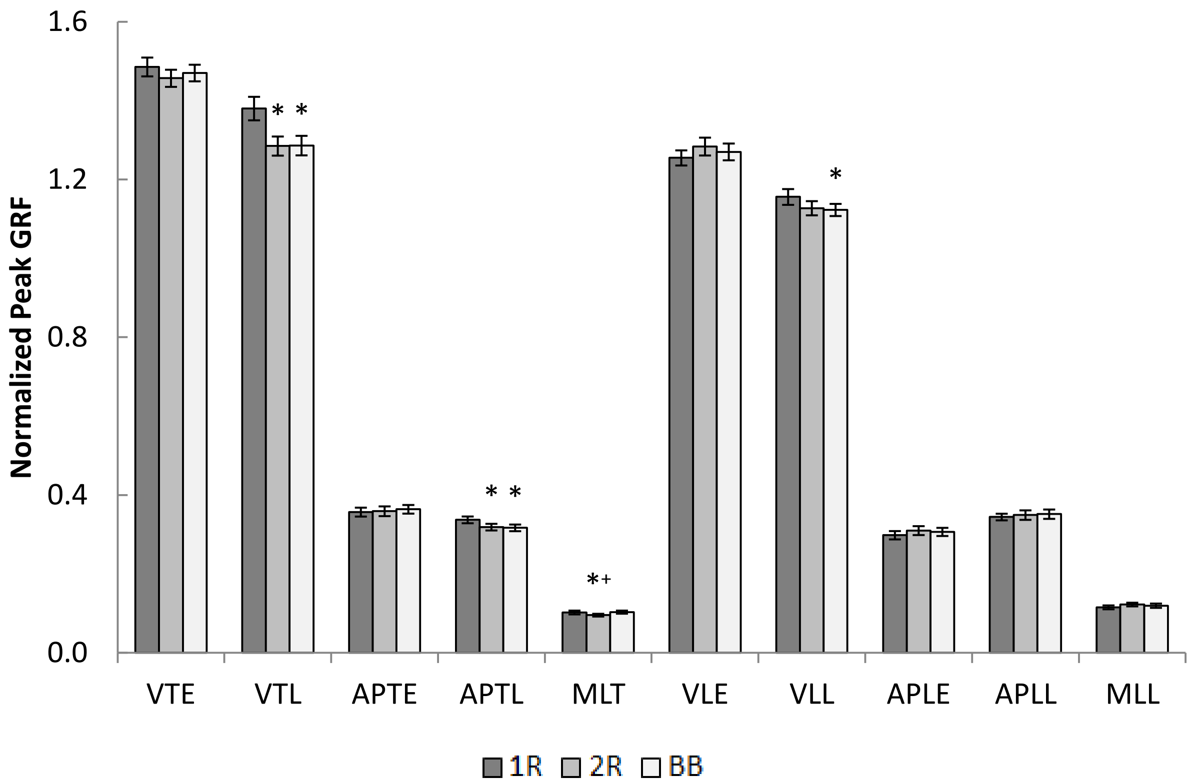

Figure 20. Group III normalized peak GRFs by exercise duration. An asterisk (*) indicates significant difference from 1R. A plus (+) indicates significant difference from BB.

The GRF MANOVA also revealed significant main effects of fatigue ($p < 0.001$) (***Figure 21***). GRF_{VTL} and GRF_{APTL} each decreased significantly with fatigue ($p < 0.001$ for both variables) by averages of 0.098 (7.1%) and 0.030 (8.7%), respectively. GRF_{APTE} increased significantly with fatigue ($p = 0.016$) by an average of 0.022 (6.2%). GRF_{VLL} decreased significantly with fatigue ($p < 0.001$) by an average value of 0.065 (5.6%). GRF_{APLE} increased significantly with fatigue ($p < 0.001$) by an average of 0.039 (13.6%).

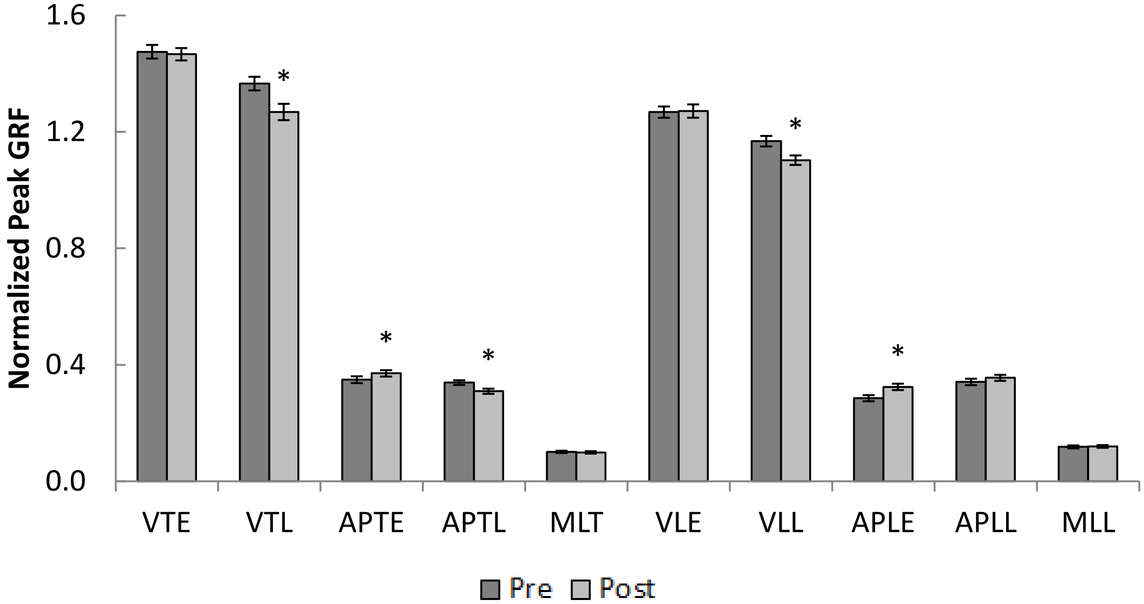

Figure 21. Group III normalized peak GRFs by fatigue. An asterisk (*) indicates significant difference from pre.

The GRF MANOVA also revealed significant exercise duration ×fatigue interaction effects ($p = 0.010$) (***Figure 22***). GRF_{VTE} was significantly affected ($p = 0.001$), increasing with fatigue for 1R and decreasing with fatigue for 2R and BB. A significant interaction effect was also observed on GRF_{VTL} ($p < 0.001$). All three exercise protocols showed decreases with fatigue, with more substantial decreases for 2R and BB than for 1R. GRF_{APTL} showed significant interaction effects as well ($p = 0.004$), resulting in a larger decrease with fatigue for the 2R and BB exercise protocols than for the 1R protocol. No significant interaction effects were observed on lead foot GRFs.

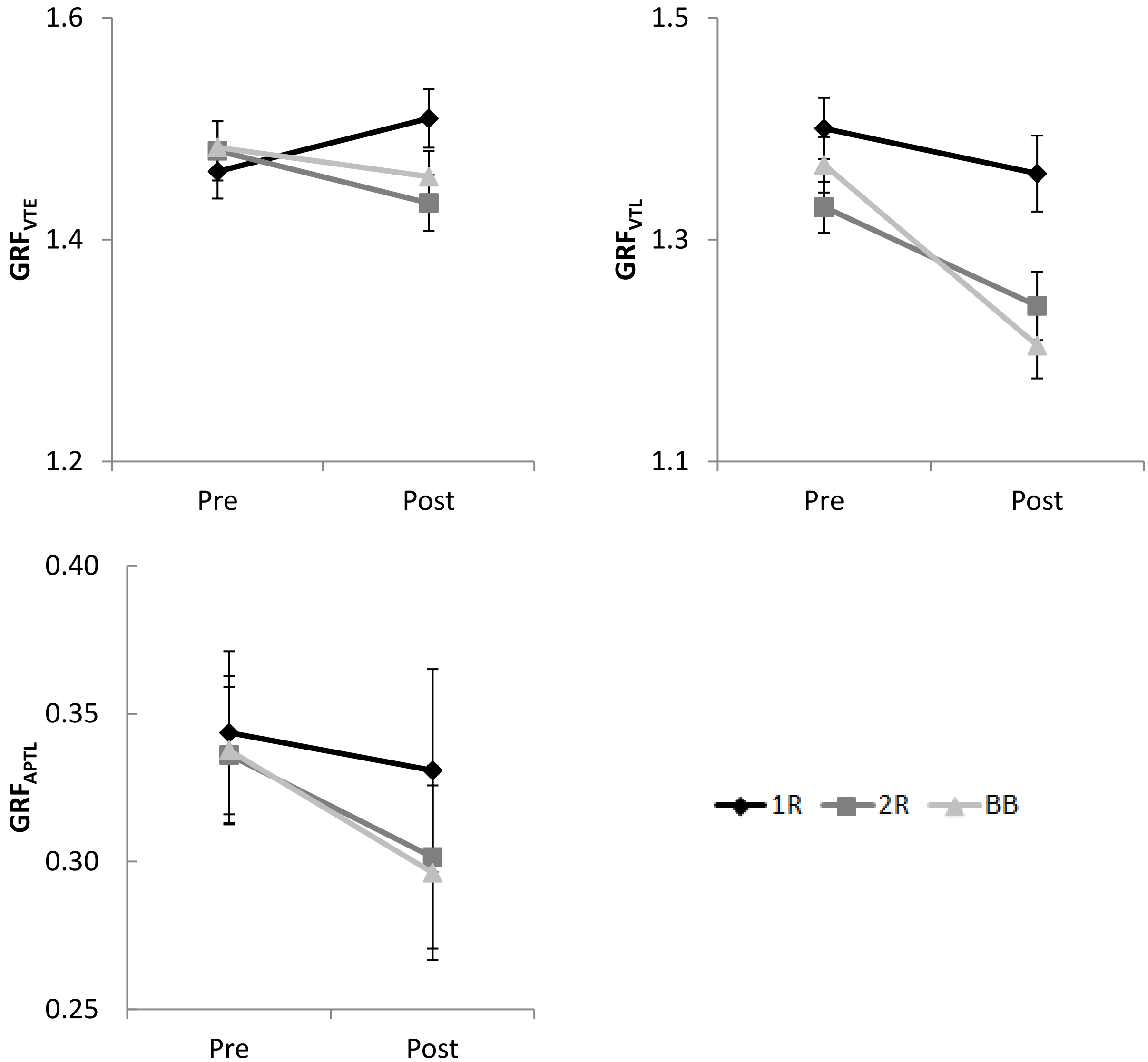

Figure 22. Group III normalized peak GRF exercise duration × fatigue interaction effects.

3.4.4 Group IV: SCBA Size × Exercise Duration

The final comparison group targeted the effects of extended duration exercise protocols in combination with SCBA size. Tests using the S30 and S60 SCBA for 1R and 2R exercise protocols were included in this comparison group.

Exercise duration appeared to be related to contact error totals, particularly with heavier SCBA (***Table 5***). More contact errors were committed post exercise for all test conditions. The increase in error totals from pre to post exercise was larger for the 2R conditions, with the increase for the S60 2R being the largest. The majority of the contact errors committed were minor (95.7%), and all but one of these were committed with the trialing foot (97.7%).

The MANOVA performed on the classic clearance metrics revealed significant main effects due to fatigue ($p = 0.008$) and exercise duration × fatigue interactions ($p = 0.010$). Follow up univariate ANOVAs revealed that VCL significantly increased with fatigue ($p = 0.049$) by an average of 0.8 cm (***Figure 23A***). The MANOVA also indicated significant interaction effects on VCL ($p = 0.038$), with a larger increase in VCL following 1R protocols versus 2R. The MANOVA performed on the radial clearances and peak boot heights also revealed significant effects due to fatigue ($p < 0.001$) and exercise duration × fatigue interactions ($p = 0.010$).Follow up univariate ANOVAs revealed CL increased significantly due to fatigue ($p < 0.001$) by an average of 1.4 cm, while hT and hL both decreased significantly with fatigue ($p = 0.006$, $p = 0.005$) by averages of 1.3 cm and 1.1 cm, respectively (***Figure 23B***). In addition, the clearance angle MANOVA revealed a significant main effect of fatigue ($p = 0.004$). Follow up ANOVAs indicated θ_L increased significantly with fatigue ($p = 0.001$) by an average of 5.7° (***Figure 23C***).Follow up ANOVAs also revealed significant exercise duration ×fatigue interaction effects on CT, hT, and hL ($p = 0.006$, $p = 0.031$, $p = 0.036$, respectively). All three variables decreased with fatigue, with a greater decrease occurring for 2R exercise protocols compared to 1R (***Figure 24***).

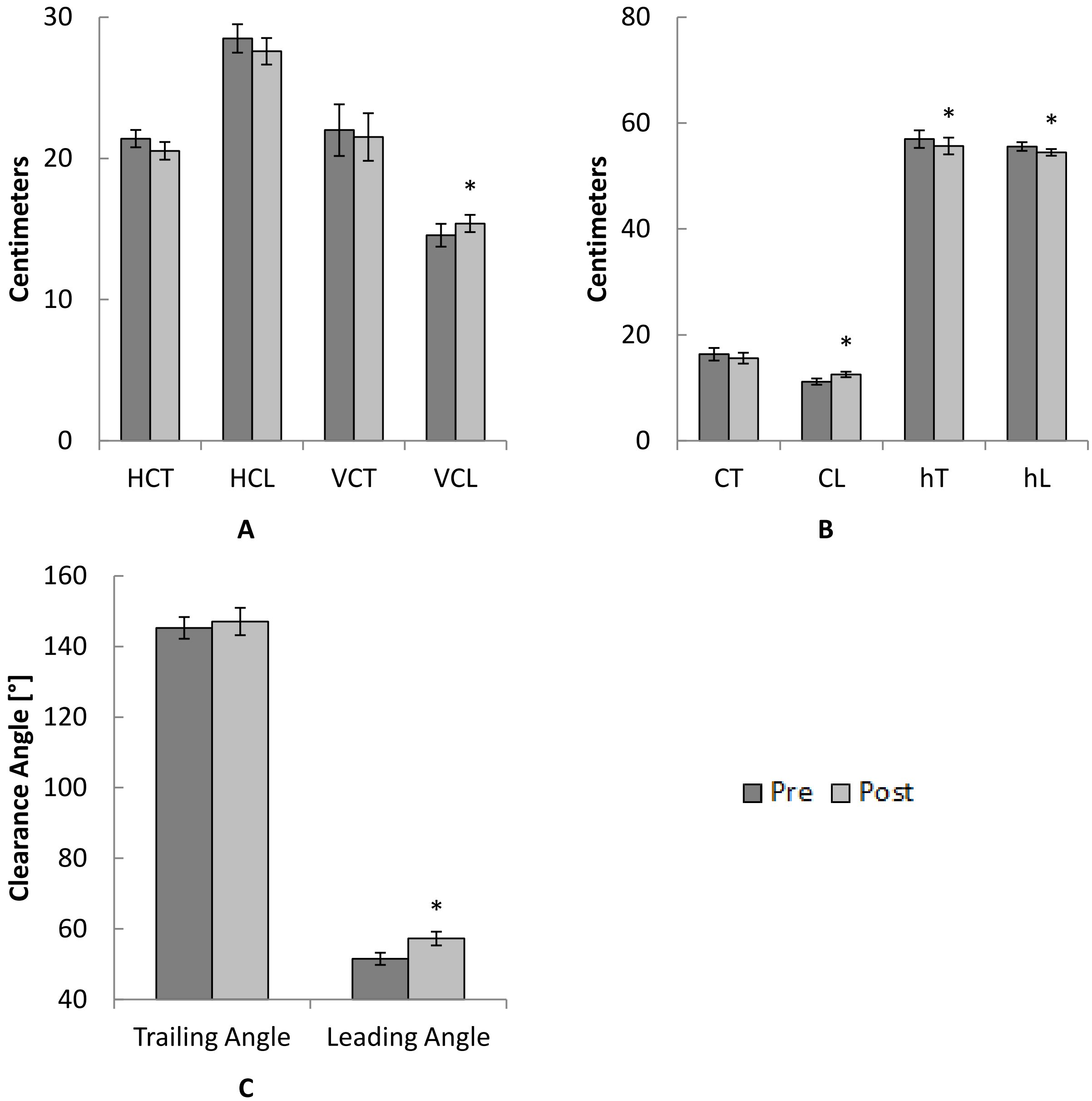

Figure 23. Group IV clearance metrics by fatigue. (A) Classic clearances. (B) Radial clearances and peak boot heights. (C) Radial clearance angles. An asterisk (*) indicates significant difference from pre-exercise.

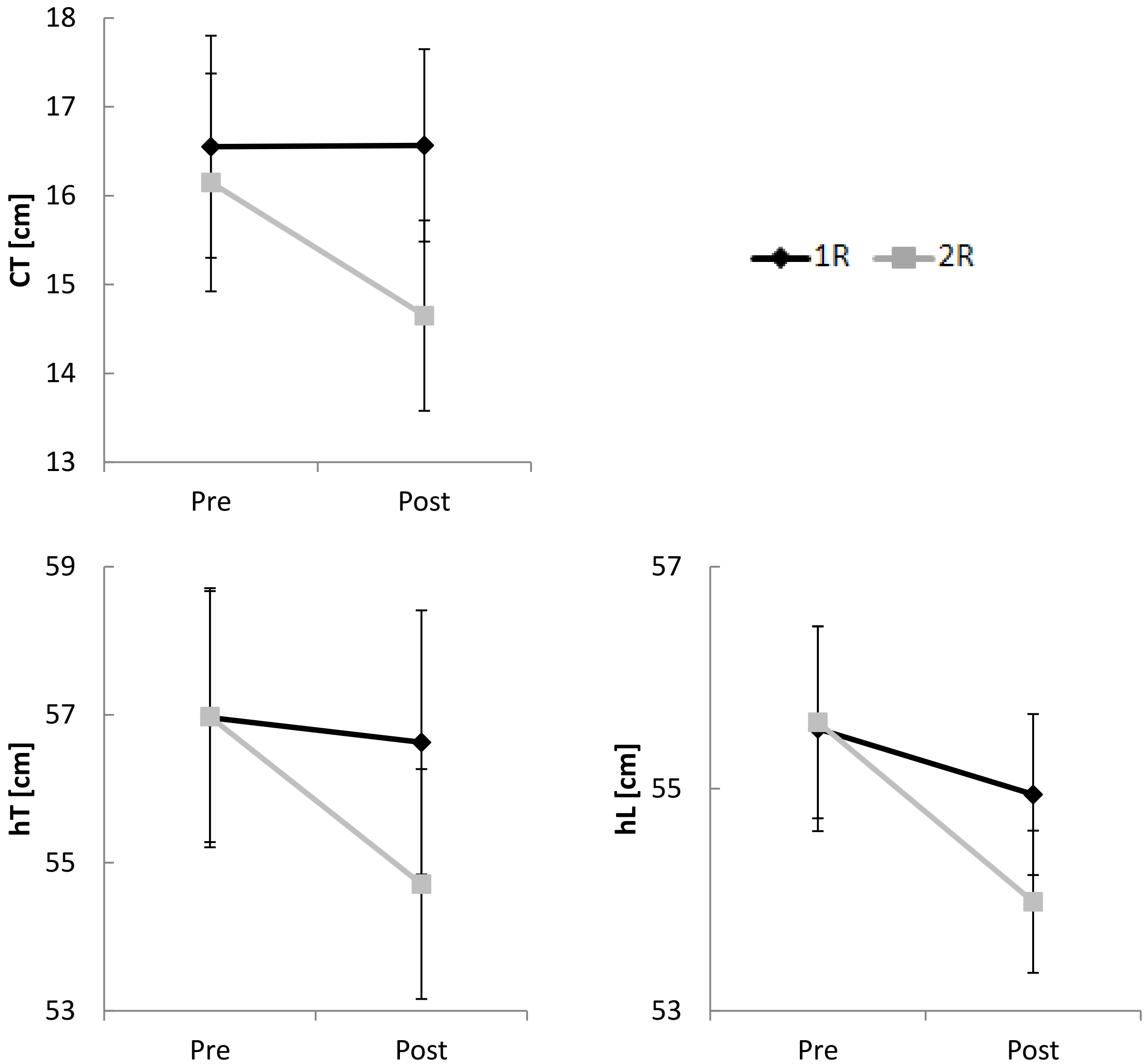

Figure 24. Group IV trailing clearance and peak boot height exercise duration × fatigue interaction effects.

The group IV MANOVA on peak GRF variables revealed significant main effects of exercise duration ($p = 0.013$) (***Figure 25***). Follow up analyses revealed GRF_{VTE} to be significantly lower for the 2R exercise protocol versus the 1R protocol ($p = 0.012$), having an average difference of 0.037 (2.5%). GRF_{VTL} and GRF_{APTL} were both significantly lower for the 2R exercise protocol relative to the 1R protocol ($p < 0.001$ for both variables), with average differences between 1R and 2R protocols of 0.083 (6.2%) and 0.018 (5.4%), respectively.

GRF_{VLL} were significantly lower for the 2R protocol relative to the 1R protocol ($p = 0.002$), with an average difference of 0.037 (3.2%).

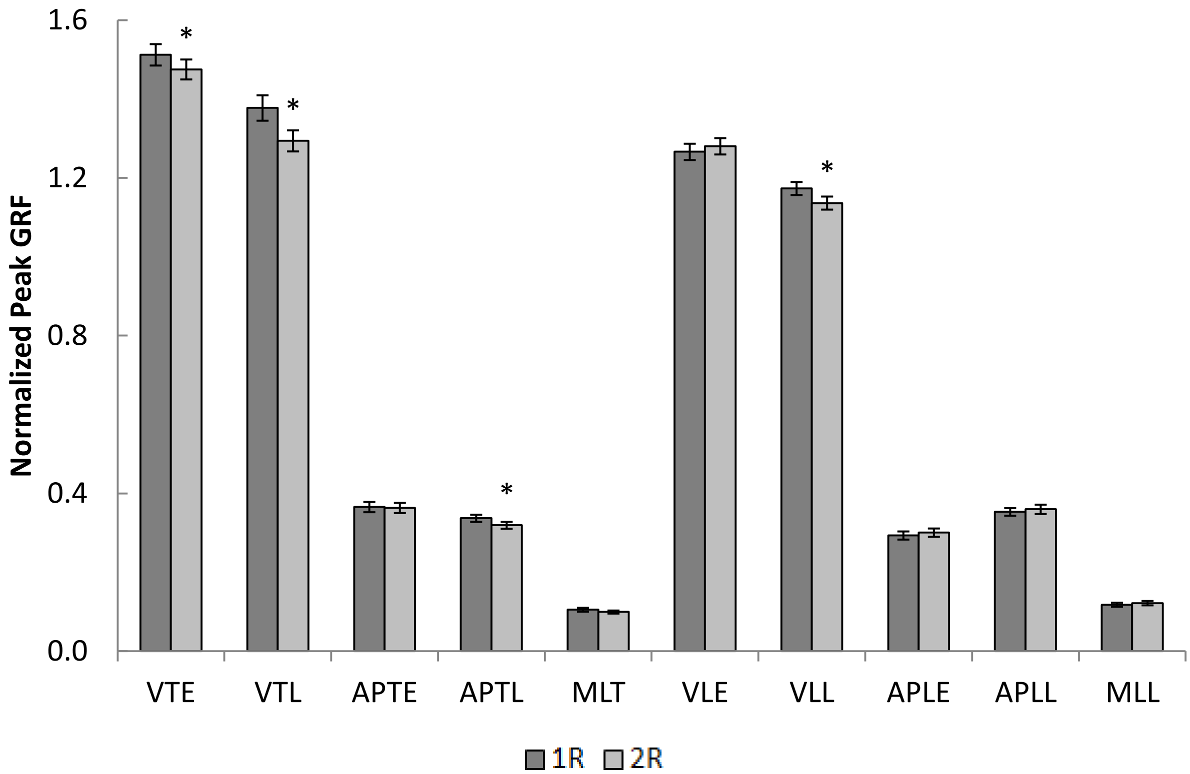

Figure 25. Group IV normalized peak GRFs by exercise duration. An asterisk (*) indicates significant difference from 1R.

The group IV MANOVA also showed significant fatigue main effects on several peak GRF variables ($p < 0.001$) (***Figure 26***). Follow up univariate ANOVAs revealed that GRF_{APTE} increased significantly with fatigue ($p < 0.001$) by 0.029 (8.4%). GRF_{VTL} and GRF_{APTL} both decreased significantly with fatigue ($p < 0.001$ in both cases) by respective averages of 0.082 (6%) and 0.032 (9.2%). GRF_{VLL} decreased significantly with fatigue ($p < 0.001$) by an average of 0.070(5.8%). GRF_{APLE} and GRF_{MLL} increased significantly with fatigue ($p < 0.001$, $p = 0.007$) by averages of 0.037 (13.4%) and 0.007 (6%), respectively.

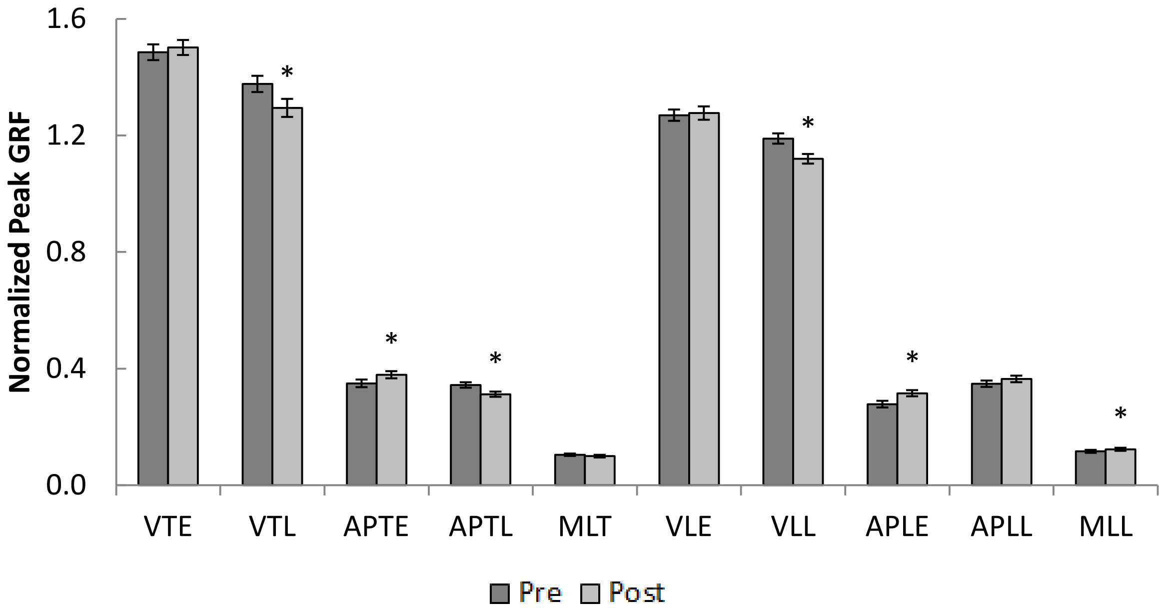

Figure 26. Group IV normalized peak GRFs by fatigue. An asterisk (*) indicates significant difference from pre.

The MANOVA also revealed significant exercise duration ×fatigue interacθtion effects on peak GRF variables (p = 0.008) (***Figure 27***). Follow up ANOVAs revealed a significant interaction effect on GRF_{VTE} (p = 0.001), which increased with fatigue for 1R and decreased with fatigue for 2R. Follow up analyses also indicated significant interaction effects on GRF_{VTL} (p = 0.028) and GRF_{APTL} (p = 0.001). For both variables, both exercise protocols showed decreases with fatigue, with larger decreases for 2R than for 1R. No significant interaction effects were observed on any lead foot GRFs.

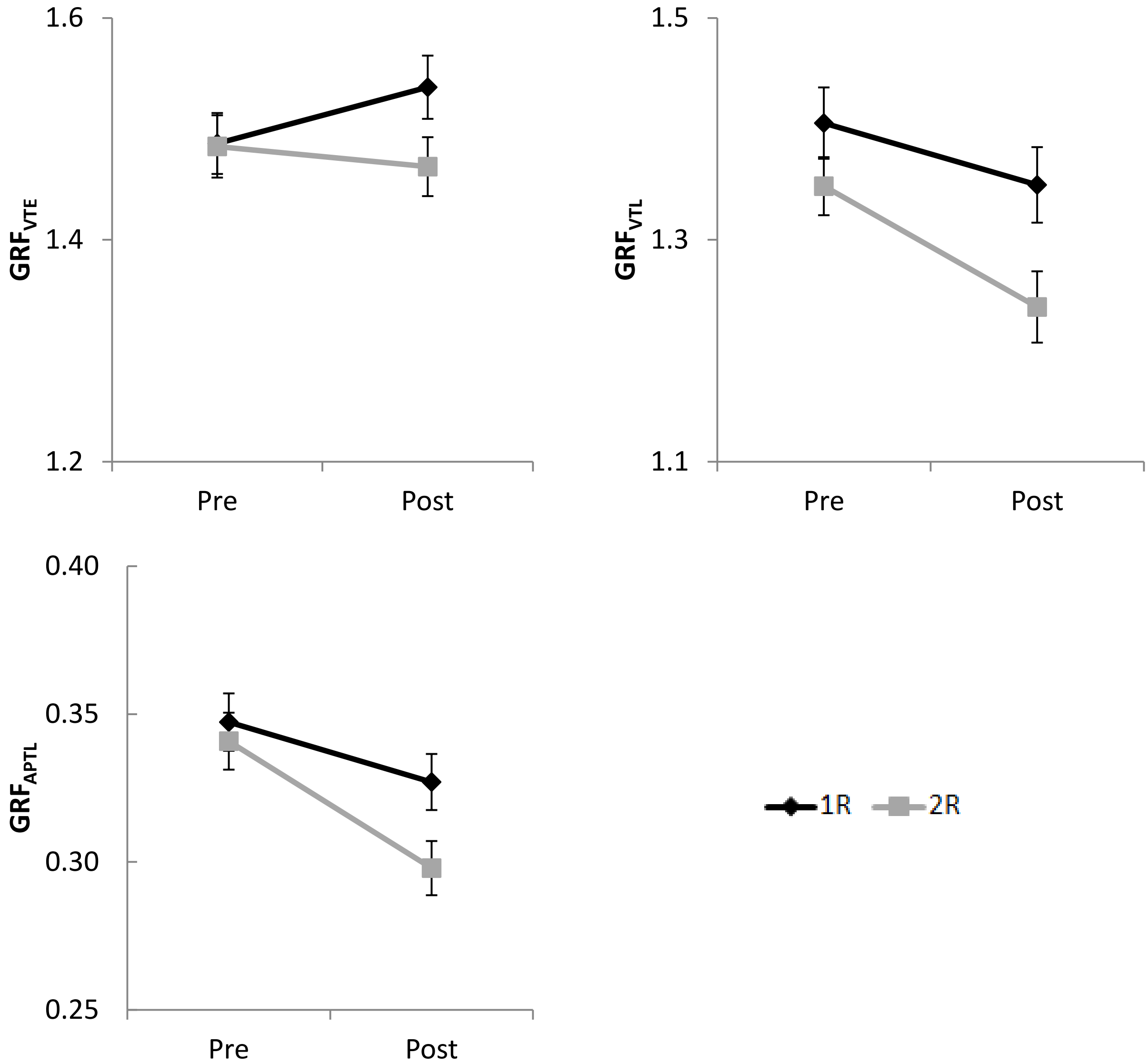

Figure 27. Group IV normalized peak GRF exercise duration × fatigue interaction effects.

3.4.5 Other Observations

- More significant effects were observed using the radial clearance metrics than with the classic clearance metrics.
- In the majority of trials (~96%), CL was the distance from the heel to the back edge of the obstacle, clearance C2 (***Figure 12***).

- The MANOVA performed on subject characteristics among the error bins revealed no significant differences among the characteristics of the subjects within the three binned groups (***Table 9***).
- As a side study, radial and classic clearance metrics were normalized by subject leg length. No differences in statistical significance of the results were observed between normalized and raw clearance values.

Table 9. Subject attributes broken down by Study 2 error bins. All values are recorded as average ± standard deviation.

Error Bin	***n***	***Age [years]***	***Experience [years]***	***Height [m]***	***Weight [kg]***	***BMI [kg/m^2]***
No Errors	*9*	*35.2 ± 8.3*	*11.4 ± 8.2*	*1.83 ± 0.07*	*93.5 ± 12.9*	*27.8 ± 2.6*
1-9 Errors	*17*	*30.1 ± 6.9*	*8.2 ± 7.2*	*1.83 ± 0.07*	*92.5 ± 16.6*	*27.6 ± 4.5*
10+ Errors	*4*	*23.3 ± 3.8*	*4.75 ± 2.2*	*1.77 ± 0.02*	*80.5 ± 6.1*	*25.8 ± 2.5*

3.5 DISCUSSION

The aim of this study was to investigate the effects of SCBA size, SCBA design, extended duration firefighting, and fatigue on obstacle crossing performance. Performance was quantified by contact errors, classic horizontal and vertical foot clearances, new clearance metrics (radial foot clearances and angles, and peak boot heights), and normalized peak GRFs for each foot. Contact error totals appeared most affected by fatigue and exercise duration. Clearances showed statistically significant differences due to fatigue and extended duration exercise, while clearance angles were only significantly affected by fatigue. Peak boot heights showed significant effects of fatigue and exercise duration. GRFs were significantly affected by SCBA design, fatigue, and exercise duration.

In all four comparison groups, the radial clearance of the lead foot CL increased significantly with fatigue. Previous studies have observed this behavior in populations at higher risk of falls, such as the elderly [65], [67], [68] and those suffering from neurological impairments [70], [73], [75], [81]. This behavior may be a compensatory strategy to account for a loss of lower limb control when fatigued. This strategy is believed to be achieved by increased lead limb hip and knee flexion [63], [121], perhaps demanding more control from the stance limb to maintain stability. Increasing CL may also require increased trailing limb single leg stance time, resulting in instability which can be hazardous [70], particularly when navigating the uneven surfaces commonly encountered on the fireground. Furthermore, this strategy may require a higher metabolic cost which can lead to additional muscular fatigue, particularly if the motion is to be frequently repeated [114]. Thus, increasing CL in response to fatigue may ensure obstacle clearance, but may introduce other instabilities which can increase risk of fireground STF injury. Further studies should examine the effect of fatigue on trailing limb stance time and metabolic cost.

Lead foot clearance angle θ_L also increased with fatigue in all four comparison groups. The increase in θ_L in combination with the increase in CL indicates an increase in the vertical component of the minimum heel clearance, taking into account that CL was the distance from the heel to the back edge of the obstacle – clearance C2 (***Figure 12***) – in the overwhelming majority of trials (~96%). This evidence may further support the conclusion that subjects employ compensatory strategies to ensure lead foot obstacle clearance when fatigued. Several trailing foot peak GRF variables were significantly affected by fatigue across all four comparison groups as well. GRF_{VTL} and GRF_{APTL} decreased with fatigue, indicating lower propulsive forces. Previous studies have found higher late stance peak GRFs to be related to increased hip joint height for the lead limb – an important gait adjustment which allows for safe obstacle negotiation [51], [63]. Since the opposite trend was observed in this study, it is possible that the lower late stance propulsive forces indicate decreased obstacle crossing performance when fatigued. Further analyses of joint kinematics are necessary to assess the validity of this conjecture. GRF_{APTE} also increased following exercise, indicating the use of a larger braking force before the obstacle crossing step. A larger braking force would require a higher coefficient of friction from the ground in order to prevent slipping, so an increase in these forces may be an indicator of increased slip risk when fatigued, particularly in the absence of an increased normal force [55], [56], [112].

Lead foot peak normalized GRFs were also significantly affected by fatigue in all groups. GRF_{APLE} increased with fatigue, showing a higher braking force after crossing the obstacle. This result may also signify an increased risk of slipping [55], [56], [112]. A lead foot slip may pose a greater risk of a fall and injury, as the obstacle obstructs the trailing foot from participating in normal recovery strategies [123]. In groups I (SCBA size group), II (SCBA design group), and IV (SCBA size × exercise duration group), GRF_{MLL} increased significantly with fatigue, with a non-statistically significant increase in group III. Higher peak ML forces may indicate a reduction in stability and increased slip risk of the lead foot [55], [56], [112]. This could also be a sign of increased fall risk, as recovery strategies from a lead foot slip are obstructed by the presence of the obstacle [123]. Similar to GRF_{VTL}, GRF_{VLL} decreased following exercise, also indicating a reduction in propulsive force [51], [63]. The reduced propulsive forces may also herald reduced performance in the steps immediately following obstacle crossing, and could have more severe consequences when walking on the types of uneven terrain typically encountered on the fireground.

3.5.1 Group I: SCBA Size

This comparison group examined potential differences among the three standard SCBA (S30, S45, S60), along with the effects of fatigue brought on by a single round of simulated firefighting activity (1R). To clarify, the test conditions evaluated were S30_1R, S45_1R, and S60_1R (***Table 4***).

Contact error totals within this group did not appear to show any effects of SCBA size, but were generally more frequent in post-exercise trials (***Table 5***).A previous study by Park et al. found that carriage of heavier loads led to higher frequency of contact errors [13]. This study yielded conflicting results. There was little difference between the S30 and S60 contact error totals, but the S45 had an unusually high frequency of errors, particularly in the pre-exercise condition. This anomalous error total for the S45 is surprising, and does not seem to indicate any particular trend, although two subjects did account for four of the ten pre-exercise S45 errors. Another study by Park et al. noted an increase in contact errors when subjects used an enhanced PPE configuration, likely due to lack of familiarity with the equipment [14]. However, in the present study most of the firefighters tested had regularly used the S45 or an SCBA of comparable size and weight during routine structural firefighting. In contrast, most had not used the S60 configuration prior to the experiment, but it did not result in a clear increase in contact errors. This result is contradictory to the hypothesis that increased SCBA size would contribute to higher contact error totals.

No effects of SCBA size were observed on any other variables in group I. These results were contradictory to the original hypothesis that increased SCBA size would lead to reduced clearances and peak boot heights, and increased peak normalized GRFs. These results are also contradictory to Park et al., who observed a decrease in the vertical clearances of both feet when crossing obstacles while equipped with heavier SCBA configurations [13]. However, Loverro et al. found an increase in minimum foot clearance of the trailing foot in soldiers when wearing either light or heavy body armor as compared to no body armor [53]. Perry et al. also observed an increase in lead toe clearances when carrying anterior loads of increasing weight [27]. In each of those studies, the differences in weight between load configurations were generally larger than those implemented in the current study. It is possible that the weight differences among the SCBA configurations used in this study (***Figure 11***) were not large enough to expose any effects of increased load carriage or to induce compensatory obstacle crossing strategies. It is worth noting that both Park et al. [13] and Loverro et al. [53] used varying obstacle heights in their studies, and the anterior load used by Perry et al. [27] obscured vision of the obstacle, likely causing subjects to change their obstacle crossing strategies and affecting clearance results. Further studies of the effects of SCBA weight have shown physiological benefits to lighter SCBA during stair stepping tasks [96] and simulated fire suppression [97]. The results of these studies may suggest that a reduction in SCBA size may improve performance in other common firefighting tasks in spite of the lack of significant effects on obstacle crossing ability.

The lack of SCBA size effects on normalized peak GRFs is in agreement with the literature, provided that the same normalization technique was used. In this study, GRFs were normalized by the static weight of the subject in full PPE with each SCBA configuration. This normalization technique was selected to attempt to isolate changes in GRFs induced by actual changes in obstacle crossing gait from those due to increased static weight. Park et al. [13] reported increases in peak GRFs with increasing load carriage during obstacle crossing, but only when the peak GRFs were normalized by bodyweight alone. When normalized by the total weight of the subject's body and load, Park et al. [13] found no statistically significant differences in the peak GRF results during obstacle crossing, matching those presented here. Results of an over ground walking study by Tilbury-Davis and Hooper [104] were similar, with no discernible changes in peak GRFs when normalized by the total weight of the subject and load. Other gait studies saw increases in peak GRFs normalized by bodyweight alone that were proportional to the static weight of the load, and have suggested that the trend signifies that changes in the acceleration of the system are less significant than the increase in static weight [21], [101]. These studies typically examined the behavior of people tasked with long periods of continued locomotion while carrying loads, such as military personnel. As such, the increased GRFs due to static loading have more critical implications regarding continued loading of limb joints and overuse injuries. For firefighters, the duration for which the SCBA must be carried is generally much shorter, so the effects of changes in the acceleration of the system may provide more insight into the contributing factors to STFs and their associated fireground injuries verses the effects of increased static weight. This was the reason that we normalized by body weight plus the weight of the SCBA configuration.

In addition to the variables significantly affected by fatigue mentioned previously, GRF_{VTE} significantly increased following simulated firefighting activities in this comparison group. This indicates a larger downward acceleration of the COM upon impact before crossing the obstacle. Previous studies have found increased vertical peak GRFs at higher over ground walking and running speeds [124], [125]. Although no spatiotemporal variables were examined in this study, those results suggest that the increase in GRF_{VTE} may imply increased gait speed prior to crossing the obstacle. However, in both of those studies, increases were observed in both the early stance and late stance peaks with walking speed, while in this study the late stance peak decreased following exercise. This discrepancy may be due to the presence of the obstacle in our study, and further gait analysis is suggested.

3.5.2 Group II: SCBA Design

This comparison group examined potential differences among the standard 60-minute SCBA (S60) and the prototype 45-minute SCBA (P45), along with the effects of fatigue brought on by a single round of simulated firefighting activity (1R). These two SCBA configurations were compared because they have differing geometries, but comparable weights (***Figure 11***). To clarify, the test conditions evaluated were S60_1R and P45_1R (***Table 4***).

Effects of SCBA design were minimal on nearly all of the examined outcome variables. Slightly fewer contact errors were committed when subjects crossed the obstacle using the prototype SCBA P45 relative to the large cylinder S60, with the difference more pronounced pre-exercise. This result may suggest that the shift of the total system center of mass (COM) closer to the body's natural unloaded COM facilitates subjects' ability to safely navigate the obstacle. However, the frequency of errors was low, so a much larger sample size would likely be required to determine this conclusively. This result is somewhat surprising, as none of the firefighters tested in the present study had worn the P45 before participating in the experiment. In contrast, firefighters in previous studies were more apt to make obstacle contact errors when wearing an unfamiliar PPE configuration [14]. GRF_{VTL} was also statistically significantly lower in trials using the P45 (***Figure 16***). This result suggests a reduction in propulsive force in preparation for the trailing limb to cross the obstacle when using the P45, potentially indicating decreased gait performance during crossing [51]. However, the difference in GRF_{VTL} between the S60 and P45 was small (2.7%), which may call into question the clinical significance of this result.

No other variables showed significant effects of SCBA design. These results may indicate that the shift of the body and gear system COM closer to the natural COM of the body by the P45 does not provide any advantages in obstacle crossing gait performance, supporting the original hypothesis. Park et al. [13] have shown similar results when examining the effects of ergonomically redesigned SCBA on firefighter obstacle crossing. Further load carriage studies have shown redistribution of load so as to keep the system COM as close as possible to the body's natural COM to have some benefits in functional tasks other than obstacle crossing. Lloyd et al. [100] found slight reductions in support times and propulsive GRFs in soldiers using rucksacks with more natural load distributions. Kinoshita et al. [101] showed advantages in walking gait performance while wearing a double pack (front and back loads) as opposed to a backpack for carrying loads. Griefahn et al. [46] observed increased performance and physiological benefits when using SCBA designed for better weight distribution in simulated smoke diving tasks. Love et al. [108] found that SCBA which produce lower moments of inertia about the body's COM received higher comfort ratings and led to improved performance in functional tests. These observed benefits may imply that – although no positive effects of novel SCBA design were observed on obstacle crossing – SCBA designs which redistribute weight to a more ergonomically favorable position may have advantages over traditional cylinders when performing other functional tasks on the fireground. Further examination of the other functional tasks included in the larger scope of this investigation may assist in clarifying this inference.

In addition to the increase in CL mentioned previously (***Figure 15***), a statistically significant increase with fatigue in the classic clearance metric VCL was also observed in this group. Like the increase in CL, this may be due to a compensatory strategy to ensure obstacle clearance when fatigued [70], [73], [81]. However, the absence of statistically significant effects on peak boot heights seems to suggest that the compensation was achieved through some technique other than simply lifting the foot higher off the ground. Further study including joint kinematics may help to shed light on this issue, although tracking subject motion while wearing PPE currently remains challenging.

Similar to the results observed in group I, GRF_{VTE} significantly increased with fatigue in this comparison group (***Figure 17***). Again, this signifies a larger downward acceleration of the COM prior to lead foot swing over the obstacle. As stated in the previous section, higher vertical peak GRFs have been observed at higher walking and running speeds during level locomotion [124], [125], which may suggest that the higher GRF_{VTE} seen here implies increased gait speed approaching the obstacle. Because the trends in the late stance GRF peaks were not similar, however, it is unclear whether there was an increase in gait speed in the absence of spatiotemporal data.

3.5.3 Group III: Exercise Duration

This comparison group observed potential differences in the fatigue induced by the three exercise protocols implemented in this study. To reiterate, these protocols were a single round of simulated firefighting activities (1R), two rounds of activities with a five-minute rehabilitation break between rounds (2R) and two rounds of back-to-back activity with no break (BB). For all tests included in this analysis group, only the S60 SCBA configuration was used. To clarify, the test conditions evaluated were the S60_1R, S60_2R, and S60_BB (***Table 4***).

Contact error totals appeared to be dependent on exercise protocol (***Table 5***). Contact errors increased with fatigue for all three protocols, with larger increases following 2R and BB protocols (***Table 5***). These increases suggest that extended duration exercise leads to increased risk of obstacle contact, which may translate to a higher frequency of trips and falls on the fireground. Studies have shown that longer duration exercise can result in greater fatigue, with muscles requiring longer recovery periods before returning to baseline performance levels [93]. While there was an observed increase from the 1R exercise protocol, the difference in errors between the 2R and BB protocols was small, supporting the hypothesis that the potential benefits of the five-minute rehabilitation break between bouts of simulated firefighting activity may have been negligible. Previous studies have shown that extended rehabilitation periods – even in the presence of active cooling – are often necessary to reduce thermal and physiological strain from strenuous activity [29], [33], [34], [40], [82], [94], [95]. It is therefore likely that the five-minute rehabilitation period was not sufficient to provide any tangible benefits of recovery.

Trailing foot clearance was also significantly affected by exercise protocol. Average CT for 2R and BB protocols were lower than for 1R, but were not significantly different from each other (***Figure 18***). Although the exercise protocol × testing period interaction was not statistically significant for CT, non-statistically significant trends show that CT changed little following 1R protocols, but decreased noticeably after 2R and BB exercise protocols (***Table 6***). These results are in agreement with those of the contact error analysis, especially considering that the majority of contact errors were committed by the trailing foot. They also further support the hypothesis that the effects of the rehabilitation break are minimal, as several studies have suggested [29], [33], [34], [40], [82], [94], [95]. The increase in contact errors and decrease in CT suggest that the likelihood of trailing foot obstacle contact is increased by performing extended duration firefighting activities. This may point toward increased trip and fall risk with higher degrees of fatigue. The literature suggests that fatigue results in reduced sense of limb position [90], [91]. Higher degrees of fatigue and lack of tangible effects of rehabilitation can amplify this effect, particularly for the trailing limb, for which visual feedback is not available [63]. Although the risk of contact is increased, the literature suggests that lead foot errors may be more hazardous than trailing foot errors due to the motion of the body's COM in relation to the base of support at the instance of contact, increasing likelihood of a fall [70], [116], [121]. However, trailing foot errors can still result in falls, and their high frequency only furthers their contributions to STFs injury risk.

Several normalized peak GRF variables showed significant differences among the three exercise protocols (***Figure 20***). GRF_{VTL} and GRF_{APTL} marginal means were significantly lower for 2R and BB exercise protocols compared to 1R, indicating a reduction in propulsion of the trailing limb after the lead foot has crossed the obstacle. These results may indicate reduced hip joint height, and consequently reduced gait performance during obstacle crossing [51], [63], [121], and are consistent with the previous results suggesting that extended duration firefighting may increase risk of obstacle contact. GRF_{VLL} was also significantly lower for the BB and borderline significantly lower for the 2R relative to the 1R protocol, signifying reduced lead foot propulsive force when taking the first step after crossing the obstacle. This may indicate reduced gait performance in the steps immediately following obstacle crossing, which could be hazardous on the uneven terrain commonly encountered on the fireground..

Perhaps the most compelling GRF results were those which showed significant exercise duration ×fatigue interaction effects (***Figure 22***). Because the pre-exercise conditions were very similar for all three exercise protocols, the interaction effects may provide a clearer picture of the effects of the different protocols than the exercise duration main effect alone. GRF_{VTE} tended to increase from pre to post exercise for 1R protocols, but decreased for 2R and BB protocols. This indicates that subjects had a tendency to apply a lower load to their trailing limb prior to lead foot swing over the obstacle following 2R and BB protocols. Previous studies have observed reduced gait speed during obstacle crossing in populations at higher risk of falls [66], [77], [81], of which reduced GRF_{VTE} may be an indicator [124], [125]. GRF_{VTL} and GRF_{APTL} decreased with following exercise for all three protocols, with more pronounced reductions for the 2R and BB protocols. This result indicates decreased propulsive forces in preparation for the trailing foot step over the obstacle, and potentially causing decreased hip joint height during crossing [51], [63], [121]. The sharper decrease in GRF_{VTL} and GRF_{APTL} may also be related to the higher occurrence of contact errors and decreased CT observed for the extended duration protocols, as the force with which the trailing foot pushed off from the ground was reduced. These decreases in trailing foot GRFs indicate poor gait performance when fatigued – particularly following extended duration exercise protocols – and may signify increased risk of STF injury. The lack of differences between 2R and BB GRF trends further supports the hypothesis that the effects of the rehabilitation period in the 2R protocol do not provide any clear benefits, likely due to the brevity of the break.

Although CL increased with fatigue, hL significantly decreased following exercise (***Figure 19***). As mentioned previously, the increase in CL may be a compensatory strategy to maximize obstacle avoidance when fatigued. Previous studies have observed increases in lead foot vertical clearances in populations at higher risk of falling, perhaps employed for the same purpose [65], [67], [68], [70], [81]. However, the reduction in hL seems to indicate that there is more to this strategy than simply lifting the lead foot higher off the ground. The literature suggests that this strategy is achieved through increased lead limb knee flexion and hip abduction [63], [121]. Examination of joint kinematics may be able to help define the characteristics of the compensation more clearly, although at present, motion tracking of subjects' body segments while wearing PPE is beyond the means of the investigators.

3.5.4 Group IV: SCBA Size × Exercise Duration

This comparison group examined potential effects of extended duration firefighting in conjunction with SCBA size. This group included tests using the S30 and S60 SCBA configurations, and the 1R and 2R simulated firefighting activity protocols. To clarify, the test conditions evaluated were the S30_1R, S30_2R, S60_1R, and S60_2R (***Table 4***).

Observed contact error results were similar to those seen in group III. For both SCBA, contact error totals appeared to be affected by exercise duration and fatigue (***Table 5***). Contact error totals increased with fatigue, with larger increases following 2R simulated firefighting activity protocols relative to 1R. A slightly higher number of errors were committed using the S60 versus the S30, particularly following 2R exercise protocols. However, it is unclear whether these differences in contact error totals are a direct result of the SCBA due to the low frequency of errors.

Also similar to group III, significant exercise duration × fatigue interaction effects were observed on CT within this comparison group (***Figure 24***). Fatigue effects on CT following 1R protocols were negligible, while 2R protocols caused notable decreases following exercise. Recalling that most contact errors were committed by the trailing foot, these results further support the hypothesis that extended duration firefighting and the fatigue brought on as a result increase the likelihood of obstacle contact. Although the literature suggests that lead foot obstacle contact poses a greater risk of falling [70], [116], [120], falls as a result of trailing foot obstacle contact are still a concern since trailing foot obstacle contact is such a common occurrence.

Several normalized peak GRF variables were significantly affected by exercise duration (***Figure 20***). GRF_{VTE} marginal means were lower for 2R protocols relative to 1R, suggesting reduced braking forces and possibly exhibiting evidence of reduced gait speed when approaching the obstacle. GRF_{APTL} marginal means were also significantly lower for 2R protocols compared to 1R, indicating reduced propulsion of the trailing foot prior to swing over the obstacle. The reduction in propulsive forces may reveal poorer gait performance, and is in agreement with the lower trailing foot clearances and higher contact error totals observed following 2R protocols in this group. GRF_{VLL} marginal mean was also significantly lower for the 2R protocol versus the 1R, demonstrating reduced propulsion of the lead foot when taking the first step after crossing the obstacle. This may point to reduced gait performance in the steps immediately after obstacle crossing, which can be detrimental on uneven terrain such as that encountered on the fireground.

The same peak normalized GRF variables showed significant exercise duration ×fatigue interaction effects as those in group III (***Figure 27***). Here, the pre-exercise conditions for each SCBA were the similar for both 1R and 2R exercise protocols. As such, the interaction effects may be a better indicator of the fatiguing effects of the two protocols than the exercise duration main effect alone. GRF_{VTE} tended to increase from pre to post exercise for 1R protocols, but decreased for 2R protocols, indicating that subjects applied less force to their trailing limb in preparation for crossing the obstacle following 2R protocols. This may point to decreased gait speed during obstacle crossing [124], [125], which has been observed in higher fall risk populations [66], [77], [81]. GRF_{VTL} and GRF_{APTL} decreased with testing period for both 1R and 2R protocols, but more so for 2R. This suggests a sharper decrease in propulsion in preparation for stepping over the obstacle with the trailing limb – possibly related to decreased hip joint height [51], [63], [121] – leading to decreased obstacle crossing gait performance. As such, the higher occurrence of contact errors and decreased CT observed in trials following 2R protocols could be related to the reduction in GRF_{VTL} and GRF_{APTL}, as reduced trailing foot propulsive forces may have made it more difficult for subjects to lift the trailing foot over the obstacle.

Like group II, a statistically significant increase in VCL was observed with fatigue (***Figure 23***). Similar to the increase in CL, this likely demonstrates a compensatory strategy to ensure obstacle clearance when fatigued. Previous studies have observed increases in lead foot vertical clearances in populations at higher risk of falling, perhaps employed for the same purpose [65], [67], [68], [70], [73], [81]. However, similarly to group III, hL decreased following simulated firefighting activities in this group, which seems to suggest that the compensation was achieved through some technique other than simply lifting the foot higher off the ground. Again, the decrease in hL may be due to reduced lead limb hip height, signified by the lower GRF_{VTL} [51], [63], [121]. Motion data for subjects' lower limb segments may assist in elucidating this compensatory strategy, although at present this remains difficult while subjects are equipped in full PPE.

3.5.5 Other Observations

Two different sets of metrics for calculating obstacle clearances were implemented in analyzing the motion data collected during this study. The first were the classic horizontal and vertical clearance metrics used in the previous study (HCL, HCT, VCL, VCT) (***Figure 4***). The second were the minimum radial clearances and clearance angles (CL, CT, θ_L, θ_T) (***Figure 12A***), along with the peak boot heights (hL, hT) (***Figure 12B***). The classic metrics provide information concerning the location of the obstacle relative to the subject during crossing and the height of the toes or heels when the vertical planes of the obstacle edges are broken. However, the point at which the foot is closest to contacting the obstacle often does not occur at the instance when the toes or heels break these planes, nor does the maximum height the foot reaches during crossing (***Figure** 28*). Foot clearance metrics similar to the second set have been analyzed with success in previous studies [52]–[54]. It was believed that the second set of metrics may provide more detailed information concerning the proximity of the subject's foot to the obstacle throughout crossing, as well as the maximum height to which the subject is able to lift each foot. Based on these hypotheses, the second set of metrics could potentially be a better indicator of the risk of contact errors, and may also be better suited to identify characteristics of potential compensatory strategies. The results of this study showed that the radial clearance metrics may be more sensitive to changes in obstacle crossing behavior, evidenced by the higher frequency of observed statistically significant effects. As such, while they may not provide enough information to serve as an out-and-out replacement for the classic clearance metrics, their application to further study of obstacle crossing appears to have some merit.

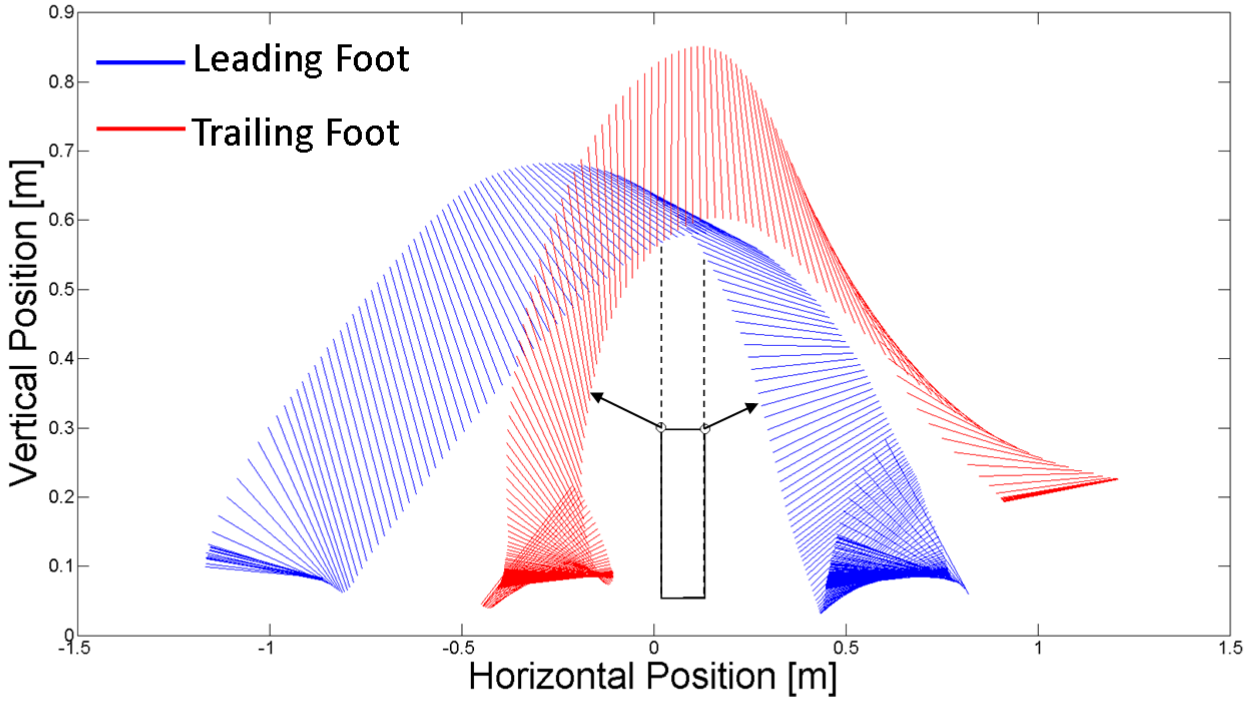

Figure 28. Foot trajectories throughout obstacle crossing. Blue and red line segments connect heel and toe locations on each foot at each captured data frame. Arrows indicate approximate locations of the minimum radial clearance. Dashed lines indicate locations of vertical clearances.

The overall MANOVA comparing the characteristics of the subjects in each of the three error bins observed in this study revealed no statistically significant differences (***Table 9***). This is contrary to the study presented in Chapter 2, in which the individuals who committed no errors throughout the duration of the study were significantly older, taller, and longer-legged. In the current study, standard deviations of characteristics may have been too large to reveal any significant differences among the bins. Non-statistically significant trends revealed that the average age and experience of the members of each bin were inversely related to their error totals, with the no-errors bin being the oldest and most experienced. The 10+ errors bin members were also smaller on average compared to the other two groups. However, based on observations made during data collection throughout the experiment, the four members of the 10+ errors bin appeared to be far less conscientious of avoiding obstacle contact. As such, it may be that the high frequency of errors committed by these individuals was more a product of personality than physical characteristics.

In addition to analyzing the classic clearances, radial clearances, and peak boot heights in the form in which they have been presented thus far, a side study was carried out in which they were normalized by each subject's respective leg length prior to statistical analysis. Subject leg lengths ranged from 81 cm to 105 cm, so the investigators sought to ensure that any significant effects on clearances and peak boot heights were not skewed due to differences in physical characteristics. Statistical tests ultimately revealed that the statistical significance was the same for all outcome variables, normalized or otherwise. Thus, the clearances and peak boot heights presented here are reported as centimeter measurement rather than nondimensional quantities, as the investigators believe interpreting the results in this form may make more intuitive sense to the reader.

3.6 CONCLUSION

The goal of this study was to quantify the effects of SCBA size, SCBA design, simulated firefighting exercise duration, and fatigue on firefighters' ability to navigate a stationary obstacle. Results showed increases in contact errors following exercise, particularly for 2R and BB exercise protocols. Clearances, peak boot heights, and normalized peak GRFs were significantly affected by testing period and extended duration firefighting activity, with several showing interaction effects between the two factors. Effects of SCBA size and design were scarce, and may not have been of any clinical significance. Further, the use of radial obstacle clearance metrics was more sensitive to gait changes than the traditionally employed horizontal and vertical obstacle clearance metrics, evidenced by the higher occurrence of statistically significant outcomes. These results do not support the hypotheses that larger SCBA would cause reductions in obstacle crossing performance. The results presented in this study do, however, support the hypotheses that the novel SCBA design would not affect obstacle crossing performance. Results also support the hypothesis that extended duration firefighting protocols – irrespective of rehabilitation breaks – would result in decreased obstacle crossing ability. The results also support the hypotheses that extended duration exercise would detrimentally impact obstacle crossing performance, while allowance for rehabilitation would not provide any tangible advantages in recovery from fatigue. Understanding the results of this study may ultimately help lead to a reduction in fireground injuries by emphasizing the importance of adequate rehabilitation following strenuous activity and providing for a better understanding of how fatigue and SCBA can impact fireground locomotor ability.

CHAPTER 4: CONCLUSIONS AND FUTURE WORK

To better understand the effects of fatigue and load carriage on firefighters' ability to cross stationary obstacles, two investigations were carried out. In the first study, foot clearances and contact errors were examined to determine firefighters' responses to different exercise protocols and carriage of a unilateral hose load. The second study examined contact errors, two different foot clearance metrics, peak boot heights, and normalized peak GRFs in order to explore the effects of SCBA size and design, fatigue, and exercise duration on firefighter obstacle crossing ability.

Results of the first study showed increases in contact errors following exercise, particularly for ECFF and BBFF protocols. Clearances were significantly affected by both fatigue and the presence of a unilateral hose load. These results suggest that firefighters may utilize compensatory strategies to ensure obstacle clearance when fatigued or carrying asymmetrical loads. These results also suggest that the strain brought on by the ECFF and BBFF protocols is similar, but greater than that of the ECTM protocol. Thus, ECFF may be a safe alternative to BBFF and can be adapted to develop a standard for simulated firefighting in a safe, controlled environment.

Results of the second study showed increases in contact errors following exercise, particularly for 2R and BB exercise protocols. Clearances, peak boot heights, and normalized peak GRFs were significantly affected by testing period and extended duration firefighting activity, with several showing interaction effects between the two factors. Overall, effects of SCBA size and design were scarce, and may not have been of any clinical significance. Extended duration firefighting activity protocols – both with and without allowance for rehabilitation and rehydration –resulted in similarly decreased proficiency in obstacle crossing. Radial obstacle clearance metrics were more sensitive to gait changes than the traditionally employed horizontal and vertical obstacle clearances, evidenced by the higher occurrence of statistically significant outcomes. These results suggest that firefighters' risk of STF injury may be greatly increased following long periods of strenuous activity. These results also suggest that SCBA size and design to not affect obstacle crossing performance its associated tripping and falling risk. These results may also help contribute to decision making concerning SCBA purchase by fire departments and SCBA design by product developers.

The results of these studies may ultimately help to reduce the frequency of fireground STF injuries. Understanding the effects of fatigue and carriage of heavy loads on locomotor ability – along with the strategies employed to compensate for them – may help to improve firefighter training and situational awareness. Furthermore, these results stress the importance of adequate rehabilitation following strenuous activity, particularly when performed for long durations.

While a great deal of effort has been put forth into investigation of the causes and risk factors associated with fireground injuries, there is still a great deal more that can be done. Although the error totals provide information into general trends, statistical analysis of the discrete error data is still necessary to conclusively determine what factors may impact the occurrence of contact errors. Also, further investigation into subjects' obstacle crossing strategies while carrying unilateral loads – particularly into the choice of the loaded or unloaded limb as the lead foot – may help to explain some of the observations made during the first study.

Finally, one of the limitations of the studies presented here was the inability to fit subjects with motion capture markers to measure body segment and joint kinematics due to the subjects'

PPE. If a technique could be developed to do so, it could greatly enhance investigators' ability to identify the characteristics of some of the compensatory strategies presented in this discussion through the application of joint kinematics, as well as open the doors to the collection of valuable data during performance of other functional tasks.

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